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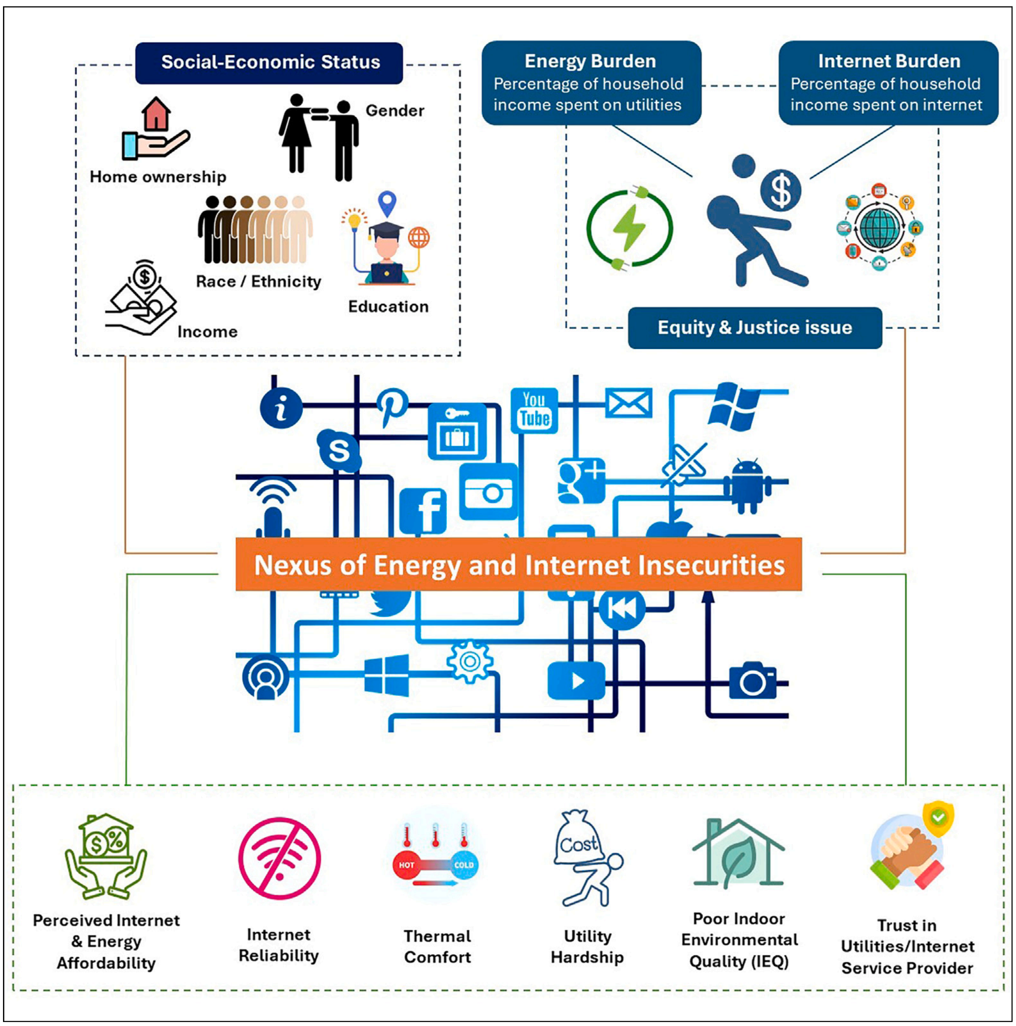

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Highlights

Reveal the digital divide and energy insecurity issues among underserved communities

Psychological impacts on trust in utility and internet providers beyond finances

Increased energy and internet burdens adversely affect indoor environmental quality

Offer policy insights prioritizing social justice to tackle intersecting inequalities

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When concentrated disadvantage happens: Exploring the nexus of energy and internet insecurities among vulnerable households

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SUMMARY

Digital divide and energy insecurity are pervasive issues among underserved communities, issues that become prounoued during the COVID-19 lockdowns. These disparities underscore the critical need to address them promptly to narrow socio-economic gaps. Our study, based on an online survey of 2,588 respondents in the United Kingdom, explores how concentrated socio-economic disadvantage exacerbates insecurities relating to energy and internet access. Our findings reveal that marginalized groups including low-income households, women, renters, ethnic minorities, and individuals with lower educational attainment are disproportionately affected. Our research extends beyond financial implications to explore the broader social and psychological effects such as trust in utility and internet providers. The study also demonstrates how heightened burdens from energy and internet costs adversely affect the quality of indoor environments, underscoring the interconnected nature of these challenges. Based on these insights, we advocate for policy interventions that adopt comprehensive social justice frameworks to tackle these intersecting inequalities effectively.

INTRODUCTION

The digital divide and energy insecurity are pervasive problems among underserved communities in many modern societies.[1–4] The digital divide is defined as the gap in who owns and has access to high-quality internet and digital technologies, which impacts people's adoption of other smart energy technologies.[5,6] Subsequently, internet insecurity is likely to be linked to energy insecurity. Energy insecurity, defined as the inability to access services and infrastructure (e.g., heating, cooling, cooking, and medical device), encompasses a range of issues, including energy poverty, fuel poverty, financial energy burden (EB—the percentage of income spending on utilities), and more.[7,8] However, while researchers have paid greater attention to the issue of the digital divide and EB among underserved communities, it is less known how energy insecurity is compounded by internet insecurity and vice versa. This lack of understanding includes the impacts of the financial cost of a high internet burden (IB), defined as the percentage of income spent on internet or broadband costs and associated insecure experiences.[2]

The interconnection between energy and digital infrastructures has accelerated across multiple scales in energy systems, as digitalization is a critical pillar of low-carbon transitions.[9] An example of this interconnection includes the proliferation of smart grid technologies, smart buildings, electric vehicles, and home energy management systems (HEMS).[9,10] Digital technologies maintained by internet connectivity are described as the Internet of Things (IoT) and increasingly enable the integration of energy-related smart technology with multiple applications, including IoT smart thermostats and lighting, energy forecasting and monitoring, energy use scheduling, and energy efficiency estimation.[11,12] Such technologies and features are often more cost effective and efficient for energy suppliers and consumers by helping them to keep track of energy consumption and shift demand to cheaper times of the day, among other benefits.[13,14] Yet, this system creates a link between energy and internet or broadband infrastructures, requiring consumers to be able to access reliable and affordable digital technologies.[2] Internet and energy insecurities remain an issue among underserved communities (e.g., low-income households [LIHs], renters, people with a disability, or poor health) in many high-income countries in the Global North, including the United States (US) and the United Kingdom (UK).

Previous research has focused primarily on the financial burdens of energy and internet usage,[7,15] with less focus on the extended impacts on individuals' social-psychological perceptions and insecure experiences, including thermal discomfort, perceived affordability, service quality of utility and internet providers, trust in service providers, and indoor environmental quality (IEQ). Therefore, this study takes a novel approach to broaden the literature on energy and internet insecurities by analyzing financial, physical, and housing impacts in underserved

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communities based on the framework of concentrated disadvantage.[16,17] This approach will include a range of intersectional axes of social-demographic differences, such as gender, race, ethnicity, income, education, and homeownership. The paper uses the general term internet when mentioning the technologies of the internet, broadband, and Wi-Fi, unless otherwise specified.

Impacts of energy insecurity

Despite multiple iterations of government initiatives to increase energy efficiency and internet and digital technology access in the UK, funding has been insufficient to address the scale of energy and internet insecurities in the broader context of reduced spending on public services.[18] Similar challenges persist in the US, despite the availability of energy assistance and other social programs.[19] Vulnerable households, including those with disproportionately low income and those burdened by energy costs, continue to face these difficulties, with some spending more than 10% of their household income on energy services.[20] As a result, disadvantaged households, such as LIHs, older adults, ethnic minorities, and private renters, continue to have unequal access to digital technologies and the internet[21–23] and disproportionately experience energy insecurity.[24,25] In addition, some of these groups, especially older adults, are less likely to have the necessary digital skills, confidence, and levels of trust to engage with new technologies.[26–28] These digital and energy inequalities reflect social and structural racial, class, and gender discrimination patterns, especially in poverty, technology ownership, housing, healthcare access, education, and occupations.[29–32]

Energy insecurity occurs when a household experiences inadequate access to energy services in the home (e.g., heating, cooking, or lighting) that negatively impacts their health and well-being.[33,34] Energy insecurity in the UK often revolves around the drivers of low incomes, high energy prices, and energy-inefficient housing,[35,36] with a particular focus on a lack of heating.[37] For example, at least two-thirds of UK households reported a poor IEQ, including drafts, dampness, mold, or overheating problems.[38] Thermal discomfort, which often results from leaks that let heating out or a lack of heating, can exacerbate medical conditions such as arthritis and chronic obstructive pulmonary disease and lengthen the recovery time from serious illness, ultimately causing more excess deaths during the winter months.[35] During the summertime, the intensification of extreme weather conditions due to severe global warming has exacerbated difficulties stemming from overheating risks and energy insecurity. This complex challenge underscores the pressing need to understand energy expenses among disadvantaged households, driven by the impact of climate change. While air conditioning significantly mitigates the effect of heat exposure on mortality,[39] its viability as a climate adaptation hinges on household financial capacity. Vulnerability to the adverse consequences of extreme heat could be heightened for households unable to bear the costs of cooling.[19] Furthermore, being homebound with a health condition has been associated with increased electricity consumption and reduced mobility.[40] Households lacking access to affordable energy services have worse mental and physical health outcomes,[41] higher mortality during extreme events such as heatwaves and pandemics,[20,29] and increased social isolation, which has been found to exacerbate the experience of poverty.[42]

During the COVID-19 pandemic, many households have been unable to meet basic energy needs, especially among LIHs.[43] Additionally, LIHs were more likely to experience increases in their home energy consumption due to government-mandated lockdowns[44,45] and temporary or permanent layoffs exacerbating their inability to pay for utilities than other households.[46]

