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Unraveling the complexities: Impacts of energy burden on the built environment challenges among assistance-dependent populations in the United Kingdom

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ABSTRACT

The intricate relationship between energy burden (EB) and indoor environmental quality (IEQ) is vital for human well-being within the built environment. While previous studies have focused on vulnerable groups, individuals with health concerns have received limited attention. This interdisciplinary study delves into the disparities and cumulative impacts of EB, the built environment, and social demographics, with a particular focus on assistance-dependent populations (ADPs). Based on 2588 online respondents in the U.K. during the COVID-19 pandemic, our research unveils significant relationships between EB, heating insecurity, and perceived thermal discomfort. ADPs reported an average EB of 5.5% and poorer housing quality than their counterparts, with inadequate temperatures emerging as a primary concern. The correlation analysis highlights a strong connection between the perception of thermal discomfort and energy-saving behaviors. We also explored the interactions of EB, homeownership, and assistance-dependent status to uncover concentrated disadvantages in housing issues and identified vulnerable groups. Notably, irrespective of their EB, ADPs face more challenges than non-ADPs, highlighting the greater predictive significance of assistance-dependent status over EB. Moreover, our findings suggest that assistance-dependent renters constitute the most vulnerable group. Considering that ADPs already contend with preexisting physical illnesses, the revelation that they are more prone to experiencing higher EB and residing in inferior conditions is of utmost importance. It underscores the urgency of mitigating these additional health risks and ensuring the availability of a healthy and safe living environment for vulnerable demographics, thereby advancing the goal of equity within the built environment for overall well-being.

1. Introduction

In the face of global warming and extreme weather events, the intricate relationship between energy burden (EB) [1], energy insecurity [2,3], and indoor environmental quality (IEQ) becomes increasingly vital for human health and well-being within the built environment [4]. As temperatures dramatically rise in summer and drop in winter due to climate change, the demand for improving better housing conditions becomes critical issues related to the built environment and energy cost, especially that thermal comfort and energy efficiency are often the conflict goals [5,6]. Poor IEQ such as inadequate ventilation, exacerbated by a desire to reduce energy consumption, can have significant health implications [7,8]. These include increased risks of respiratory problems, allergies, and exacerbated conditions like asthma, especially for vulnerable populations [9]. Concurrently, extreme weather events like heatwaves or prolonged cold spells can directly affect indoor conditions. Inadequate heating and cooling during such events can result in discomfort and even life-threatening situations, particularly for those who cannot afford the energy costs associated with maintaining a comfortable indoor environment. To address these multifaceted challenges, high-level discussions have expanded to encompass not only energy efficiency and resilience measures [10] but also the critical need to enhance IEQ within the built environment.

There were numerous previous studies focused on the well-being needs of various vulnerable groups, particularly minorities, people with low socio-economic status, and vulnerable age groups; however,

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there were very few studies about some of the subgroups within people with health concerns [7]. Unique to this study, we propose an interdisciplinary study to address the inequity issues focusing on the EB, built environment, heating insecurity challenges and social demographics factor. Utilizing survey data, our investigation delves into these matters through the lens of individuals' subjective perceptions, with a particular emphasis on households living with individuals with disabilities and with electricity medical needs that are affected by heating/cooling, which is defined as assistance-dependent populations (ADPs) in this study. By prioritizing these factors, our discussions endeavor to promote healthier indoor environments, particularly for vulnerable populations, where well-being is intrinsically linked to both energy consumption and quality of life. Furthermore, we aim to amplify the needs and distinctive challenges faced by ADPs, thereby contributing to a more inclusive and equitable society. This holistic approach underscores the imperative for comprehensive research and equitable recommendation in the realms of energy consumption and the built environment, especially in an era marked by the challenges of climate change and energy poverty [11].

2. Literature review

The growing recognition of the importance of achieving optimal building energy efficiency while simultaneously ensuring Indoor Environmental Quality (IEQ) and thermal comfort has become a prominent focus. Numerous well-established indexes and criteria endorsed by esteemed organizations such as American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Leadership in Energy and Environmental Design (LEED), and health standards such as WELL [12], underscore the strong correlation between the energy use, built environment, well-being, health, productivity, and cost-effective building operation. Furthermore, international standards, exemplified by ISO 17772–1 [13] and EN 16798–1 [14], have defined criteria for IEQ levels and energy performance in buildings. These standards also work to address resilience, environmental sustainability, and health-related equity goals within the built environment [7]. Since built environment plays an essential role in addressing the basic needs of society, such as having places to live, work, learn, travel, and entertain [7], the well-being within these structures assumes paramount significance.

High-quality indoor environments have been confirmed to play a pivotal role in influencing health, performance, and absenteeism [15]. Researchers have been exploring strategies to balance and optimize indoor environmental quality (IEQ), thermal comfort, and energy efficiency across various building types [16,17]. However, the built environment is particularly critical in residential buildings, where people spend a significant portion of their time engaged in diverse activities. This profoundly influences occupants' well-being, affecting productivity [18], educational outcomes [19], and health [20]. Of particular concern is the profound housing crisis affecting vulnerable populations who face exceptionally complex challenges. These relate not only to the burden of energy expenses but also to the overall quality of their living conditions, especially in the era of climate change and increasingly frequent extreme weather events [21]. On the other hand, the design, construction, or operation of built environments to cater to the specific needs of one group may not necessarily fulfill the requirements of other groups [7,22]. The disparities in human needs and behaviors within built environments can be considerable, particularly when considering diverse demographics, such as varying income levels, educational backgrounds, or individuals with physical disabilities and specific medical needs. Therefore, researchers should place greater emphasis on uncovering the challenges faced by different individuals to address these gaps. This study specifically provides an overview of the literature focusing on the challenges related to the built environment, energy insecurity, and living conditions experienced by vulnerable populations.

In the realm of socio-economic studies concerning the built environment and EB across diverse demographics, with a particular focus on vulnerable populations, it becomes evident that investigating the intricate relationship between the two factors is of paramount importance. Within this framework, energy insecurity, conceptualized as a multi-dimensional construct that describes the interplay between physical conditions of housing, household energy expenditures and energy-related coping strategies [2,23], reflecting the challenges and dilemmas faced in daily life. Vulnerable populations, including low-income households (LIHs), people of color (POC), individuals dealing with illnesses [24], grapple with significant challenges arising from energy insecurity, subpar housing conditions and inadequate thermal comfort, among other factors, all of which collectively exert detrimental effects on their overall health and well-being [1,25]. Moreover, these financial implications extend to additional costs incurred by people with disabilities to ensure their health, safety, and quality of life, encompassing expenses related to accessibility needs and other accommodations [26]. Hence, there has been a growing emphasis on studies aimed at understanding the needs and challenges of energy insecurity and housing quality faced by vulnerable populations. Malik et al. [27] conducted a detailed study in Mumbai, India, focusing on how people in low-income housing adapt to temperature conditions. Their comprehensive field measurements and surveys provide policy implications and design guidelines for creating thermally comfortable low-income dwellings. Chen et al. [1] offer valuable insights that delve into the complex dimensions of energy insecurity experienced by vulnerable populations (e.g., LIHs, POC, low-income renters, etc.), encompassing aspects related to the built environment, energy-related financial difficulties, and energy-related behavioral patterns, all of which involve various strategies aimed at alleviating the physical, health, and economic consequences associated with energy insecurity.