Impacts of internet insecurity

In an increasingly digitized world, accessing and engaging with digital technologies and spaces is increasingly important for connecting with people, accessing essential services and information, and engaging with the broader economy and society.[47,48] Although digital inequalities replicate internationally,[49,50] a digital divide exists in the UK between those who can and cannot access digital technologies and infrastructures, including access to the internet.[21] The digital divide extends to those without the skills to engage with a digitally mediated world, who are consequently unable to benefit from the positive outcomes associated with internet and technology access (e.g., employment opportunities, education, and competitively priced products).[6,51] The Local Government Association estimates that 11.7 million people in the UK (7% of the population) lack the digital skills necessary for participation in everyday life; meanwhile, 3.6 million people (2% of the population) are almost entirely "offline."[52] Furthermore, digitalization is increasingly recognized as a critical component of future low-carbon transitions.[53]

In a review of the digital divide in advanced economies, Vassilakopoulou and Hustad[49] evidenced how digital inequality tends to mirror offline socioeconomic disparities. Digital competencies and internet skills have also been positively related to age, affluence, and levels of education.[54–56] For example, in Britain, 90% of households earning over £20,000 per year use the internet compared to around 60% of households earning less than £12,500.[56] Additionally, relatively remote rural areas still lag behind urban broadband coverage and usage.[57,58] Internet or digital inequalities have received greater attention as government-mandated COVID-19 lockdowns deepened the consequences of digital or internet exclusion due to a rapid online transition of many daily activities.[59,60] For instance, dependence on the internet increased during the pandemic and internet services have seen usage rise from 40% to 100%, compared to pre-lockdown levels.[61] Video-conferencing services like Zoom have seen ten times increase in usage, and content delivery services like Akamai have seen a 30% increase in content usage.[62] In addition, the pandemic has exacerbated educational inequality.[63–65] Many school children worldwide, especially those in financially disadvantaged households, have limited opportunities to access technologies such as the Internet, TVs, and computers. This lack of internet access has increased educational disparities due to widespread school closures.[66] The changes during COVID-19 highlighted both the indispensability and the inequality of internet access. As a result, tackling the digital divide or internet inequality is recognized by policymakers as a crucial component of addressing wider socioeconomic disparities. It is often central to "leveling up" policies.[60]

Energy burden and internet burden interactions

The interaction between EB and IB creates a compounding effect on vulnerable populations. In particular, households facing high energy burdens may be forced to prioritize their limited resources, often having to choose between essential utilities. For a household already struggling with energy costs, the additional financial burden of maintaining internet connectivity can be substantial.[67] Similarly, a high IB could limit a household's ability to invest in energy-efficient appliances or pay for energy bills,[68] thus reinforcing energy insecurity. This cyclical dilemma can lead to increased instances of self-disconnection from energy services to manage expenses, which, in turn, further limits access to digital technologies and the benefits they provide.

The implications of this interaction extend beyond immediate financial strain. Energy insecurity can lead to adverse health outcomes due to inadequate heating, cooling, or ventilation, as well as limited ability to preserve food or medication at safe temperatures.[69] Internet insecurity compounds these risks by hindering access to online health resources, telemedicine services, and emergency communication that are vital for managing health, especially in times of crisis such as heatwaves or pandemics. Moreover, the IB directly affects educational and employment opportunities.[66] As the world increasingly moves toward online platforms for learning and work, those without reliable internet access are at a significant disadvantage. In an education context, children from households with high EB and IB may struggle to complete homework or participate in digital learning, which exacerbates educational inequalities. For adults, the inability to search for jobs, access online training, or work remotely can lead to employment insecurities, which in turn can feedback into higher energy and internet burdens due to reduced income.

It is also essential to consider the broader societal implications of the intersection between EB and IB The proliferation of smart technologies and the IoT in urban planning and management presupposes a level of digital literacy and access that may not be present in energy-insecure households.[70] This mismatch can lead to a lack of engagement with smart energy-saving measures or city services that are increasingly delivered or managed online, further alienating underserved communities from participating in smart, sustainable city initiatives. The compounded effect of EB and IB can perpetuate social isolation. Social networks and community support systems have increasingly moved online, and without access to these digital platforms, individuals may become more isolated.[71] This social isolation can have significant psychological impacts and prevent individuals from accessing community resources that could otherwise help alleviate both energy and internet burdens.

Trust in energy and internet service providers

Bodó[72] asserted that the advent of digitalization has precipitated a crisis of trust. Traditional interpersonal and institutional norms are ill-equipped to grapple with the novel risks and uncertainties introduced by digital technologies, especially within the energy system. In times such as the COVID-19 pandemic, where reliance on online information surged, households needed assurance in the reliability and benevolent intent of these technologies.[73] Scholars have scrutinized the nexus between trust in service providers, energy efficiency behavior, and technology adoption.[74] According to Rousseau and colleagues, trust is a psychological state characterized by a willingness to embrace vulnerability based on positive expectations of another's intentions or conduct. In contexts where individuals possess limited knowledge about energy efficiency technologies or programs, their willingness to embrace novelty hinges mainly on their trust in the companies or providers overseeing the service.[75]

Confidence in service providers profoundly impacts residents' intention to adopt HEMS,[76,77] smart home services,[78] and smart meters.[79] Chen and associates posit that, even among customers with limited comprehension of smart meter technology, the likelihood of adopting such meters increases when trust in their utility company is established.[75] Elevated levels of trust also correlate with a greater propensity to share personal information with utilities.[80] Conversely, mistrust prompts customers to scrutinize the motives behind energy or internet suppliers' energy-saving initiatives, potentially engendering more severe issues.[81]

Research further indicates that prospective technology users focus on the technical aspects and subjective impressions of institutions' motivations.[69] For instance, households are often more inclined to place trust and confidence in digital and energy technologies when a trusted local intermediary, such as a friend, family member, or local community group, is involved.[82] Nonetheless, the significance of trust frequently varies across income groups, impacting the reception and success of energy efficiency programs and digital policies, such as electricity disconnections during the COVID-19 pandemic. Moreover, there exists a lack of evidence regarding consumer trust, decision-making processes, and policy acceptance among different income brackets. A recent study uncovered that higher-income households exhibit greater trust in utilities than those with medium and lower incomes when evaluating HEMS.[74] This disparity exacerbates energy insecurity for LIHs, particularly given their tendency to reside in less energy-efficient homes.[83] This is partially attributed to lower levels of trust and limited familiarity with energy efficiency technologies or programs, which impede their adoption of new technologies.

Theoretical framework

This paper employs the sociological framework of concentrated disadvantage to elucidate the insecurities surrounding the internet and energy burdens and access. Concentrated disadvantage encapsulates how various interrelated factors—political, economic, geographical, and social—combine to shape the experiences of communities.[16,17] Previous research has analyzed the effects of concentrated disadvantage on health outcomes,[84] education attainment,[85] and more. Recent related research has also begun utilizing the concept of concentrated disadvantage to clarify environmental and energy justice issues, recognizing the systemic socioeconomic and demographic discriminations underpinning these challenges.[86,87]

In energy insecurity, researchers have increasingly acknowledged the importance of comprehending the "constellation of energy deprivation" by scrutinizing the influence of different social characteristics within households on the occurrence and experience of energy

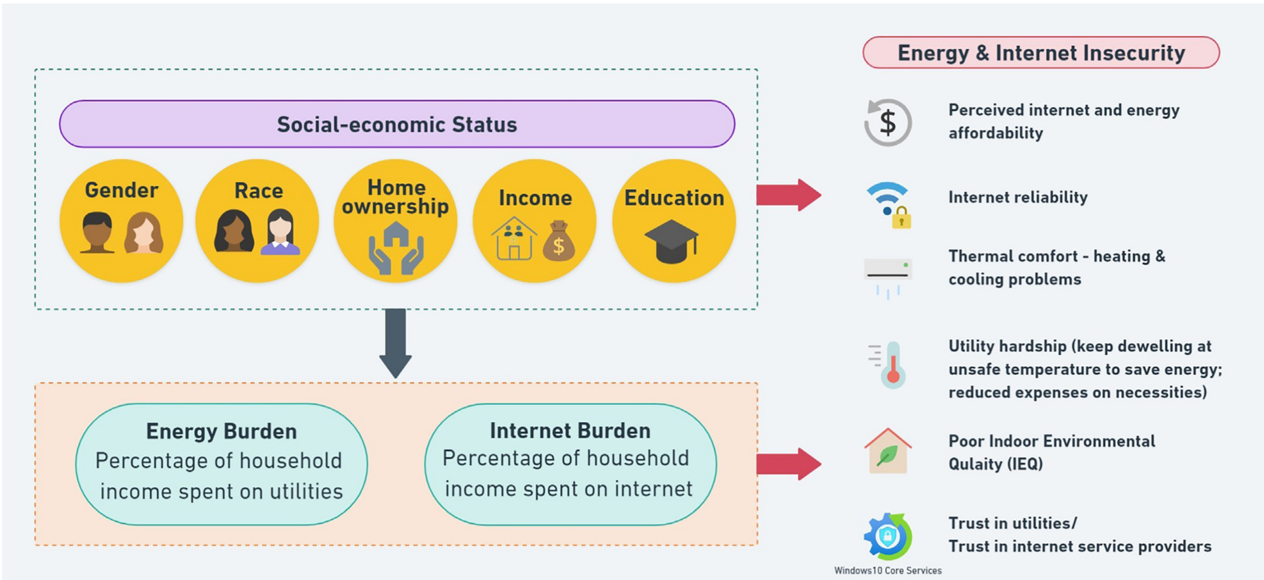

Figure 1. Framework of concentrated disadvantaged applied to energy and internet insecurities

insecurity.[88] Intersections of energy poverty with other forms of disadvantage have been examined to understand how various stressors compound one another, as seen in instances of transport energy insecurities[89] and broader forms of deprivation.[90] Despite existing research establishing the link between social, economic, and spatial disparities in energy poverty and internet access,[53,91] applying the theory of concentrated disadvantage to analyze cumulative energy and internet insecurities has primarily been confined to the US.[2] Therefore, this study applies the framework of concentrated disadvantage to explore how various forms of focused disadvantage compound energy and internet insecurities in other contexts in the Global North, such as the UK. We are particularly interested in understanding how the intersections of gender, race/ethnicity, income, home ownership, and education have contributed to adverse outcomes and inequalities during the COVID-19 pandemic. Extending previous energy justice research,[2,7] this study has proposed a framework to encapsulate the concepts of energy and internet insecurities and their intersections (see Figure 1).