EB, measured by the proportion of household income allocated to energy expenses, is one of the critical challenges disproportionately affecting individuals with lower incomes [9,28,29]. In the US, for instance, LIHs allocate approximately 10% of their total income to energy bills, whereas higher-income households spend only around 3.3% [25]. The influence of dwelling characteristics, as highlighted in Chen et al.'s research, plays a significant role in determining energy consumption patterns, shedding light on potential explanations for EB within LIHs. Particularly, individuals with lower incomes often resort to inefficient appliances, elevating their energy consumption and compounding their EB [3,28]. This energy insecurity is not solely dependent on economic hardships but also on physical housing conditions and occupants' behaviors that can increase costs. Additionally, previous research [30] has established a connection between poor housing quality, unmet social needs, stress, and depression among low-income smokers, which underscores the impact of energy expenses and housing quality on physical and mental health, emphasizing that distinct demographic groups encounter unique challenges related to their well-being. Besides, to cope with these challenges, individuals experiencing energy insecurity may resort to risky behaviors, such as forgoing basic needs, relying on payday lending, or using less reliable energy sources to compensate for their energy needs [23,29]. For instance, LIHs often resort to unsafe practices for energy-saving, such as using stoves and space heaters, leading to fire risks and diminished air quality, jeopardizing their health and safety [9,23]; EB may compel occupants to set their heating or cooling systems at uncomfortable temperatures to reduce energy use, ultimately affecting their overall well-being [31]. Interestingly, the findings of one study underscore the high thermal tolerance exhibited by low-income occupants, potentially attributed to adjusted expectations due to resource constraints or adaptation to high-temperature and humidity conditions [27].

The correlation between housing conditions and energy poverty is evident, with factors like poor housing quality, inadequate insulation, and lack of basic energy services contributing to energy insecurity [28]. Notably, housing characteristics and socio-demographic factors have substantial implications on residential energy use intensity, with lower-income households and ADPs often residing in less energy-efficient homes with leaky structures and less efficient appliances [25,32]. Racial, educational, and household characteristics have been identified as factors influencing energy insecurity, with certain demographics being more vulnerable to this issue [1,24]. Survey results reveal that a significant portion of LIHs struggle with affording energy bills and face potential disconnection due to non-payment. Material hardship, unemployment, and COVID-19-related factors are statistically associated with various forms of energy insecurity [24]. The aforementioned indicated that the interplay among socio-economic status, energy costs, and trade-off behaviors is a complex issue with profound implications, emphasizing the necessity for comprehensive policies and interventions aimed at alleviating the EB and energy insecurity faced by vulnerable populations and ensuring equitable access to essential resources and fundamental living quality.

Individuals with disabilities face a unique set of challenges when it comes to energy insecurity, making them particularly vulnerable to its consequences. This vulnerability is especially pronounced for those who rely on electric medical devices or experience difficulties with thermoregulation, as access to heating or cooling becomes a critical need for their well-being. For individuals with disabilities, the burden of energy insecurity is compounded by a range of additional expenses that result from their unique circumstances. These include higher energy costs due to physical inactivity, prolonged periods spent at home, increased laundry requirements, specialized dietary needs, and the use of electrical aids such as mobility devices [23]. Moreover, many disabled individuals and families with disabled children often find themselves in situations where they are living in poverty or on a low income, residing in substandard housing, and facing additional essential costs of living, with energy costs being a significant part of this financial strain [26]. Moreover, previous studies have shown that energy insecurity is notably more prevalent in households of individuals with disabilities. This issue is particularly critical for those with disabilities who depend on electric medical devices for their livelihood or struggle with thermoregulation in the absence of heating or cooling. The absence of dependable access to electricity presents significant risks, especially for those relying on life-sustaining medical equipment, such as ventilators and power wheelchairs [23]. In such cases, any interruption in the power supply can have life-threatening consequences, making energy insecurity a matter of life and death. It is important to recognize that these energy- and housing-related issues disproportionately affect certain demographic groups, including single parents, the elderly, the disabled, and individuals with low or fixed incomes [3]. This disproportionate impact highlights the concept of “concentrated disadvantage,” which sheds light on the profound difficulties these vulnerable groups face. The concept of concentrated disadvantage emphasizes the interconnected relationship among demographic and socio-economic factors, which collectively create multiple challenges for individuals within these groups. This can include low-income ADPs, renters within the ADP group, and ADPs with high EB who must allocate a significant portion of their limited income to cover energy costs [1].

For ADPs particularly, issues within the built environment, such as inadequate ventilation, mold infestations, and noise pollution, further contribute to the intricate chain reaction among EB, built environment/IEQ, thermal comfort, and health. The health hazards posed by these built environmental factors present a significant risk to those who are chronically disabled [2,33], and the impacts on ADPs are more profound than on other individuals. In recent studies, there has been a growing effort to raise awareness about energy insecurity and built environment challenges faced by vulnerable demographics like LIHs and people with chronic diseases [34]. Nevertheless, it is worth noting that the concept of concentrated disadvantage has not yet received formal exploration in these domains [1], especially in the context of individuals with physical disabilities and medical needs. To address these research gaps, this study focuses on the ADPs to investigate and elucidate the multifaceted challenges these concentrated disadvantaged groups encounter in their pursuit of well-being concerning energy and the built environment issues. By recognizing and addressing these issues, we can work towards a more inclusive and equitable energy system that supports the well-being and independence of all members of society.

3. Purpose of the study

This study aims to address the significant impact of the EB and the built environment on individuals' well-being considering the socio-demographic factors, with a particular focus on ADPs (Fig. 1). The rationale behind this emphasis is rooted in the recognition that ADPs, due to various circumstances and vulnerabilities, face a unique set of challenges in their living conditions. Our study endeavors to delve deeper into the complex web of factors that contribute to these challenges. Given the UK's temperate climate, our study primarily addresses heating issues, as cooling demand accounts for merely 10% of electricity use [35]. Our investigation will shed light on how EB influences heating-related behaviors and seek to clarify the intricate relationship between EB and heating insecurity, particularly thermal discomfort, subsequently affecting their overall living quality. Uniquely, previous studies tended to utilize modeling or surveys focusing on the physical condition of the built environment, while this study places greater emphasis on occupants' subjective perceptions to reveal their intuitive perspective on living conditions. Moreover, it is worth noting that many occupant behaviors were measured by a single, absolute response concerning a particular choice in dealing with latent variables [36]. However, individuals tend to demonstrate greater accuracy and consistency when providing comparative responses involving two or more choices, influenced by their specific situation and personal experiences [37]. In addition, there is a lack of utilizing the measurement which considers the latent variables in the previous studies related to the built environment. Consequently, our research endeavors to discern pivotal issues within the realm of the built environment and heating challenges encountered by ADPs, along with an exploration of their associated behaviors based on the survey methodologies of social science. The overarching aim is to offer insights and implications regarding housing quality, with the goal of advancing the health and well-being of vulnerable individuals. This study attempts to answer the following research questions:

1) Does EB significantly relate to conditions of the built environment, perceived thermal discomfort, and heating insecurity?
2) Do ADPs experience higher EB or encounter more challenges related to the built environment, heating insecurity, and thermal discomfort compared to their counterparts?
3) What are the most severe issues of built environment, perceived thermal discomfort and heating insecurity experienced by ADPs?
4) Exploring the correlation between “thermal discomfort” and “heating insecurity” to identify potential causes of thermal discomfort.
5) How does the built environment, thermal discomfort, and heating insecurity differ among ADPs with high-risk EB (HEB) and non-HEB, as well as different homeownership statuses?

4. Methodology

4.1. Survey procedures

This study conducted an online survey (n = 2588) among UK residents in 2021, using an internet-based questionnaire distributed through Qualtrics Paid Panel Service, a widely utilized online data collection platform for researchers. Online volunteers were recruited as the sample, with a deliberate effort to mirror the UK's income and gender distribution. The survey covered a spectrum of key domains, including assessments of energy and internet expenses and their associated challenges, experiences with insecurities related to both energy and internet access, evaluations of the participants' subjective perception related to the built environment, encompassing aspects like housing conditions, thermal comfort and IEQ, scrutiny of social-psychological factors such as

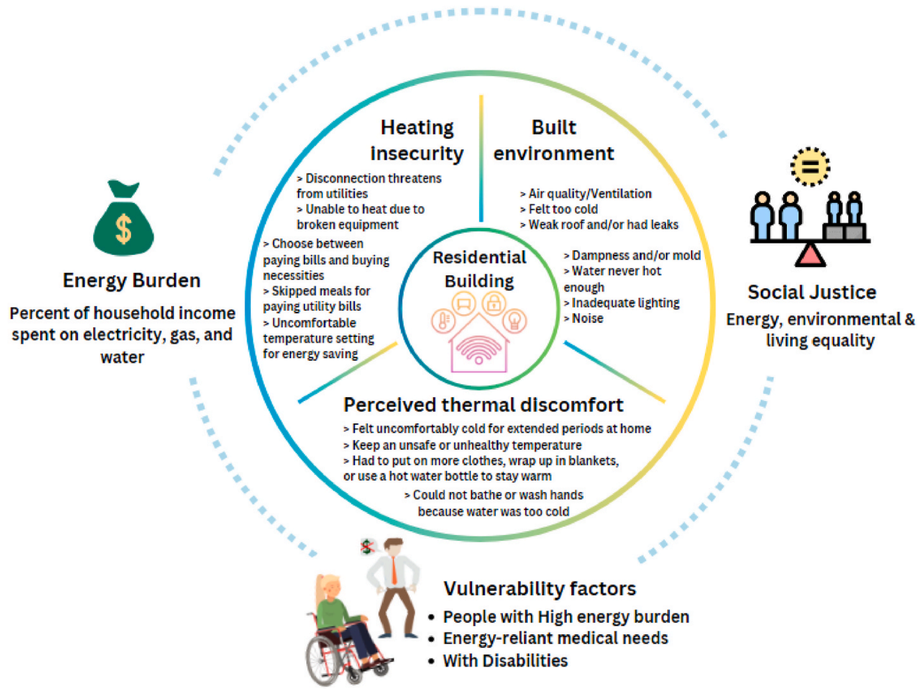

Fig. 1. Conceptual diagram of the key variables considered in this study.

trust and perceived affordability, and a comprehensive exploration of demographic information. Additionally, the primary objective behind distributing the survey was to assess the influence of COVID-19 restrictions on household energy and internet usage. The pandemic altered people's work patterns, resulting in extended periods spent at home. Consequently, this shift had a notable impact on how individuals perceived their housing conditions, especially regarding indoor thermal comfort and heating/cooling expenses. The prolonged duration spent at home further exacerbated the interconnectedness of these issues. Moreover, individuals with disabilities or medical needs affected by heating and cooling may experience heightened stress, compounding their existing health issues, particularly in light of the pandemic-induced shifts in their living situations. Thus, we extracted the questions in the survey, and focused on the impact of EB and its relationship with the built environment, thermal discomfort and occupants' trade-off behaviors when encountering issues related to paying energy bills and housing quality to clarify their specific needs. Section 4.3.1 provides detailed information on the measurement of critical variables targeted in this study.

4.2. Participants' demographics and the definition of ADPs and non-ADPs

The demographic information of the respondents is shown in Table 1. Among the participants, the gender distribution was balanced, with 49.7% identified as women, 49.8% identified as men, and 0.5% preferred not to answer. In terms of age, the majority (63.5%) fell within the middle-aged bracket (31–60 years old), while 18.2% were young (18–30 years old), and another 18.2% were older individuals (61 years old or older). The racial distribution reflects the diversity of the population, with 11.59% of respondents reported as POC, comprising subgroups: Black (2.5%), Latino (0.5%), Asian (6.4%), and mixed races (2%). The majority, constituting 88.4%, were reported as White individuals. Income-wise, a significant portion had an annual household income before tax ranging from £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 in Scotland, Wales, and Northern Ireland. Over half of the participants (58.4%) owned their residence, while 41.6% rented (either socially or privately), indicating our sample has a good representation of renters and homeowners. For dwelling size, most participants did not know their dwelling size (40.1%), while 27.9% lived on a property between 75 and 125 square meters, 18.2% lived on a property of less than 75 square meters, and 13.8% lived on a property of more than 125 square meters. The majority of households were comprised of one or two occupants (48.9%), followed by three or four occupants (42.1%), and a smaller percentage with five or more (9%).

In this study, we focus on the vulnerable groups of households living with individuals with disabilities and those with electrical medical needs affected by heating/cooling. These two types of households are defined as ADPs in this study. According to the descriptive statistics, the ADP accounts for 24.5% ($n = 634$) of the entire sample. Within this ADP population, 39.3% ($n = 249$) are households with individuals with disabilities, and 60.7% ($n = 385$) are households with individuals who have electrical medical needs affected by heating/cooling; furthermore, 21.6% ($n = 137$) have both conditions. We further investigated the interaction of income level and ADPs/non-ADPs. As shown in Fig. 2, in the non-ADP group, a minority of 28.5% fall into the LIH category, the majority of 50.7% are classified as MIH, and the remaining 20.9% are in the HIH category. Conversely, the ADP group shows a larger proportion of LIH at 38.8%, a slightly smaller proportion of MIH at 45%, and a notably smaller proportion of HIH at 16.3%. This result highlights a clear shift toward lower income brackets when comparing the non-ADP group with the ADP group, suggesting a possible correlation between ADP categorization and lower household income levels, as evidenced by the higher proportion of LIH within the ADP group.

4.3. Procedure of measurement and statistical analysis

Most survey measures in this research project utilized a 5-point Likert scale, excluding demographic and household information,

Table 1
Participant demographic characteristics.

Participant characteristics	Frequency (%)
Primary Demographics	
Gender	
Male	49.8
Female	49.7
Not to answer	0.5
Age	
18–30 years old	18.2
31–60 years old	63.5
61 years old or older	18.2
Race/ethnicity	
White	88.4
Black	2.5
Latino	0.5
Asian	6.5
Mixed races	2
Income	
Less than £25,000	30
£25,501 to £50,000	49.9
More than £50,000	20.1
Education	
Secondary Education	24.8
High-Level Education or college degree	63.6
Post-graduate degree	11.6
Employment	
Employed full-time	50.9
Employed part-time	18.2
Unemployed	13.5
Retired and others	17.4
Household Demographics	
Residential area	
England residence	85
Scotland, Wales, and Northern Ireland residence	15
Homeownership status	
Owner	58.4
Renter	41.6
Dwelling size	
Less than 75 square meters	18.2
75–125 square meters	27.9
More than 125 square meters	13.8
Do not know	40.1
Household size	
One or two occupants	48.9
Three or four occupants	42.1
Five or more	9

which were handled differently. In this 5-point Likert-type scale, a rating of one corresponds to responses indicating disagreement, unlikelihood, unconcern, worsening, below-average, ease, unimportance, affordability, or rarity. Conversely, a rating of five corresponds to responses indicating agreement, likelihood, concern, above average, or frequency (i.e., very often). Demographic and household-related questions were measured using options such as yes, no, and unsure/do not know.

Uniquely, the key variables measured in this study were obtained using a multi-item approach in our survey, combining latent variables based on relevant theories for assessing social psychological attributes and human attitudes. Specifically, factor analysis [38,39], a statistical method used to elucidate relationships among observed and correlated variables in terms of a potentially smaller set of unobserved variables, was employed to identify the crucial variables for further analysis.

4.3.1. Key variables

Four key variables are considered in this study, including EB, built environment, heating insecurity, and perceived thermal discomfort. These variables encompass the aspects of financial concerns, physical conditions of built environment, occupants' behaviors when encountering thermal discomfort, and their trade-off behaviors regarding paying energy bills and their living quality.

Energy burden (EB) was defined as the percentage of gross household income spent on energy costs [40]. In this study, EB quantified the portion of a household's monthly income allocated to utility expenses such as electricity, water, and gas in February 2021. We collected data on their income and energy bill costs to estimate participants' EB.