Study purpose

Based on an online survey, the demographic compositions are shown in Table 1, this study scrutinizes social inequalities, encompassing factors such as gender, income, race/ethnicity, education, and homeownership disparities, to discern how concentrated socioeconomic disadvantage can amplify energy and internet insecurities within the UK. Additionally, we are particularly interested in analyzing how people's perceptions of internet access have evolved across demographics during the 2021 COVID-19 pandemic. Our research offers two significant contributions. Firstly, we provide empirical evidence demonstrating that individuals facing concentrated forms of disadvantage are linked with intersections of gender, income, race/ethnicity, and homeownership disparities. Secondly, our findings underscore the necessity for energy and internet policies to recognize how various facets of social inequality intersect and exacerbate energy and internet security issues. This holds not only in the context of COVID-19 but extends to encompass broader financial challenges. Specifically, this study answers the following questions.

- What disparities exist in energy and IB strains across various socio-demographics, including income, gender, race/ethnicity, and homeownership?
- Which concentrated disadvantaged groups, such as low-income ethnic minorities, low-income renters, and low-income women, are more likely to experience higher energy and internet burdens than their counterparts?
- What are the relationships between EB and insecurity, including perceived utility affordability, utility hardship (UH) experience, poor IEQ, thermal discomfort, alternative heating source, water issue, and trust in utilities?
- What are the relationships between IB and insecurity, including perceived internet affordability and reliability, IEQ, and trust in internet providers?

RESULTS

The following results detail the findings of various statistical tests to address the research question listed previously. Chi-square tests of independence were used to check whether two variables were likely to be related. Two-way analysis of variance (ANOVA) models were used to understand how two independent variables, in combination, affect a dependent variable. Significant ANOVA results were further analyzed

Table 1. Participant demographic characteristics

Participant characteristics	Frequency (%)	
Primary Demographics	Within the sample	Within U.K. in 2021∼2023[115–118]
Gender		
Male	49.8	49.5
Female	49.7	50.5
Not to answer	0.5	N/A
Age		
18-30 years old	18.2	14.8
31-60 years old	63.5	40.1
61 years old or older	18.2	24.2
Race/ethnicity		
White	88.4	82.9
Black & Latino	3	3
Asian	6.5	6.3
Mixed races	2	2
Other ethnic	N/A	0.9
Income		
Less than £25,000 (LIH)	30	21
£25,501 to £50,000 (MIH)	49.9	42
More than £50,000 (HIH)	20.1	36
Education		
Secondary Education	24.8	22
High-Level Education or college degree	63.6	55.4
Post-graduate degree	11.6	22.6
Household Demographics		
Residential area		
England residence	85	83.9
Scotland, Wales, and Northern Ireland residence	15	16.1
Homeownership status		
Owner	58.4	50
Renter	41.6	40
Other	N/A	10

with Tukey's honest significant difference (HSD) post-hoc tests to establish which group means were different compared to other groups. The null hypothesis for ANOVA is that the mean (average value of EB or IB, one of the dependent variables) is the same for all groups (categorical, independent variables), while the research hypothesis is that the average is not the same for all groups. Before conducting ANOVA, we performed Levene's test to assess the null hypothesis that the variance was equal across groups, ensuring the models did not violate the assumption of homogeneity of variance. This study used several ordinary least squares (OLS) regression models to analyze the relationships between dependent and independent variables.

Regression diagnostics

This study examined regression assumptions and diagnostics for all models. First, our linear regression indicates the relationship between independent and dependent variables to be linear. Second, linear regression analysis requires all variables to be multivariate normal. The Q-Q plots showed that all variables were close to a normal distribution, except for minor energy and internet bill skewness due to the inequality of energy and internet costs. Third, we found no multicollinearity with variance inflation factors (VIFs) well under the recommended limit of five. Fourth, examining homoscedasticity assumptions suggested that the expected mean values of the error terms (residuals) were zero, and the error terms' observation was uncorrelated. When inspecting for potential outliers, the P-P plots showed a slight deviation from

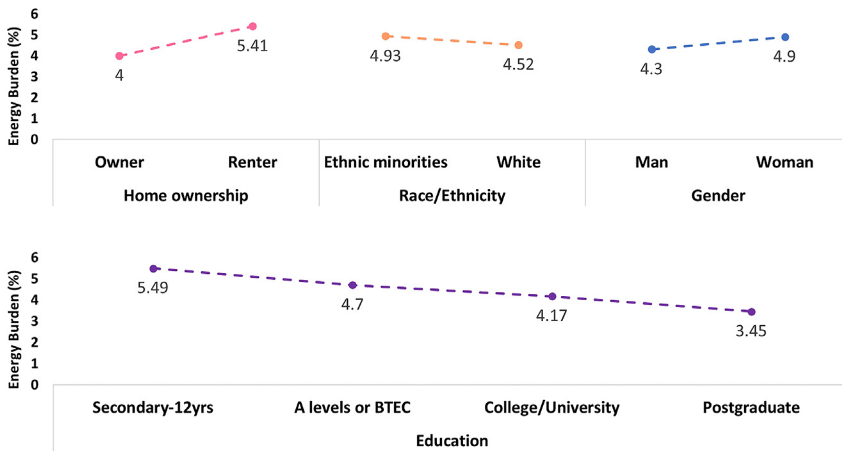

Figure 2. Interaction effects of education, home ownership, race/ethnicity, gender on energy burden (%)

normality around the tails but were otherwise normal. Given the large sample size that the data are quite robust, we decided not to remove outliers.

Utility costs and energy burden across income levels

This study categorized utility costs in February 2021 into seven levels, ranging from £80 or less to £281 or more. The reason for using the February bill as a reference point was the potential higher cost of energy bills during the COVID-19 home restriction order. Although evaluating the cost of utility bills, we were not able to collect data about the amount of energy a household achieved for this price. It is worth considering when interpreting our results that many households are likely to deliberately under consume energy if they are struggling financially.[92,93]

The chi-square independence test results show that utility bills were significantly different by income levels, $\chi2$ (14, 2588) = 100.325, $p < 0.001$. However, overall utility costs tended to be on the lower end (see Figure 2). High-income households' (HIHs) utility bills were higher than those of other income groups, with 15.5% of HIHs paying more than £160 a month. HIHs most frequently reported paying £81–£120 (40.5%), £80 or less (26.0%), and £121–-£160 (17.9%). In comparison, only 8.3% of LIHs and 9.3% of MIHs paid more than £160. On closer examination, most LIHs (45.4%) spent £80 or less on their utility bills, 34.6% paid £81–£120, and 11.7% paid between £121–£160. The utility bills of MIHs were higher than those of LIHs. These results might be because higher-income households have larger houses with more energy-related appliances. However, lower-income households with a lower income generally experienced a high-risk EB, defined as a monthly EB of 6% or higher 2,7; therefore, this paper further examined EBs across different demographic groups and other relevant indicators.

The distribution analysis of EB shows that the average monthly EB for the entire sample was 4.6%, and the median was 3.7%. However, there was a wide range of EB values, with a minimum of 0.5% and a maximum of 28.9%, indicating that some vulnerable residents experienced an extremely high monthly EB close to 29%. We further analyzed statistical differences in average and high-risk EBs (identified as 6% or higher) across income groups. Results of one-way ANOVA showed that EB differs across income levels, F (2, 2585) = 868.657, $p < 0.001$. The post-hoc analysis reported that LIHs experienced the highest EBs (M = 7.7%, SD = 0.040) when compared to MIHs (M = 3.7%, SD = 0.018) and HIHs (M = 2.0%, SD = 0.010). Additionally, our independent chi-square analysis showed a significant relationship between high-risk EB and income levels, $\chi2$ (2, 2588) = 961.611, $p < 0.001$. Table 2 shows that among all participants, 18.9% of them were LIHs with a high-risk EB, compared with only 4.9% MIHs and no HIHs with high-risk EBs. Observing only the high-risk EB group, approximately 79.4% were LIHs.

This section further demonstrates the monthly average EB across gender, race/ethnicity, homeownership, and education groups, followed by the statistical analysis of average EB and high-risk comparisons across demographic groups. An ANOVA model (Figure 2) shows that renters were more likely to experience a higher EB (M = 5.41%, SD = 0.036) than homeowners (M = 4.0%, SD = 0.029), F (1, 2586) = 98.719, $p < 0.001$. Therefore, when examining the relationship between renters and high-risk EB, our analysis confirms that among the high EB-risk group, approximately 58.8% were renters, whereas 41.5% were homeowners, $\chi2$ (1, 2588) = 95.162, $p < 0.001$, based on the independent chi-square analysis. Regarding race/ethnicity, results of the significant ANOVA model, F (1, 2586) = 3.842, $p < 0.05$, indicated that ethnic minorities (M = 4.93%, SD = 0.036) had higher EBs than white British residents (M = 4.52%, SD = 0.033). However, the relationship between ethnic minorities and high-risk EB was not significant.