Built environment was assessed by the level of respondents' agreement or disagreement with the 7 types of statements about their housing quality during the pandemic, including (1) lacking air quality/ventilation; (2) felt too cold at home; (3) weak roof and/or had leaks; (4) dampness and/or mold; (5) water never hot enough; (6) inadequate lighting; and (7) noise. These seven variables were further averaged to represent the indicator of "built environment" based on the factor analysis results, as shown in Table 2.

Perceived thermal discomfort was measured by the frequency of temperature-related issues and behaviors subjectively perceived and acted upon by participants. Since thermal comfort is one of the primary factors influencing occupant health, well-being, and productivity in buildings [a30], this study conducted deeper investigation regarding the aspect of thermal comfort. Perceived thermal discomfort was the average score of the variables including (1) felt uncomfortably cold for extended periods at home; (2) keep an unsafe or unhealthy temperature (3) had to put on more clothes, wrap up in blankets, or use a hot water bottle to stay warm; (4) could not bathe or wash hands because water was too cold. These four variables were also averaged to represent the indicator of "built environment" based on the factor analysis results (Table 2).

Heating insecurity serves as a crucial indicator encompassing not only the physical aspect of inadequate heating but also reflecting sociological and psychological insecurities stemming from EB and financial constraints. This multifaceted metric measures the frequency of various challenges, including (1) Disconnection threatens from utilities; (2) unable to heat due to broken equipment; (3) choose between paying bills and buying necessities (e.g. food, medicine, childcare); (4) skipped meals for paying utility bills (5) uncomfortable temperature setting for energy saving. Factor analysis (as detailed in Table 2) reveals that the average of these five variables effectively represents the composite indicator of "heating insecurity".

In addition, this study dummy coded the following variables to

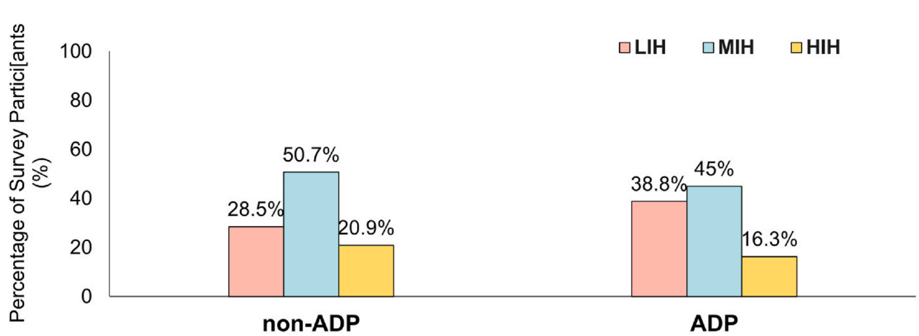

Fig. 2. Proportion of ADPs/non-ADPs across income groups.

Table 2
Factor analysis results of key variables.

Variables	Mean	S.D.	Factor Loading
Built environment: *(Do you agree or disagree with the following statements about your housing quality during the pandemic?)* *Cronbach's α = 0.88; Composite Mean = 2.13*			
Lacking air quality/ventilation	2.31	1.04	0.69
Felt too cold	2.45	1.14	0.77
Weak roof and/or had leaks	1.84	1.07	0.75
Dampness and/or mold	2.20	1.29	0.75
Water never hot enough	2.00	1.12	0.83
Inadequate lighting	1.92	1.03	0.83
Noise	2.23	1.21	0.70
Perceived thermal discomfort: (people's perception) *Cronbach's α = 0.86; Composite Mean = 2.091*			
Felt uncomfortably cold for extended periods at home	2.16	1.12	0.91
Could not bathe or wash hands because water was too cold	1.54	0.98	0.73
Had to put on more clothes, wrap up in blankets, or use a hot water bottle to stay warm	2.55	1.23	0.84
Keep an unsafe or unhealthy temperature	2.11	1.18	0.86
Heating insecurity: (related to budget, money) *Cronbach's α = 0.86; Composite Mean = 1.645*			
Disconnection threatens from utilities	1.35	0.84	0.79
Unable to heat due to broken equipment	1.51	0.96	0.81
Choose between paying bills and buying necessities (e.g. food, medicine, childcare)	1.64	1.06	0.88
Skipped meals for paying utility bills	1.62	1.04	0.84
Uncomfortable temperature setting for energy saving	2.11	1.17	0.70

conduct certain specific statistical analysis. Specifically, we created the dummy variables for ADPs and non-ADPs, where "1″ indicated belonging to the ADPs and "0″ represented the non-ADPs. Individuals whose EB ≥ 6% are categorized into HEB groups, dummy-coded as HEB = 1, while their counterparts were represented as non-HEB, dummy-coded as 0. When conducting the chi-square tests of independence to assess whether participants encountered issues related to our key variables or their detailed items, we defined and dummy-coded the variables with answers regarding agreement and frequency as the categories of yes/no. Specifically, for built environments, the answer of "neutral", "agree", and "strongly agree" are dummy-coded as yes = 1, while "disagree" and "strongly disagree" are dummy-coded as no = 0. In terms of "heating insecurity" and "thermal discomfort" with answering the frequency, the answers of "sometimes", "often", and "always" are dummy-coded as yes = 1, while "rarely" and "never" are dummy-coded as no = 0.

4.3.2. Statistical models and test

This study utilized the following statistical models, including Ordinary Least Squares (OLS) linear regression models, chi-square tests of independence, as well as one-way and two-way analysis of variance (ANOVA) models.

The OLS linear regression model with control variables aims to estimate the relationship between a dependent variable and an independent variable while accounting for the potential influence of control variables, which is a common and valid approach in statistical analysis to obtain more accurate and reliable estimates of causal effects of predictors on dependent variables. In this study, all the models controlled for the effects of race, gender, and education.

A chi-square (X^2) test of independence is a type of Pearson's chi-square test. It is conducted to assess the likelihood of a relationship between two categorical variables (Eq. (1)). These tests are based on the observed frequencies, which represent the actual counts of observations in each combined group of the variables being studied. By comparing the observed frequencies to the expected frequencies under the assumption of independence, chi-square tests help determine whether there is a statistically significant association between the variables.

$$X^2 = \sum \frac{(O-E)^2}{E} \tag{1}$$

where X^2 is the chi-square test statistic, O is the observed frequency, and E is the expected frequency.

One-way and two-way ANOVA models were utilized to explore the group differences and how combinations of two independent variables impact a dependent variable. Specifically, a one-way ANOVA model is used to compare the means of two or more independent groups, aiming to determine whether there is statistical evidence that the associated population means are significantly different. On the other hand, a two-way ANOVA is designed to assess the interrelationship of two independent variables on a dependent variable, allowing us to compare multiple groups formed by the interaction of these two factors.

In addition, we used the Pearson correlation coefficient, which measures the linear correlation between two sets of data, to explore the relationships between variables. The strength of the association between the two variables is reflected in the Pearson correlation coefficient (r). The closer r is to either +1 or −1, the stronger the positive or negative relationship, respectively. The $r = 0$ indicates no association between the two variables [41]. The Pearson correlation coefficient can be expressed by Eq. (2).

$$r = \frac{\sum (x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum (x_i - \overline{x})^2 \sum (y_i - \overline{y})^2}} \tag{2}$$

where r is the correlation coefficient, x_i is the values of the x-variable in a sample, $\overline{x}$ is the mean of the values of the x-variable, y_i is the values of the y-variable in a sample, $\overline{y}$ is the mean of the values of the y-variable.

5. Results and discussion

To clarify the proposed research questions, the following results detail the findings of various statistical analyses, which aim to elucidate the connections between energy usage and the multifaceted challenges experienced by the ADPs in relation to their living environment, thermal comfort, and heating behaviors.

5.1. Relationship between energy burden and key variables

Corresponding to our first research question, a series of OLS linear regression models was used to investigate the relationship between EB and the environmental and financial factors for the entire sample. These factors encompassed the built environment, perceived thermal discomfort resulting from improper air and water temperature settings in the house, as well as heating insecurity issues related to occupants' behaviors and budgets. Specifically, each OLS regression model used EB as the independent variable and built environment, heating insecurity, perceived thermal discomfort as the dependent variables; besides, these models accounted for potential confounding factors, including gender, ethnicity, and education. The regression results are presented in Table 3, and all the regression models indicated that EB is significantly related to the three dependent variables. Our analysis revealed a noteworthy finding that individuals with a higher EB exhibited a greater degree of concern regarding heating insecurity ($B = 0.202$; $p < 0.001$) compared to their counterparts. This outcome underscores the intricate interplay between energy using behavior, heating insecurity, and well-being. Additionally, the models highlight the challenges that individuals with higher EB were more likely to experience built environment issues ($B = 0.152$; $p < 0.001$) and perceived thermal discomfort ($B = 0.145$; $p < 0.001$). Moreover, the standard errors for the poor built environment (std. error = 0.076), heating insecurity (std. error = 0.080), and

Table 3
Results of OLS regression models.

Dependent variables	Independent variable: Energy Burden		
	Standardized Coeff. (Beta)	Std. Error	F
Built environment	0.152	0.076	(1, 2587) = 61.259***
Perceived thermal discomfort	0.145	0.069	(1, 2584) = 55.713***
Heating Insecurity	0.202	0.080	(1, 2578) = 109.777***

Note: All models are controlled for the effects of gender, ethnicity, and education. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.*

perceived thermal discomfort (std. error = 0.069) show that the results obtained from the models are dependable. Consequently, addressing EB comprehensively is not only about reducing financial stress but also about addressing its compound effects on residents' living quality and well-being.

5.2. Comparison of challenges faced by ADPs and non-ADPs

5.2.1. Energy burden

The distribution analysis of EB for the entire sample reveals 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%. In terms of the EB of ADPs and non-ADPs, the results show that ADPs (M = 5.5%, SD = 3.74) experienced higher EBs than non-ADPs (M = 4.3%, SD = 3.15), with statistically significant, $F (1, 2586) = 69.227$, $p < 0.001$. Our findings highlight the considerable disparities in EB experienced by individuals across ADPs and non-ADPs. Moreover, the higher EB observed among ADPs signifies the added burden experienced by this specific demographic, which might be derived from their unique living pattern or energy usage behaviors. Our findings are in line with the previous studies that ADPs often residing in less energy-efficient homes and using less efficient appliances, and therefore lead to higher EB. These results emphasize the importance of targeted interventions and policies to address energy-related economic disparities and provide more equitable support to those facing higher EB. Hence, our objective is to scrutinize the cascading effects on living conditions stemming from EB and elucidate the primary challenges encountered by the specific vulnerable population (i.e., ADPs). Detailed analysis results are presented in the subsequent sections.

5.2.2. Built environment, heating insecurity, and perceived thermal discomfort

Our investigation delved deeper into the extent of challenges related to living quality faced by individuals classified as ADPs in comparison to their counterparts. We conducted independent chi-square analyses to provide insights into both the variety and the number of issues simultaneously experienced by ADPs and non-ADPs, encompassing poor built environment conditions, heating insecurity, and perceived thermal discomfort. Our analysis uncovered a stark contrast between these two groups, with ADPs confronting a considerably higher extent of challenges (χ^2 (3, 2578) = 272.273; $p < 0.001$). Specifically, as depicted in Fig. 3, a noteworthy 52.2% of ADPs experienced at least one of the issues defined in this study. Even more strikingly, a substantial 33.6% of ADPs reported suffering from more than two of these issues concurrently. In stark contrast, only 23.2% of non-ADPs experienced at least one of these issues, and fewer than 10% of them encountered multiple types of challenges, whether they pertained to poor built environment conditions, heating insecurity, or perceived thermal discomfort. These findings underscore the pronounced disparities in the challenges faced by ADPs in contrast to their non-ADP counterparts, highlighting the critical need of support systems to mitigate the multifaceted issues affecting the well-being of vulnerable groups.

This study conducted a comprehensive investigation of the specific challenge categories faced by both ADPs and non-ADPs. Referring to Table 4, our findings reveal that "perceived thermal discomfort" is the most prominent challenge for ADPs, with 40.2% reporting such experiences, followed by concerns related to the built environment (38.5%) and heating insecurity (24.8%). In contrast, among non-ADPs, 13.6% encountered challenges related to perceived thermal discomfort and poor built environment, while a mere 6.0% faced issues associated with heating insecurity. These stark differences underscore the varying

Table 4
Degrees of challenges within ADPs and non-ADPs.

Number of issues	Category of the issues	Percentage within the groups (%)		Chi-square test
		ADPs	non-ADPs	
One	Built environment	38.5	13.6	χ^2 (1, 2588) = 191.591***
	Perceived thermal discomfort	40.2	13.6	χ^2 (1, 2579) = 164.319***
	Heating insecurity	24.8	6.0	χ^2 (1, 2585) = 179.685***
Two	Built environment & heating insecurity	19.8	3.6	χ^2 (1, 2585) = 257.986***
	Built environment & perceived thermal discomfort	27.4	7.1	χ^2 (2, 2585) = 257.986***
	Heating insecurity & perceived thermal discomfort	22.1	5.0	χ^2 (1, 2578) = 168.574***
Three	Built environment & heating insecurity & perceived thermal discomfort	17.9	3.1	χ^2 (1, 2578) = 272.273***

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

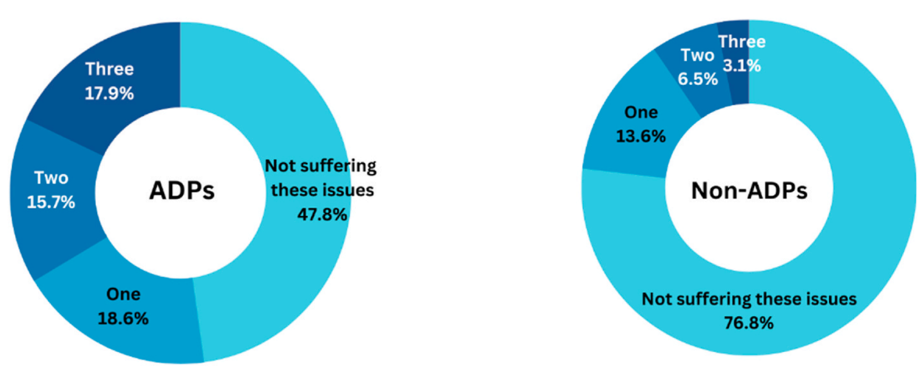

Fig. 3. Numbers of housing related issues faced by ADPs and non-ADPs.

degrees of challenges faced by these two groups, with ADPs experiencing a considerably higher prevalence of living condition issues compared to non-ADPs, highlighting the distinctive and pressing needs of ADPs.

In the case of ADPs, it is noteworthy that an average of 23.1% reported the concurrent experience of two distinct issues. Specifically, within this group, 27.4% faced the compound challenges arising from the coexistence of "built environment & perceived thermal discomfort", 22.1% encountered issues pertaining to "heating insecurity & perceived thermal comfort", and 19.8% confronted challenges related to the "built environment & heating insecurity". These findings shed light on the intersections and complexities of their experiences. In the context of non-ADPs, the predominant concern revolves around the "built environment and perceived thermal discomfort", while only 7.1% of non-ADPs concurrently experiencing these two issues. This is followed by the combination of "heating insecurity and perceived thermal comfort" at 5.0%, and "built environment and heating insecurity" at 3.6%. For those who reported grappling with all three issues simultaneously, 17.9% of ADPs reported such occurrences, whereas only 3.1% of non-ADPs reported similar experiences. Notably, a significant disparity exists in the occurrence of these issues between individuals in the two groups. Our investigation underscores the necessity for tailored interventions aimed at addressing the multifaceted challenges faced by these targeted populations.