Women (M = 4.9%, SD = 0.035) also experienced higher EBs than men (M = 4.3%, SD = 0.032), F (1, 2586) = 23.105, $p < 0.001$. When examining the relationship between gender and high-risk EB, our analysis confirms that among the high EB-risk group, 56.9% were women, whereas 43.1% were men, $\chi2$ (1, 2576) = 15.606, $p < 0.001$. Finally, results of the ANOVA model suggested that EB differed across education levels, F (1, 2586) = 23.105, $p < 0.001$. Residents with secondary school education up to 12 years (M = 5.49%, SD = 0.036) had the highest EBs, followed by those with higher or further than A-levels or BTEC degrees (M = 4.70%, SD = 0.035), college or university degree (M = 4.17%,

Table 2. High-risk EB comparison across income levels in the UK

			Income groups			
			Low	Medium	High	Total
Energy burden category	Non-high-risk EB	Count	286	1,166	519	1,971
		% within high-risk EB	15%	59%	26%	100%
		% within income groups	37%	90%	100%	76%
		% of total	11%	45%	20%	76%
	High-risk EB	Count	490	126	1	617
		% within high-risk EB	79%	20%	0%	100%
		% within income groups	63%	10%	0%	24%
		% of total	19%	5%	0%	24%
Total		Count	776	1292	520	2588
		% within high-risk EB	30%	50%	20%	100%
		% within income groups	100%	100%	100%	100%
		% of total	30%	50%	20%	100%

SD = 0.031), and postgraduate degrees (M = 3.45%, SD = 0.025). The lower education group was also likely to experience a high-risk EB, $\chi 2$ (1, 2588) = 95.162, $p < 0.001$; among the high-risk EB group, 36.6% had a secondary school education, 27.2% had A-levels or BTEC degrees, 30.3% had a college degree, and 5.9% had a postgraduate degree.

Concentrated disadvantage in energy burdens

To further test our theoretical framework and examine the relationship between concentrated disadvantaged groups and EB, we conducted three two-way ANOVA models to investigate the monthly average EB among between vulnerable groups to demonstrate its effects in conjunction with additional disadvantageous characteristics, including interactions across income, gender, race/ethnicity, and homeownership. Results of the first ANOVA model yielded significant main effects for income on EB, F (2, 2582) = 424.195, $p < 0.001$, and for the ethnic minority on EB, F (1, 2582) = 13.272, $p < 0.001$. Additionally, the interaction effect was significant, F (2, 2582) = 4.354, $p < 0.05$. The post-hoc tests indicated the average EBs for ethnic minority LIHs were the highest (M = 8.8%, SD = 0.003) of all other income and race/ethnicity groups, predominantly white British residents in the highest income group (M = 2.0% SD = 0.000) (see Figure 3A). Additionally, the average EB for the sample, 4.6%, is indicated by the black dashed line in Figures 3A, 3B, and 4.

Given previous literature suggesting low-income women are among the concentrated disadvantaged groups in EB, we conducted a second two-way ANOVA model to analyze the interaction effect of gender and income on EB. Results of the model yielded a main effect of gender on EB, F (1, 2570) = 13.814, $p < 0.001$, and another main effect of income on EB, F (2, 2570) = 846.512, $p < 0.001$. Additionally, the interaction effect was significant, F (2, 2570) = 13.050, $p < 0.001$. The post hoc test confirmed that LIH women had the highest EB (M = 8.2%, SD = 0.001) among all income and gender groups such as LIH men (M = 7.1%, SD = 0.001) (see Figure 3B). Furthermore, the EB for LIH women was substantially higher than white British men, and women with a high income (M = 2.0%, SD = 0.002).

The absence of a statistically significant interaction effect between income and home ownership was confirmed, F (2, 2579) = 0.11, $p = 0.899$. This finding underscores the nuanced nature of EBs within our study population. Notably, the post-hoc tests unveiled intriguing patterns: Low-income homeowners and renters exhibited remarkably similar and the highest average EBs, both showing 7.7% (SD = 0.04). This shared high EB value indicates the substantial energy cost burdens faced by both groups within the low-income bracket. In the medium-income category, a subtle distinction emerged. Medium-income homeowners displayed a slightly lower average EB (M = 3.7%, SD = 0.02), compared to their renting counterparts (M = 3.8%, SD = 0.02), though the difference was relatively minor. Similarly, when scrutinizing the HIHs group, we observed that homeowners had an average EB of 2.0% (SD = 0.01), which was only marginally lower by approximately 1% than the EB of HIH renters (see Figure 4).

Regression results on energy burdens and the experiences of energy insecurity

To go beyond analysis of financial cost, we used five OLS multiple regression models to analyze the relationship between EB and social-psychological perceptions of energy insecurity (i.e., concern about utility affordability, UH experience, poor IEQ, and thermal comfort/heating problem), as well as trust in utility and internet service providers. Specifically, as shown in Table 3, each OLS regression model used EB as the independent variable and perceived affordability, UH and tradeoffs, trust, IEQ level, and thermal discomfort as the dependent variables. In addition, all the regression models accounted for the effects of race/ethnicity, gender, and education.

As indicated in Table 4, the results of the regression models showed that residents with a higher EB were more likely to experience more significant concern about utility affordability (B = 0.92; $p < 0.001$) than those with a lower EB. Regarding their living experiences, people with a

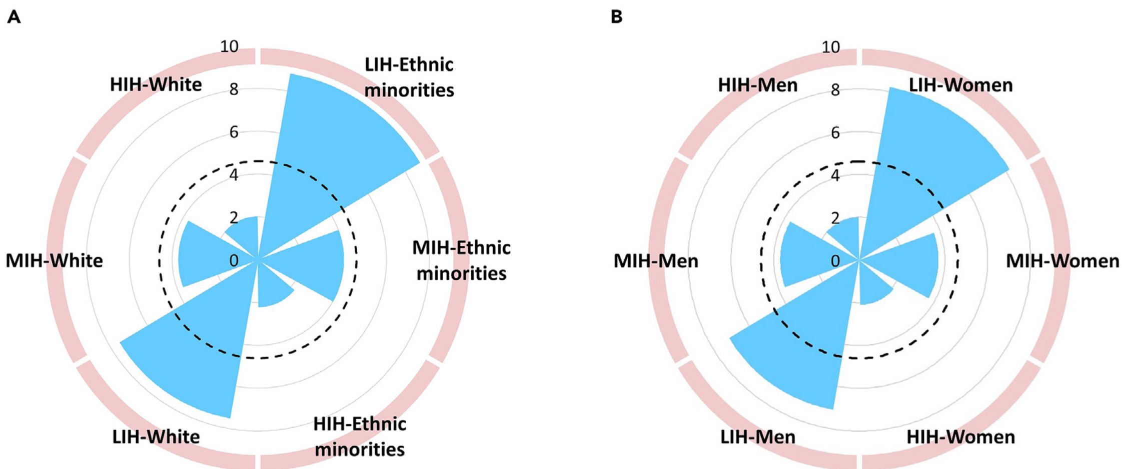

Figure 3. Distribution of energy burden (%) across income levels and (A) race/ethnicity (B) gender groups based on the interaction effect analysis
(A and B) The numerical scales on the concentric circles represent the energy burden percentage, indicating the proportion of total energy costs relative to income within each subgroup.

higher EB were more likely to experience negative UH, including disconnecting from utilities, reducing expenses for utility bills, and skipping meals (B = 0.203; $p < 0.001$) than their lower EB counterparts after accounting for gender, ethnicity, and education. Additionally, higher EB residents reported higher thermal discomfort and heating problems (B = 0.146; $p < 0.001$) than their lower-income counterparts. A higher EB also leads to a poorer IEQ level (B = 0.151; $p < 0.001$) and a lower trust level in utility companies (B = −0.109; $p < 0.001$). Based on the regression results, a high EB can erode trust in utility companies. When energy costs consume a great portion of income, concerns about affordability and transparency can lead to skepticism about utility providers' intentions and actions. Addressing EB comprehensively is not only about reducing financial stress but also about fostering trust in utility services.

We further conducted two OLS multiple regression models to investigate the specific behaviors and energy insecurity issues and found positive relationships with EB. Specifically, people who experienced higher EB were more likely to use alternative heating forms of fuel like wood, coal, or natural gas as a heat source (B = 0.059; $p < 0.001$) and could not bathe or wash their hands properly because there was not enough water, or the water was too cold (B = 0.116; $p < 0.001$). The reason for analyzing the water issue was due to some residents' utility bills including both the water and the electricity cost.[94]

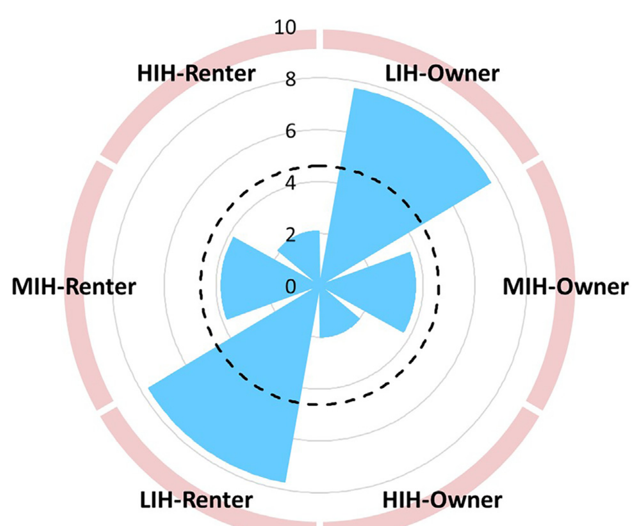

Figure 4. Distribution of energy burden (%) across income levels and homeownership status based on the interaction effect analysis
The numerical scales on the concentric circles represent the energy burden percentage, indicating the proportion of total energy costs relative to income within each subgroup.

Table 3. Results of multiple regression models on EB and energy insecurity experiences

	Independent variable: Energy burden+			
Dependent variable	Standardized Coeff. (Beta)	Std. error	p value	F
Perceived affordability of utilities	0.920***	0.680	0.000	(4,2556) = 22.191***
Utility hardship (UH)	0.203***	0.498	0.000	(4,2556) = 43.913***
Poor IEQ	0.151***	0.504	0.000	(4,2479) = 36.107***
Thermal discomfort	0.146***	0.546	0.000	(4,2556) = 32.561***
Trust in utility companies	−0.109*	0.496	0.02	(4,2479) = 4.678***
Alternative heating source	0.059***	0.354	0.000	(4,2558) = 8.913***
Water issue	0.116***	0.339	0.000	(4,2557) = 16.986***

Distribution of internet access and perceived public utility

Our sample reveals that many residents now have internet access, making it an indispensable facility for people today. 91.8% of households reported having internet connectivity in their homes. This statistic underscores the pivotal role that the internet plays in our daily lives. Figure 5A demonstrates that 89% of the population employs "Broadband" as their primary means of accessing the internet, followed by cellular data (18.6%) and satellite (4.5%). These statistics not only underscore the ubiquity of internet access in the UK but also emphasize its critical role in our society as an essential utility, especially after COVID-19.[61]

Unique to this study, we delve into the evolving perceived internet access before and during the COVID-19 pandemic, examining whether residents agree or disagree that the internet constitutes an essential public utility. Figure 5B presents data obtained from respondents who were asked two distinct questions simultaneously during the online survey. This simultaneous questioning approach allowed us to capture respondents' perspectives both before and during the COVID-19 pandemic. The results indicated a notable shift in perception within our sample. As shown in Figure 5B, 26.9% of participants strongly agreed with the statement before the pandemic. However, during the COVID-19 crisis, the percentage increased significantly by 14.6%, reaching 41.5% of participants who strongly agreed. Additionally, 37.4% agreed resulting in an overall agreement rate of 78.9%. These findings highlight the internet's evolving role from convenience to a necessary infrastructure. The pandemic has intensified the urgency of addressing internet insecurity among vulnerable populations.

Internet cost across income groups

Our regression model results show how monthly internet bills from January until March 2021 and income levels were positively related ($B = 0.054$, $p < 0.001$). For easier comparison, we group internet bill categories into four groups: £30 or less, £31–£50, £51–£70, and £71 or more. The chi-square independence test found internet bills differed significantly by income levels, $\chi 2$ (6, 2501) = 13.819, $p < 0.05$. Most LIHs (51.1%) paid less than £30 for their monthly internet bills, 32.9% paid £31–£50, and 11.6% paid between £51 and £70. Overall, HIHs had the highest internet bills, the broadest range of bill costs, and most frequently reported paying £30 or less (41.7%) and £31–£50 (40.1%), followed by £51–£70 (11.5%). The internet bills of MIHs were also higher than those of LIHs, with the majority of MIHs paying £30 or less (48.7%), followed by £31–£50 (32.9%), and £51–£70 (11.6%). However, since lower-income households experienced a higher IB, we further examined IBs across different demographic groups and other related indicators.

Internet burdens and concentrated disadvantage

Overall, the descriptive statistics of Table 4 show that average IB for the entire sample ranged from a minimum of 0.2% to a maximum of 8%, with a mean IB of 1.64% and a median IB of 1.29%. Additionally, this study defines high IB as a monthly IB of 3% or more, indicating that

Table 4. Descriptive statistic of IB within the sample

N = 2,588		IB (%)
Mean		1.64
Median		1.29
Minimum		0.20
Maximum		8.00
Percentiles	25	0.80
	50	1.29
	75	1.94

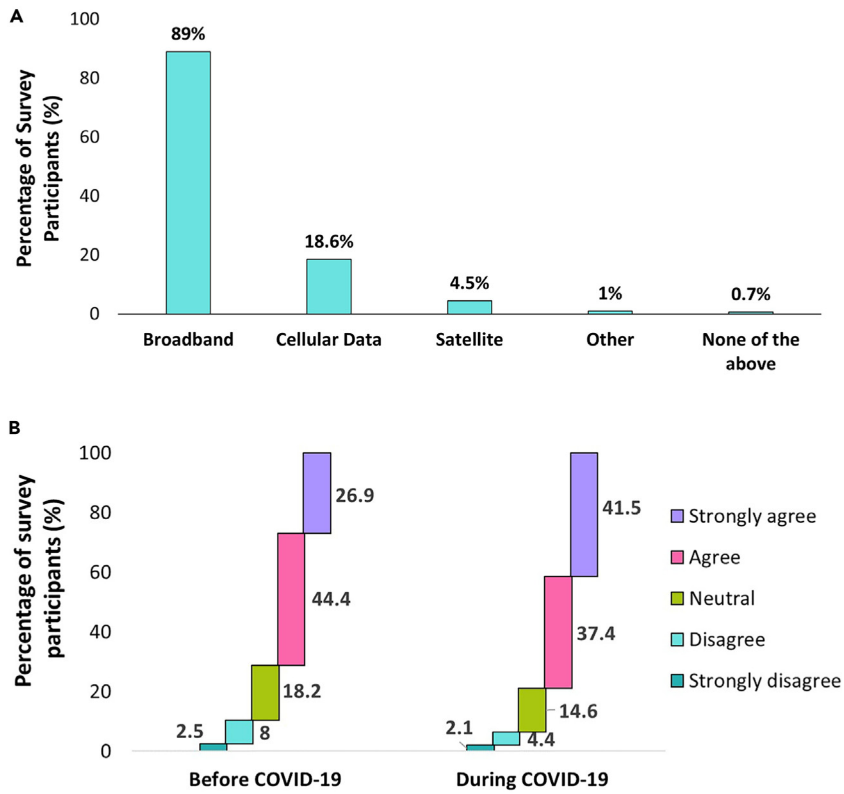

Figure 5. Proportion of participants on internet access and perceived public utility

(A and B) Proportion of participants on (A) primary access of the internet and (B) Shift in agreement on the internet constitutes an essential public utility before and during the COVID-19 pandemic.

individuals allocate 3% or greater of their monthly income toward internet access expenses. Approximately 10% of our participants reported experiencing a high IB.

This study used a logistic regression model to elucidate the connection between IB and internet access at home. The results indicated an insignificant relationship between IB and internet access. In contrast, the second logistic regression model showed a meaningful relationship between IB and fixed broadband access, $\chi 2$ (1, 2588) = 10.733, $p < 0.001$, after accounting for gender, race, and education. People with broadband access had lower IBs than those without access; people with higher IBs were 11.6 times less likely to have broadband. Those identifying as part of an ethnic minority group were approximately 7.4 times, and males were 6.3 times less likely to have fixed broadband than their counterparts. Education level was not a significant predictor of IB.

To examine IB disparity, we conducted several ANOVA models with Tukey's HSD post hoc tests to understand how IB varies across diverse demographics. Results of the one-way ANOVA suggest that IB significantly differed across income groups, F (2, 2501) = 879.2, $p < 0.001$. Unsurprisingly, as shown in Figure 6 the post-hoc tests showed that LIHs had the highest average IB at 2.9%, followed by MIHs at 1.3% and HIHs at 0.7%. IB also significantly differed by gender, F (1, 2502) = 51.3, $p < 0.001$, such that women had higher average IB (1.8%) than men (1.5%). Additionally, homeownership was significant, F (1, 2502) = 154.2, $p < 0.001$, with renters having a higher average IB at 2.0% compared to owners at 1.4%. The results also showed a significant difference in IBs across education levels, F (3, 2569) = 30.720, $p < 0.001$, and the post hoc test suggests that the lower education group had the highest IB at 1.9%, followed by those with a higher education degree (A-levels, BTEC) at 1.7%, college or university degree (1.5%), and postgraduate degree (1.2%). However, there was no difference in IB between ethnic minorities and white residents.

We performed three two-way ANOVA models to investigate the connection between IB and concentrated disadvantaged groups. These models incorporated demographic interaction terms as independent variables, exploring the relationships between income and ethnic minority, income and gender, as well as ethnic minority and homeownership. Results of the first two-way ANOVA model yielded main effects for income on IB, F (2, 2582) = 599.074, $p < 0.001$, and for ethnic minorities on IB, F (1, 2582) = 7.331, $p < 0.01$. Additionally, the interaction effect was significant, F (2, 2582) = 4.689, $p < 0.01$. The average IB for the entire sample is 1.64%, represented by the black dashed line in Figure 9A for comparison with the IB of targeted populations. As shown in Figure 7A, post-hoc tests revealed that the average IB for ethnic minority LIHs was the highest (M = 3.20%, SD = 0.001), surpassing that of white LIHs (M = 2.80%, SD = 0.001), and significantly higher than white residents in the highest income group (M = 0.70% SD = 0.000).

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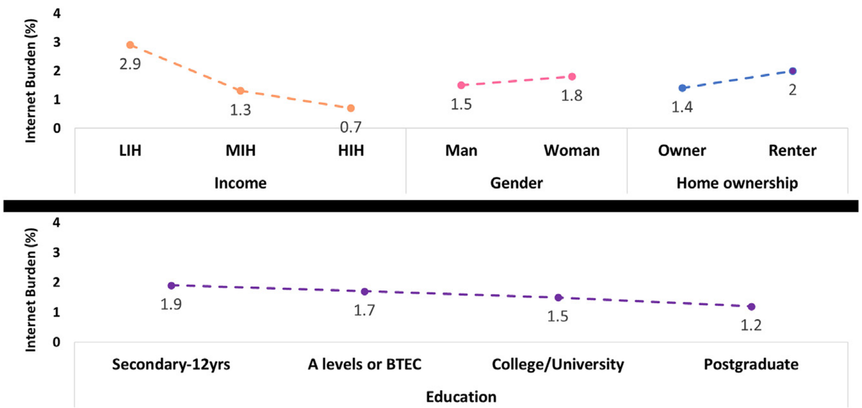

Figure 6. Internet burden (%) from January to March 2021 by income groups

Since previous literature suggests low-income women are among the concentrated disadvantaged group in EB and IB,[2] we conducted a two-way ANOVA analysis to explore the intricate relationships between income levels and gender dynamics concerning IB. Similarly, we observed a main effect of gender on IB, $F (1, 2570) = 52.520$, $p < 0.001$. The interaction effect of gender and income was also significant, $F (2, 2570) = 15.679$, $p < 0.001$, and post hoc test indicated that LIH women had the highest IB (M = 3.1%, SD = 0.000) among all income and gender groups, higher than LIH men (M = 2.6%, SD = 0.000) and considerably higher than white British men with a high income (M = 0.6%, SD = 0.000) (see Figure 7B).