Using the One-way ANOVA model, this study analyzed the group differences of the three dependent variables between ADPs and non-ADPs, the average scores of agreements for experiencing the poor built environment, heating insecurity, and perceived thermal comfort are shown in Fig. 4. For built environment issues, the one-way ANOVA results demonstrate significant variation in the built environment across ADPs and their counterparts, $F\,(1,\,2587) = 249.441$, $p < 0.001$). ADPs reported a higher average score that represented experiencing poorer built environment conditions, with the mean (M) of 2.57 ($SD = 0.95$), comparing to the mean of 1.98 ($SD = 0.77$) of non-ADPs. ADPs are also more likely to suffer greater issues related to perceived thermal discomfort in their house, with the mean of 2.55 ($SD = 1.02$) compared to their counterparts ($M = 1.93$, $SD = 0.86$). Lastly, heating insecurity significantly differed between ADPs and non-ADPs, $F\,(1,\,2584) = 362.971$, $p < 0.001$, which is related to their financial budget for energy use and the purchase of necessities, it reflects their trade-off behaviors when facing the dilemma of living conditions. ADPs are more likely to experience greater heating insecurity issues ($M = 2.13$, $SD = 0.98$) compared to non-ADPs ($M = 1.48$, $SD = 0.67$). These findings reveal that ADPs frequently encounter more severe, uncomfortable, and even unhealthy living conditions in their homes, exacerbating the challenges they face, especially in dealing with preexisting illnesses.

5.3. Clarify the detailed challenges in built environment, perceived thermal discomfort, and heating insecurity

To elucidate the foremost challenges within the domain of the built environment, as well as to comprehensively explore the dimensions of

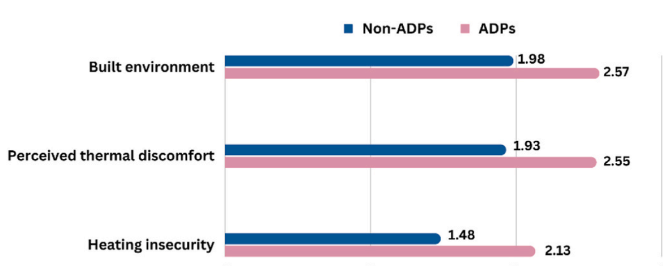

Fig. 4. One-way ANOVA results of the built environment, perceived thermal discomfort, and heating insecurity.

perceived thermal discomfort and heating insecurity experienced by ADPs, our study conducted a rigorous investigation into the nuanced facets within these categories based on the independent chi-square analyses. This methodical inquiry served to identify and elucidate the specific components and intricate details contributing to the heightened severity of issues associated with the three key variables.

First, we delved into the details of the built environment. As illustrated in Fig. 5, the results reveal that a majority of ADPs expressed concerns related to experiencing too cold in their homes (62.3%), followed closely by issues regarding inadequate air quality and ventilation (57.2%), as well as the presence of dampness and/or mold (52.8%). On the other hand, among non-ADPs, the three most prevalent issues were feeling excessively cold at home (36.2%), encountering poor air quality and ventilation (35%), and experiencing noise disturbances (29.7%). Additionally, the independent chi-square analysis revealed a significant relationship between each variable and whether individuals are assistance dependent (Table 5). Comprehensively, inadequate indoor temperature is the critical issues for the entire sample, leading to the thermal discomfort. While the types of issues are similar between the two groups, a noteworthy distinction emerges – significantly fewer individuals among the non-ADP group reported suffering from these problems. These findings also underscore the substantial challenges that ADPs encounter within their built environments when compared to their non-ADP counterparts. Such disparities point to the distinctive and often more acute environmental challenges that ADPs must grapple with in their daily lives.

Given that the majority of participants reported feeling excessively cold in their homes, this study conducted a detailed investigation into the disparities among items within the variable of "perceived thermal discomfort". These items were identified through factor analysis based on survey questions related to subjective thermal discomfort perception. Our aim was to uncover the underlying reasons and behaviors related to their perception of thermal discomfort. Based on the findings depicted in Fig. 6, it is evident that a significant majority of ADPs (66.4%) reported having a negative experience of needing to wear additional clothing, wrap themselves in blankets, or use hot water bottles to maintain warmth; on the other hand, a substantial portion of non-ADPs (46.9%) also encountered this particular challenge, which emerged as the most prevalent issue shared by both groups. The second and third most significant challenges encountered by both groups are comparable that ADPs and non-ADPs reported prolonged discomfort due to cold indoor temperatures, followed by concerns related to maintaining unsafe or unhealthy temperatures within their homes. The discomfort associated with cold water-related issues exhibits a relatively minor impact among these variables. Besides, the independent chi-square analysis also revealed a significant relationship between each variable within the issues related to perceived thermal discomfort and whether individuals are assistance dependent (Table 6).

Heating insecurity exhibits a profound connection with financial considerations, underscoring the intricate interplay between budgetary constraints and the maintenance of a comfortable and safe living environment. Referring to Fig. 7, a significant 53.9% of ADPs reported adjusting their home temperatures to uncomfortable levels to reduce energy consumption, a percentage notably higher than that observed among their counterparts (30.7%). Remarkably, 41.3% of ADPs faced the dilemma of choosing between paying utility bills and purchasing necessities due to budget limitations, a challenge significantly less prevalent among non-ADPs, where only 15.6% encountered a similar predicament. Furthermore, 40.4% of ADPs were compelled to make the distressing choice of sacrificing meals to fulfill their utility payment obligations, while this situation was experienced by merely 12.9% of non-ADPs. This composite measurement offers valuable insights into the complex challenges faced by individuals in balancing their financial resources with the need for adequate heating and well-being.

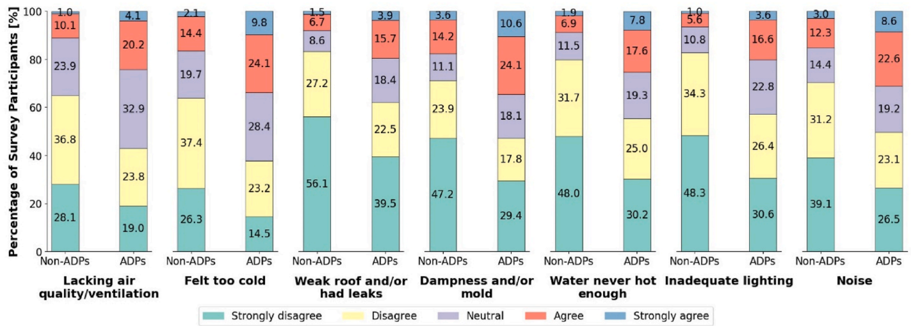

Fig. 5. Comparison of the built environment issues faced by ADPs and non-ADPs.

Table 5
Results of independent Chi-square analyses for the built environment.

Issues within built environment	Chi-square test
Lacking air quality/ventilation	χ^2 (4, 2588) = 121.558***
Felt too cold	χ^2 (4, 2588) = 175.702***
Weak roof and/or had leaks	χ^2 (4, 2588) = 131.867***
Dampness and/or mold	χ^2 (4, 2588) = 137.347***
Water never hot enough	χ^2 (4, 2588) = 176.495***
Inadequate lighting	χ^2 (4, 2588) = 186.825***
Noise	χ^2 (4, 2588) = 110.75***

**p* < 0.05, ***p* < 0.01, ****p* < 0.001.

5.4. Correlation perceived thermal discomfort and heating insecurity within ADPs

Perceived thermal discomfort and heating insecurity share a common nature as issues. The former pertains to occupants' subjective thermal perception, while the latter relates to occupants' behaviors influenced by financial constraints and energy consumption. These factors may result in a range of outcomes related to thermal perception. The Pearson correlation coefficient between the two sets of items within these categories can aid in identifying potential causes and assessing the relationship between associated difficulties. The variables and their abbreviations presented in Fig. 8 are shown in Table 7.