The results of the third two-way ANOVA indicated a significant main effect for homeownership on IB, $F (1, 2579) = 46.311$, $p < 0.001$, whereas the main effect for ethnic minorities was not significant. Interestingly, the interaction effect was also significant, $F (1, 2579) = 3.828$, $p < 0.05$, suggesting that the impact of homeownership status was more pronounced compared to identifying as part of an ethnic minority group. The post-hoc tests revealed that the average IB for ethnic minority renters (M = 1.90%, SD = 0.013) and white British renters (M = 2.00%, SD = 0.013) were comparable and higher than the average values observed in other renter and owner groups (Figure 8).

Regression results on the relationship between internet burdens and the experiences of internet insecurity

Similar to the previous analysis regarding the impacts of selected variables on energy burden, this section presents the model results on the variables that influenced the impacts of IB and internet insecurity. We used IB as the critical predictor and "internet access and reliability," "trust in internet service providers," and "poor IEQ" as the dependent variables. To go beyond the analysis of internet cost, we further analyzed perceived affordability of internet, internet access and reliability, poor IEQ, and trust in internet service providers. As illuminated by the four linear regression models, the results reveal noteworthy findings. As shown in Table 5, individuals with a higher IB were less likely to perceive their internet was reliable ($B = -0.072$; $p < 0.001$) during the COVID pandemic. This observation underscores the challenges faced

Figure 7. Distribution of internet burden (%) across income levels and (A) race/ethnicity (B) gender groups based on the interaction effect analysis

(A and B) The numerical scales on the concentric circles represent the internet burden percentage, indicating the proportion of total costs related to internet access relative to income within each subgroup.

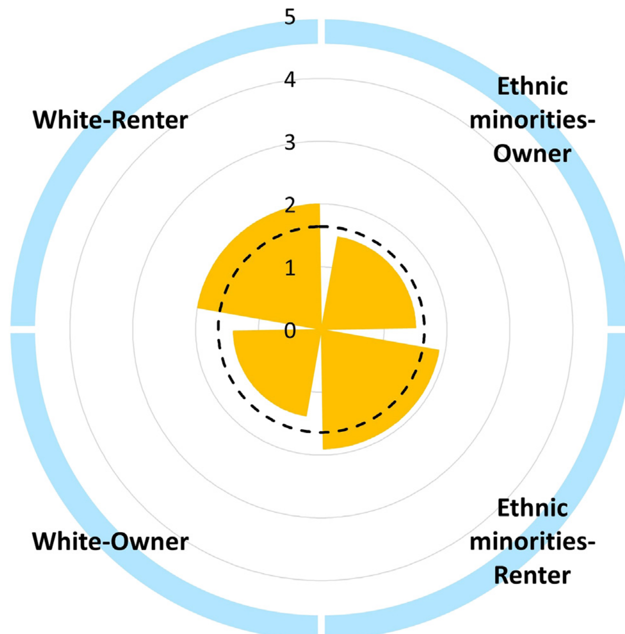

Figure 8. Distribution of internet burden (%) across income levels and homeownership status based on the interaction effect analysis
The numerical scales on the concentric circles represent the internet burden percentage, indicating the proportion of total costs related to internet access relative to income within each subgroup.

by those who have a heavier IB that affects their confidence in the reliability of their internet service. Furthermore, our analysis unveiled a significant association between a higher IB and a lower level of IEQ (B = 0.176; $p < 0.001$). This implies that individuals with greater IBs may contend with compromised living experiences, potentially linked to their housing conditions.

The level of trust individuals place in these providers directly impacts the dependability and security of internet services, thereby playing a pivotal role in addressing internet insecurity. According to the results of our regression model, individuals with a higher IB tend to have lower levels of trust in their internet service providers (B = −0.58; $p < 0.05$) compared to those without a higher IB. This intriguing observation prompts further inquiry into the factors that influence this trust dynamic, bringing into focus the need to address and improve trust-related issues in the digital era. Ultimately, such investigations are essential in our ongoing efforts to ensure equitable and secure internet access for all.

The interaction of energy and internet burden in vulnerable groups

This section investigates the relationship between income levels and the interaction of EB and IB. Results from the chi-square independence test indicate significant variations in the prevalence of high-risk EB across different income groups, $\chi 2$ (2, 2588) = 961.611, $p < 0.001$. Similarly, high-risk IB and the combination of both high-risk EB and IB also exhibit significant variations, with respective results from the chi-square independence tests of $\chi 2$ (2, 2588) = 551.455, $p < 0.001$, and $\chi 2$ (2, 2588) = 444.498, $p < 0.001$. Specifically, as shown in Figure 9, a substantial 79.4% of people who experienced the challenge of high-risk EB were recognized as LIH. The disparities are even more pronounced when it comes to the issue of high-risk IB. Among individuals who faced the challenges of high-risk IB, a significant 87.6% of them were LIHs, surpassing the figures for EB. This was followed by a significant drop in MIHs at 12.4%, with no instances identified as HIHs. The results highlight a notable finding that high-risk IB issues are more severe than EB issues among LIHs, indicating that affordability for IB is more challenging than

Table 5. Results of multiple regression models on IB and insecurity

	Independent variable: Internet burden			
Dependent variable	Standardized Coeff. (Beta)	Std. error	*p* value	F
Perceived affordability of internet	0.277***	1.546	0.000	(4,2556) = 59.796***
Internet access and reliability	−0.072***	1.375	0.000	(4,2479) = 15.395***
Poor IEQ	0.176***	1.386	0.000	(4,2556) = 41.304***
Trust in internet service providers	−0.058*	1.106	0.03	(4,2479) = 4.678***

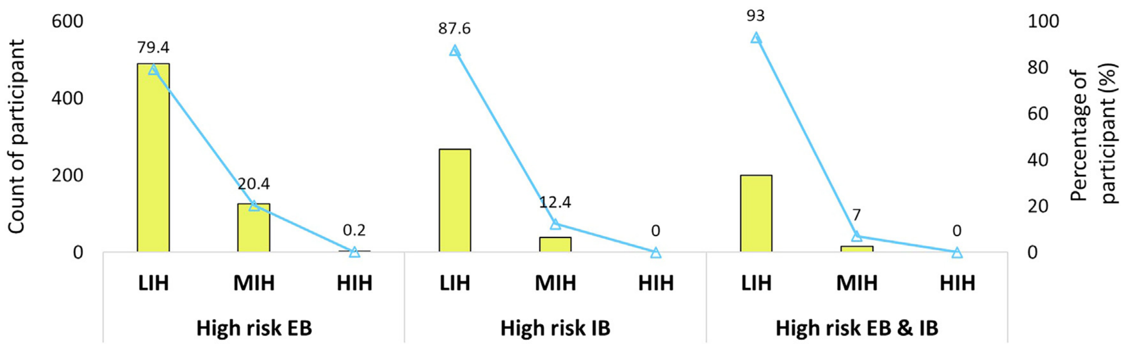

Figure 9. Comparative analysis of participant count and percentage across income levels for high-risk energy burden and internet burden

covering daily utility expenses. Moreover, among participants reporting both high-risk EB and IB, 93% were identified as LIH. These findings underscore the urgent need for targeted interventions to address these burdens, particularly for vulnerable populations.

We employed binary logistic regressions to examine the disparities and further explore the variations in experiencing both high-risk EB and IB across different demographics, we employed binary logistic regressions to examine the disparities. According to Table 6, the issue of experiencing both high-risk EB and IB varies significantly between genders and homeownership ($p < 0.001$); however, the relationship between different ethnicities and high-risk EB as well as IB was not significant. In a revealing gender contrast, 10.6% of women grappled with the dual challenges of high-risk EB and IB, while only 6% of men reported a similar struggle. This suggests that women were 1.75 times more likely than men to concurrently experience high-risk EB and IB (C.I. [1.30, 2.35]). Shifting our focus to ethnicity and homeownership, ethnic minority populations were 1.35 times more likely than their white British counterparts to face the dual burdens of high-risk EB and IB (C.I. [0.91, 2.01]). Notably, renters were the most affected, being 2.14 times more likely than homeowners to confront the combined challenges of EB and IB (C.I. [1.60, 2.85]).

DISCUSSION

Summary of key findings

This study illuminates the intricate interplay between energy and internet insecurity within vulnerable households amid the backdrop of the COVID-19 pandemic. In the following text, we delineate three pivotal findings.

First, relying solely on average values for energy and internet burdens proves inadequate in discerning energy justice issues among marginalized populations; instead, we gain a profound understanding of the disparities at play by scrutinizing the outliers and the extremities of these burdens. Notably, our analysis reveals a substantial range in the financial EB and IB, with some individuals grappling with extraordinary circumstances, such as a monthly EB of 28.9% and IB of 7.78%. In stark contrast, others contend with significantly lower burdens, registering at 0.52% EB or 0.17% IB within our sample. Consequently, a representation based solely on the median (e.g., 3.7% of EB) or mean (e.g., 4.57% of EB) does not adequately capture the challenges faced by many vulnerable groups. These extreme EB and IB are exacerbated by the relatively low-income levels of specific vulnerable households.

Second, the compounding challenges of EB and IB are particularly pronounced among concentrated disadvantaged groups. In alignment with research conducted by US scholars (e.g., a study by Chen et al.[2]), this study identifies a positive relationship between financial EB and IB.

Table 6. Disparities of experiencing of both high-risk EB and IB across gender, ethnicity/race, and homeownership

High risk EB and high risk IB	% Demographic		Odd ratio; 95% C.I. [Lower, Upper] p value
Gender	Men	Women	
Yes	6.0%	10.6%	1.75; [1.30, 2.35]
No	94.0%	89.4%	<0.001
Race/ethnicity	White British	Ethnic minority	
Yes	7.9%	11.3%	1.35; [0.91, 2.01]
No	92.1%	88.7%	$p = 0.139$
Homeownership	Owner	Renter	
Yes	5.6%	12.1%	2.14; [1.60, 2.85]
No	94.4%	87.9%	<0.001

This finding suggests that individuals experiencing high financial EB also tend to face high IB, a trend observed among LIHs, women, ethnic minorities, and renters. Moreover, in examining the "tipping point" of high-risk EB (defined as 6% or higher), LIHs, renters, women, and individuals with lower levels of education emerge as the most vulnerable groups. Scrutinizing the concept of concentrated disadvantage, it becomes evident that low-income ethnic minorities exhibit higher EB than their low-income white British counterparts. Notably, among all income and gender groups, low-income women bear the heaviest burden in both energy and internet expenses. These findings mirror those discovered in the US during the 2021 COVID-19 pandemic,[2] underscoring how concentrated socioeconomic disadvantages can compound the pre-existing challenges of internet and energy insecurity within vulnerable households. Surprisingly, we found that out of those who encountered the difficulties associated with high-risk IB, 87.6% belonged to the LIH category, exceeding the proportion for EB. The findings reveal that among LIHs, high-risk issues related to the internet are more severe than those related to essential expenses. This highlights the urgent need for targeted interventions to support vulnerable populations.

Third, it is crucial to recognize that higher EB and IB entail a range of adverse experiences that extend beyond the realm of financial costs. This study acknowledges that these burdens encompass a multifaceted interplay of socio-technical factors, including building performance (such as IEQ and thermal discomfort) and psychological aspects (such as trust in utility and internet service providers). These findings shed light on substantial barriers that transcend financial considerations, impacting housing, social, and political dimensions.[2,31] In our analysis, participants experiencing higher EB often resort to maintaining their living spaces at unsafe or uncomfortable temperatures to conserve energy or allocate funds for other essential needs like food and medicine. Additionally, they grapple with utility-related hardships, facing threats of disconnection from service providers and enduring increased discomfort due to heating issues, aligning with numerous studies conducted in the US.[2,8] Surprisingly, individuals with higher EB also face challenges in basic hygiene practices, such as bathing or washing their hands properly, due to insufficient water supply or excessively cold temperatures. Furthermore, elevated EB and IB contribute to deteriorated IEQ, with significant implications for both mental and physical health—a finding consistent with prior research.[30]

Our study underscores the bundled impacts of energy and internet insecurities on health, access to essential services, and trust in relevant institutions. Regarding trust, scholars posit that alleviating energy poverty hinges on individuals' relationships with stakeholders, making trust a cornerstone of this dynamic.[95] According to our regression model findings, individuals with a higher IB generally exhibit reduced trust in their internet service providers when compared to those without a higher IB. This noteworthy insight raises questions about the underlying factors influencing this trust relationship, underscoring the importance of addressing and enhancing trust-related concerns in the digital age. Previous studies also suggested that lacking trust in energy and internet service providers can diminish individuals' capacity to adapt and cope with these insecurities.[53,95] Similarly, trust plays a pivotal role in an individual's willingness to adopt technology, particularly emerging technologies like the IoT, thereby influencing the profound digital divide.[96] These investigations are pivotal in our ongoing efforts to ensure equitable and secure internet access for all.

These findings address the link between energy and internet insecurities and how they coalesce to create a multifaceted challenge for vulnerable populations, especially during a global crisis, such as the COVID-19 pandemic. The disparities highlighted by EB and IB reveal a need for a nuanced understanding of energy justice. Beyond mere financial metrics, the burdens of energy and internet costs are interwoven with issues of social equity and public health. The positive correlation between high financial EB and IB observed among LIHs, women, ethnic minorities, and renters not only indicates a compounded financial strain but also reflects broader systemic inequities that these groups face. It is apparent from these data that energy and internet costs are not merely line items in a budget but are indicative of deeper socioeconomic vulnerabilities. These expenses often compete with other critical needs, amplifying the negative impact on well-being and societal participation of these populations. The finding that LIHs are disproportionately affected by high-risk IB, even more than by EB, is important given the current essentiality of the internet for employment, education, health information, and social connectivity. This signals a societal shift where internet access has transitioned from a luxury to a necessity, akin to utilities like electricity and water. In this light, the high-risk IB for LIHs is not just a financial issue but a significant barrier to societal integration and upward mobility.

Furthermore, our findings point to the "bundled impacts" of energy and internet insecurities, which manifest in lived experiences of socio-technical and psychological hardships. For instance, participants enduring high EBs frequently experience uncomfortable living conditions, such as unsafe temperatures, that directly affect their health. This reveals an overlap between financial, physical, and psychological domains where the quality of living space—a factor of IEQ—becomes compromised due to the prioritization of other needs over energy costs. The relationship between elevated EB and IB and the deterioration of IEQ also has implications for mental health, as indicated by the consistency with prior research. Poor IEQ can lead to a range of mental health issues, including stress, anxiety, and depression,[97] thereby creating an additional layer of vulnerability for already disadvantaged groups.

The role of trust in utility and internet service providers extends beyond the concept of consumer satisfaction to influence the adoption and utilization of services that could alleviate EB and IB Our study reveals that higher IB correlates with diminished trust in service providers, which not only inhibits individuals from leveraging available resources but also impedes the adoption of cost-saving and energy-efficient technologies like IoT. This breakdown in trust can further alienate individuals from engaging with digital transitions and smart technology integrations that are central to energy conservation and efficiency. The intersectionality of energy and internet burdens reveals that tackling these issues in isolation is insufficient. Our research advocates for integrated solutions that consider the compounded nature of these burdens, emphasizing the importance of trust and accessibility in the broader narrative of energy justice. Addressing these burdens effectively requires systemic changes that incorporate affordability, reliability, and the socio-technical dimensions of energy and internet access. Such an approach must also factor in the unique challenges faced by vulnerable groups, ensuring that no one is left behind as we stride toward a more equitable and technologically inclusive future.

Limitations and future study

This study has certain limitations that offer avenues for future research. First, although this study endeavored to closely match our sample with the UK demographic composition, it is crucial to recognize that our sample might not entirely mirror the broader population. Nevertheless, our statistical analysis has unveiled significant relationships among the groups within our sample size. These findings imply that within the confines of our study and the participants accessible to us, meaningful patterns and relationships exist, albeit they may not extend to the entire population due to the constraints of our sample. We will consider utilizing the weighting methodology for future analyses to better compare statistical outcomes. Second, given that our survey was conducted online, while we effectively engaged a considerable number of LIHs, and some individuals with disabilities and medical needs, our study may not fully capture internet insecurity issues faced by residents with low digital skills and literacy. Therefore, our future work aims to conduct qualitative research methods such as focus groups or interviews to provide additional information. Besides, future research will make effort to reach a more diverse range of LIHs or vulnerable populations, particularly those with limited internet broadband access or older persons to collect their feedback through offline channels. Third, investigating the root causes of energy and internet insecurities, including factors like financial support for energy efficiency, digital skills training, and landlord attitudes toward infrastructure upgrades, could provide valuable insights. Fourth, this study collected data during the COVID-19 pandemic in 2021, reflecting a snapshot in time with a unique social and political landscape. Future research might consider how the ongoing energy price crisis, energy system digitalization, or future low-carbon transitions and infrastructure design might shape internet and energy burdens. Lastly, exploring residents' perspectives on their needs and policy supports relating to energy and internet security could be a valuable area of investigation beyond socio-demographic factors.

Conclusion and policy implications

Our findings imply that changes must be made to current energy and internet security policies. Accordingly, we have provided five policy recommendations:

First, to effectively address the intersecting challenges of energy and internet inequalities, a comprehensive policy approach grounded in broader social justice imperatives is imperative, transcending mere financial interventions. Several European governments, even those with robust social welfare programs, often rely predominantly on poverty alleviation measures to tackle energy and internet disparities.[98] Nevertheless, our study underscores that these insecurities are intricate and multifaceted, necessitating a more encompassing approach rooted in social justice principles. Existing scholarship has extensively applied justice frameworks to comprehend energy poverty[99,100] and, to a lesser extent, internet inequality.[101] The concept of energy justice encompasses critical dimensions including recognition (i.e., acknowledging the political rights of various social groups and their concerns), distributional (i.e., rectifying the uneven allocation of resources), restorative (i.e., addressing the needs of marginalized groups historically subjected to injustice or prejudice), and procedural justice (i.e., ensuring equitable and inclusive participation of all stakeholders in decision-making).[102–104] By adopting energy justice perspectives, initiatives can be formulated to tackle the underlying causes of social disparities that contribute to energy poverty and digital inequality.

Second, it is imperative to extend current policies to assist households in affording high energy and internet bills in the UK. For instance, the Warm Home Discount scheme currently benefits only 2.2 million households. Moreover, while it caters to qualifying LIHs, its primary beneficiaries tend to be pensioners or individuals receiving specific means-tested benefits. The UK government lacks targeted social support tailored explicitly to home internet expenses. Existing support revolves around a system allowing internet providers to verify that individuals are recipients of a qualifying social benefit payment for a social tariff. Research suggests that investing in household energy efficiency measures represents a pivotal step society can take to mitigate greenhouse gas emissions.[105] Additionally, a comparative analysis of energy poverty policies across five E.U. countries revealed that regional approaches exhibit greater effectiveness than national policies in addressing energy poverty.[106] A notable instance of government-backed internet support is the US Affordable Connectivity Program, which extends up to $75 in direct broadband payments to qualifying households based on their income.[107]

Third, although energy and internet inequality are typically addressed in distinct policy realms, both have been significantly influenced by austerity, a defining feature of UK public policy in the past decade. Austerity, defined as the fiscal cutbacks of state spending for public programs, has garnered criticism for its adverse effects on social equality.[108,109] Bouzarovski and colleagues[108] argue that austerity, along with other "systemic dynamics of stigmatization and exclusion," lies at the core of energy poverty challenges in the UK. Austerity measures also impact internet access and utilization by diminishing the availability of support systems, compelling households to make choices between essential needs, at times viewing internet access as a luxury. One pivotal recommendation for moving away from austerity is to involve a more comprehensive array of stakeholders in tackling the issues of energy and internet poverty. As highlighted by Creutzfeldt et al.,[110] non-governmental organizations play a crucial role in providing a form of "nodal governance" that profoundly influences the day-to-day experiences of energy poverty and internet insecurity.