As shown in Fig. 8, the most pronounced correlations were identified between "uncomfortable temperature setting for energy saving" and "felt uncomfortably cold for extended periods at home" (r = 0.74, p < 0.001). Additionally, a notable correlation was also observed with the variable "keep an unsafe or unhealthy temperature" (r = 0.73, p < 0.001). These findings imply that, in pursuit of reducing energy consumption, individuals are inclined to set inadequate temperatures, resulting in prolonged thermal discomfort, as well as the possibility of maintaining unsafe or unhealthy indoor temperatures within their homes. It is important to highlight that the receipt of disconnection threats from utilities is greatly correlated with the following factors: having to choose between paying bills and purchasing necessities (r = 0.64, p < 0.001), inability to heat due to broken equipment (r = 0.63, p < 0.001), and inability to bathe or wash hands due to cold water (r = 0.54, p < 0.001). These correlations underscore the compounded impact of financial constraints, which may prevent individuals from affording the purchase or repair of essential heating and water equipment.

5.5. Interaction effects of concentrated disadvantage

This section aims to provide a more in-depth exploration to clarify the connection between these housing-related issues and concentrated disadvantage. We extended our analysis to encompass three two-way ANOVA models for the built environment, perceived thermal discomfort, and heating insecurity. These models incorporated demographic interaction terms as independent variables, exploring the interaction effect of assistance-dependent status, EB, and homeownership. Specifically, given that renters tend to experience higher EB in comparison to homeowners [1], we embarked on an investigation into the interplay among ADPs, non-ADPs, and their respective homeownership status. Furthermore, with a particular focus on ADPs, especially those reliant on electric medical devices, the utilization of electrical aids and the necessity to charge batteries for mobility devices could potentially lead to substantial cascading effects on housing and living conditions, all of which are intricately linked to EB.

Table 6
Results of independent chi-square analyses for the perceived thermal discomfort.

Issues within perceived thermal discomfort	Chi-square test
Felt uncomfortably cold for extended periods at home	χ^2 (4, 2585) = 167.104***
Could not bathe or wash hands because water was too cold	χ^2 (4, 2585) = 239.114***
Had to put on more clothes, wrap up in blankets, or use a hot water bottle to stay warm	χ^2 (4, 2584) = 108.385***
Keep an unsafe or unhealthy temperature	χ^2 (4, 2382) = 161.461***

**p* < 0.05, ***p* < 0.01, ****p* < 0.001.

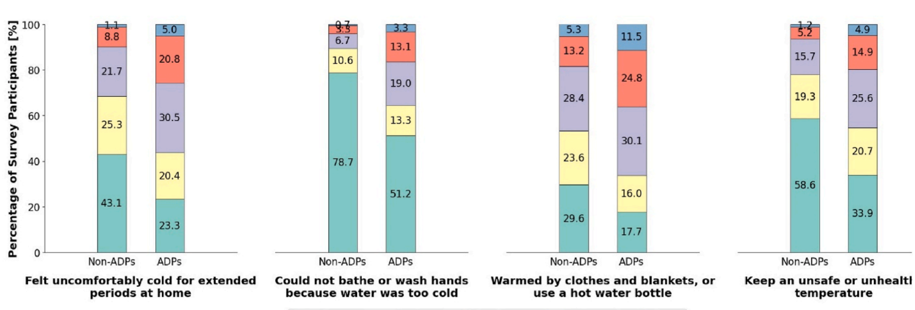

Fig. 6. Comparison of the perceived thermal discomfort issues faced by ADPs and non-ADPs.

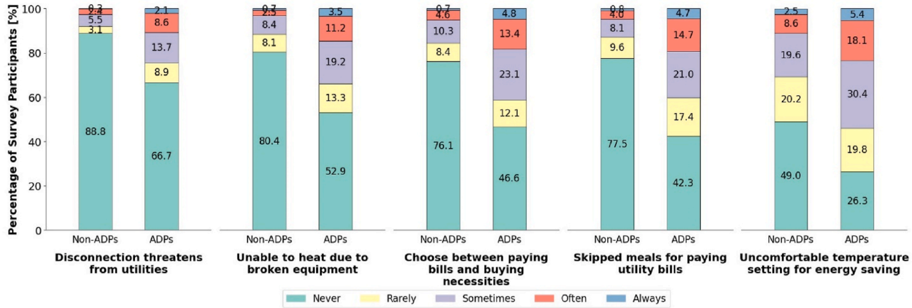

Fig. 7. Comparison of the heating insecurity issues faced by ADPs and non-ADPs.

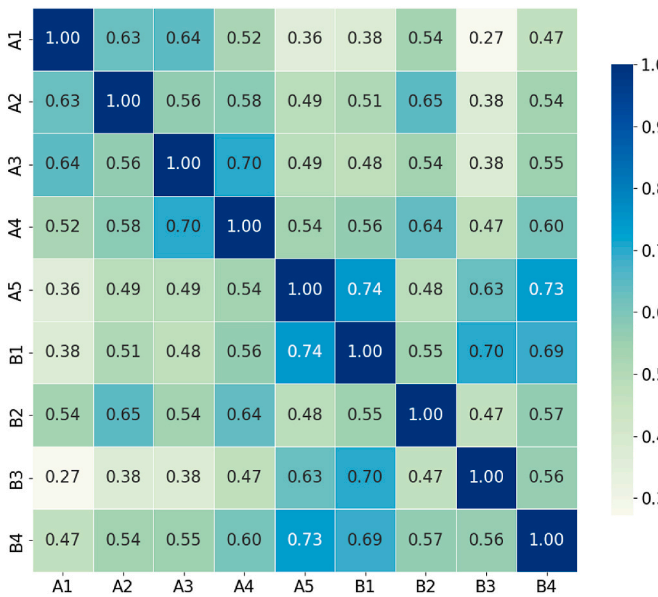

Fig. 8. The correlation matrix heatmap between the variables related to perceived thermal discomfort and heating insecurity.

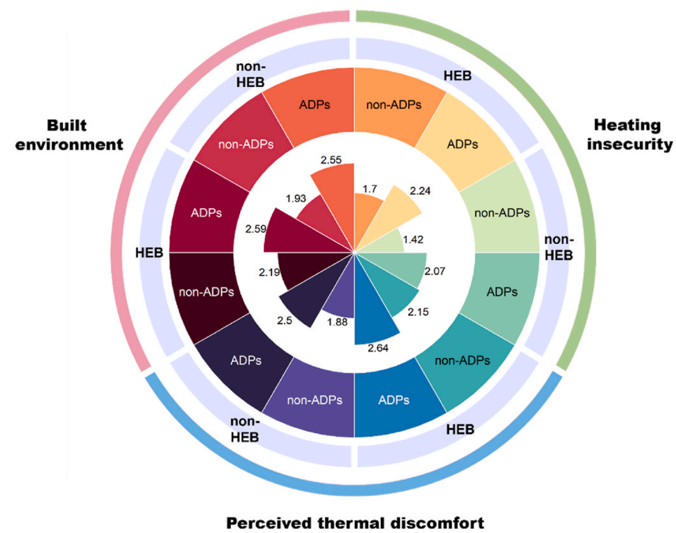

Fig. 9. Interaction effects of HEB and assistance-dependent status on the built environment, heating insecurity, and perceived thermal discomfort.

Table 7
Index of the variables shown in Fig. 8.