Fourth, governments exacerbate household internet and energy inequalities through policies such as "digital by default," in addition to austerity. For example, the UK recently announced an approach to social welfare programs to streamline services and cut costs. Still, research has shown that resources to support this transition are inadequate.[111] The "Digital by Default" strategy by the UK government instructs government and civil service agencies to consider making social services available digitally and to reduce non-digital modes of access. While there are considerations in this guidance to continue to make social welfare services available offline to those who need them, there is evidence that these programs not only sustain existing systems of social disadvantage but produce new forms of digital exclusion.[112] Indeed, in digital-by-default systems, marginalized populations are further pushed to the fringes of social support, as they are often last in line behind those with digital access and the required skills and resources to navigate the system. It is, therefore, necessary for policymakers to consider how digital strategies themselves may be both reinforcing and creating new forms of social inequality.

Fifth, "Internet exclusion" is not solely a consequence of economic hardship, but rather a symptom of broader inequalities, including disparities in housing.[113,114] The accessibility to the digital service ecosystem, encompassing technologies for in-home energy, presents itself as an economic and infrastructural hurdle. Yet, this challenge transcends individual circumstances, operating at a more encompassing societal level. Our study highlights combinations of inequalities, such as those related to race/ethnicity and gender, which compound access issues. Therefore, policies focused solely on poverty alleviation or infrastructure enhancement will not effectively address society's more profound structural disparities contributing to energy and internet burdens. A telling example lies in migrant populations, often facing language barriers and constrained access to services due to residing in substandard accommodations or areas lacking essential resources and support services. Moreover, internet exclusion is intimately tied to housing quality, subsequently influencing a household's capacity to regulate and manage their energy consumption and living standards. To effectively address this issue, policies must consider a range of social factors beyond income, and there should be a well-defined strategy for treating the internet and energy as an integrated ecosystem of services.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCES TABLE
- RESOURCE AVAILABILITY
  - Lead contact
  - Materials availability
  - Data and code availability
- METHOD DETAILS
  - Survey procedures and instrument
  - Participant demographics
  - Measures
  - Key variables
  - Classification of income groups

SUPPLEMENTAL INFORMATION

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AUTHOR CONTRIBUTIONS

C.-f.C. conceptualized the research designed the research framework and drafted the manuscript; C.-f.C. leads the overall manuscript writing and conducted OLS regression models; W.-A.C. and J.G. conducted the data analysis and led the result interpretation; C.R. contributed writing in conclusions and literature review. W.-A.C., J.G., and C.R. contributed revising and reviewing the entire manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Energy Burden	This study	The energy burden was based on the survey data and calculated by this study
Internet Burden	This study	The internet burden was based on the survey data and calculated by this study
Software and algorithms		
SPSS Statistics	IBM	https://www.ibm.com/products/spss-statistics

RESOURCE AVAILABILITY

Lead contact

Requests for further information and resources should be directed to the lead contact, Chien-fei Chen (cchen26@utk.edu).

Materials availability

This study did not generate new materials.

Data and code availability

Data and code can be obtained from the lead contact upon request.

METHOD DETAILS

Survey procedures and instrument

This study distributed an online survey (n = 2,588) through Qualtrics in 2021 to residents in the U.K.. An internet-based questionnaire was designed with and administered through Qualtrics Paid Panel Service (see S1), a popular online data collection platform used by researchers. The sample was collected online voluntarily, based on the U.K.'s gender and ethnicity representative ratio. However, to gather additional insights from vulnerable populations, we intentionally oversampled LIHs to prioritize their experiences. Respondents received a small financial reward for participating. The survey gauged four main areas: energy and internet costs and burdens, experiences of energy and internet insecurities, built environment (i.e., thermal comfort and IEQ), social-psychological factors (i.e., trust and perceived affordability), and demographics. Finally, the survey collected demographics (e.g., gender, age, education level, and race/ethnicity) and household characteristics (e.g., dwelling type, homeownership, household size). Below sections details of the measurement for critical variables.

Participant demographics

The demographic information of the respondents is shown in Table 6; in addition, the comparison of how respondent demographics align with UK demographics is presented in Table 6 as well. Among the participants in our survey, 49.7% identified as women, 49.8% identified as men, and 0.5% preferred not to answer. Most participants (63.5%) were middle-aged (31-60 years old), 18.2% were young (18-30 years old), and 18.2% were older persons (61 years old or older). The racial distribution reflects the diversity of the population, with 11.6% of respondents reported as POC, comprising subgroups: Black and Latino (3%), Asian (6.4%), and mixed races (2%). The majority, constituting 88.4%, were reported as White individuals. The majority had an annual household income before tax of £25,501 to £50,000 (49.9%), followed by less than £25,000 (30%) and more than £50,000 (20.1%). Education levels indicate diversification, with 24.8% having secondary education, 63.6% attaining a high-level education or college degree, and 11.6% holding a post-graduate degree. Additionally, half of the participants are employed full-time (50.9%), with 18.2% employed part-time, 13.5% unemployed, 17.4% retired and others. Regarding the household demographics, most participants lived in England (85%), while the remaining 15% were respectively 8% in Scotland, 6.8% in Wales, and 0.2 % in Northern Ireland. Approximately 58.4% owned their residence, while 41.6% rented (either socially or privately).

Measures

Most survey measures, except for demographics and household information, were based on a 5-point Likert scale. For the 5-point Likert-type scale in this study, one indicates "strongly disagree," "very unlikely," "very unconcerned," "much worse than before," "much lower than average," "easy," "very unimportant," "very affordable," or "never," and a five indicates "strongly agree," "very likely," "very concerned," "much better than before," "much higher than average," "difficult," "very important," "very expensive," or "very often." In addition, other demographic and household-related questions were measured with yes, no, and unsure/do not know. Below are all the details for measuring each variable.

Key variables

IB measured the average share of a household's monthly income spent on monthly Wi-Fi, internet, or broadband connection from January to March 2021. The percentage of IB was measured by dividing the average monthly internet costs by monthly household income.

EB measured the share of a household's monthly income spent on utility bills (e.g., electricity, water, and gas) in February 2021. Specifically, the percentage of EB was measured by the monthly utility bill divided by the monthly household income. The utility bill in February 2021 was mainly used as the representative bill because of the third national lockdown on January 4th, 2021, when most residents likely spent more money on utilities.

Utility hardship (UH) measured the frequency with which households dealt with three utility-related issues from March-June during the COVID-pandemic in 2021: 1) skipping meals or other expenses to save money for utility bills, 2) reducing expenses on other necessities like food and medicine to afford utility bills, and/or 3) receiving a disconnection threat from their utility service provider. The three items were further averaged to represent the UH index based on the factor analysis results, and the internal reliability was relatively high (Cronbach alpha = 0.83).

Trust in utility companies measured the level of respondents' agreement or disagreement with the following statements, including my utilities "are reliable generally," and provide "fair rates and services," "good quality services, "special support to vulnerable groups at higher risk of COVID infection and spread (e.g., seniors, low-income families), and special support or programs to customers, "and "provide special support or programs to customers during the pandemic." (Cronbach alpha = 0.88).

Trust in internet service providers measured the level of respondents' agreement or disagreement with the following statements: "In general, my internet provider always keeps customers' best interests in mind, "In general, my internet provider provides reliable services," and "during COVID-19, my internet provider has taken several protection steps for customers such as preventing scams," "…has the plan to prevent service disconnection for nonpayment," and "…my overall opinions on my internet provider has improved." (Cronbach alpha = 0.80).

Thermal discomfort measured the frequency of experiencing heating problems, including being unable to heat because of broken heating equipment, feeling uncomfortably cold for extended periods at home, and keeping an uncomfortable temperature to save energy. (Cronbach alpha = 0.87).

Poor IEQ measured the frequency of experiencing lacking air quality/ventilation, too cold during the winter, weak roof and/or leaks, dampness and/or mold, cold water, inadequate lighting, and noise (Cronbach alpha = 0.88).

Internet access and reliability measured two questions indicating if participants had access to the internet, Wi-Fi, and fixed broadband at home and the frequency of experiencing reliable internet services during the pandemic, respectively.

Perceived affordability of utilities and internet

Two statements were used to measure perceived affordability, including "How affordable was your internet access during the COVID-19 pandemic in 2021?" and "How affordable were your utility bills during the COVID-19 pandemic in 2021?"

Demographics include questions about age, gender, homeownership/renter, race/ ethnicity, and education level. Age was measured on a continuous scale from one (less than 18 years old) to 16 (74 years old or more) with an interval of a five-year difference. Gender was dummy coded, so 1 = women, and 0 = men. Homeownership status was dummy coded, where 1 = renters and 0 = owners. Education measured the secondary school education up to 16 years, higher or further education (A-levels, Business, and Technology Education Council, BETC, etc.), college or university degree, or postgraduate degree. Race/ethnicity measured participants' race/ethnicity background, including White, Black, Asian and Pacific Islander, Latino, multiple ethnicities, and other ethnicities. We dummy-coded minority ethnicity as 1, encompassing individuals who identified as non-White or multiracial, while White participants were coded as 0.

Classification of income groups

For further comparison, we categorized income levels into three identifiable groups based on the U.K. median household income: low-, medium-, and high-income households (LIHs, MIHs, and HIHs, respectively). LIHs represented households earning less than £25,000 a year, MIHs were £25,000-£50,000, and HIHs were £50,000 or more before tax.