Abbreviations	Variables
A1	Disconnection threatens from utilities
A2	Unable to heat due to broken equipment
A3	Choose between paying bills and buying necessities (e.g. food, medicine, childcare)
A4	Skipped meals for paying utility bills
A5	Uncomfortable temperature setting for energy saving
B1	Felt uncomfortably cold for extended periods at home
B2	Could not bathe or wash hands because water was too cold
B3	Had to put on more clothes, wrap up in blankets, or use a hot water bottle to stay warm
B4	Keep an unsafe or unhealthy temperature

5.5.1. *Assistance-dependent status and high-risk energy burden*

The results of the first series of two-way ANOVA models were analyzed to compare the mean scores for the three main issues among ADPs, non-ADPs, and the interaction between these groups based on whether they are categorized as HEB or not (Fig. 9). The two-way ANOVA models demonstrated main effects for assistance-dependence, F (1, 2584) = 159.056, $p < 0.001$, and for the HEB, F (1, 2584) = 12.917, $p < 0.001$, on the built environment. Specifically, ADPs with HEB reported the highest extent of facing poor built environment (M = 2.59, SD = 0.91), followed by ADPs without HEB (M = 2.55, SD = 0.97), non-ADPs with HEB (M = 2.19, SD = 0.76), and non-ADPs without HEB (M = 1.93, SD = 0.76). These results indicated that assistance-dependent status is a more critical factor than EB when predicting the conditions of built environment. Similarly, in the context of heating insecurity, both ADPs, whether with HEB (M = 2.24, SD = 0.97) or without HEB (M = 2.07, SD = 0.98), reported significantly higher scores compared to their non-ADP counterparts, including those with HEB (M = 1.7, SD = 0.76) and those without HEB (M = 1.42, SD = 0.63). It is also statistically significant for assistance-dependence, F (2, 2585) = 251.112, $p < 0.001$, and for the HEB, F (1, 2585) = 35.421, $p < 0.001$, on the heating insecurity. In terms of perceived thermal discomfort, with statistically significant for assistance-dependence, F (2, 2579) = 155.839, $p < 0.001$, and for the HEB, F (1, 2579) = 20.424, $p < 0.001$, ADPs with HEB reported the highest score (M = 2.64, SD = 1.09), slightly exceeding ADPs without HEB (M = 2.5, SD = 0.98). Non-ADPs, both with HEB (M = 2.15, SD = 0.92) and without HEB (M = 1.88, SD = 0.84), reported slightly lower scores in this issue compared to the built environment but higher than in heating insecurity.

Among these three variables, a notable pattern emerged, underscoring stark disparities between ADPs and their counterparts. This striking contrast in reported scores between ADPs and non-ADPs, regardless of their economic burden status, highlights the profound impact of assistance-dependence. It is evident that being assistance-dependent is a key factor in shaping individuals' concerns regarding their housing conditions and perceptions, with ADPs consistently reporting higher levels of insecurity compared to their non-ADP counterparts.

5.5.2. Assistance-dependent status and homeownership

The second series of two-way ANOVA models unveils the interaction between ADPs, non-ADPs, and their respective homeownership status (Fig. 10). The results of the ANOVA models also yielded significant main effects for homeownership status on the built environment, F (2, 2579) = 87.539, $p < 0.001$, perceived thermal discomfort, F (2, 2570) = 47.958, $p < 0.001$, and heating insecurity, F (1, 2576) = 47.209, $p < 0.001$. Fig. 10 illustrates that among the three categories, renters with assistance-dependence exhibited the highest scores, with an average of 2.73 (SD = 0.87) for the built environment, 2.7 (SD = 0.99) for perceived thermal discomfort, and 2.29 (SD = 0.93) for heating insecurity. For homeowners, ADPs still reported encountering higher levels of these issues compared to non-ADPs. Specifically, homeowners with assistance-dependence had a mean score of 2.38 (SD = 1.0) for the built environment, significantly higher than non-ADPs (M = 1.86, SD = 0.72). In terms of perceived thermal discomfort, the average scores for homeowners with and without assistance-dependence were 2.4 (SD = 1.03) and 1.83 (SD = 0.82), respectively. It's worth mentioning that, with respect to heating insecurity, both homeowners with and without assistance-dependence reported comparatively lower scores in this category, suggesting that they encountered fewer challenges associated with budget concerns. These findings reveal that renters consistently faced the highest challenges across categories. Homeowners with assistance-dependence also reported higher levels of issues, notably in the built environment. However, it's noteworthy that heating insecurity appeared to be less of a concern for homeowners, indicating fewer budget-related challenges.

6. Discussion

This study explored the connection between EB and individuals' well-being, with a specific focus on ADPs. The dimensions of the built environment, heating insecurity, and perceived thermal discomfort were encompassed, while also considering the influence of socio-demographic factors. The key findings of the investigation on ADPs' distinct set of challenges in their EBs and living conditions are summarized below.

1. *Relationship between EB and its intricate impact.* In this study, EB demonstrates a significant relationship with the three key variables, namely the built environment, heating insecurity, and perceived thermal discomfort, as indicated by the regression results. This finding highlights that EB not only impacts financial difficulties but also compounds its effects on residents' well-being. Consistent with previous research [1,24], individuals with higher EB are more likely to encounter issues related to energy and internet security, technology, and housing burdens compared to their counterparts. Therefore, it is imperative to promote healthier indoor environments that inherently integrate well-being with energy consumption and overall quality of life, aiming to achieve a multi-dimensional perspective on energy and living justice.

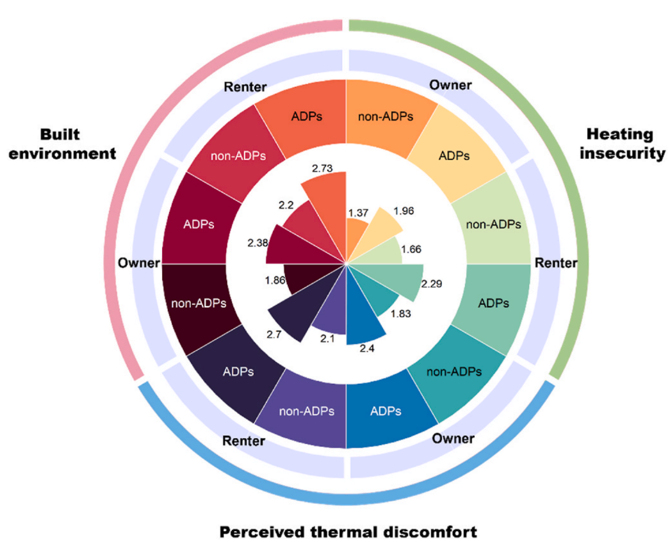

Fig. 10. Interaction effects of homeownership and assistance-dependent status on the built environment, heating insecurity, and perceived thermal discomfort.

2. *Profound challenges for ADPs.* Regarding the comparison between EB and the average scores of the three targeted variables among ADPs and non-ADPs, our findings indicated that ADPs reported higher EB and poorer housing quality than their counterparts. Specifically, ADPs appear to be an especially vulnerable group facing a range of challenges, including subpar living conditions, the difficult choice between paying bills and buying necessities, and inadequate indoor temperature settings to save energy. These results align with previous studies, which have shown that ADPs often reside in less energy-efficient homes with leaky structures and less efficient appliances [25,32]. We further investigated the homeownership status among individuals with ADPs to determine if there is an association between their housing quality, energy efficiency, and homeownership status. The results depicted in Fig. 11 indicate that a higher percentage of individuals with ADPs are renters (54.2%) compared to those without ADPs (39.6%), as confirmed by a chi-square test result of χ^2 (1, N = 2528) = 19.06; p < .001. This result suggested that individuals with ADPs might be living in housing of poorer quality or less energy-efficient, as rental properties can sometimes fall into these categories for various reasons, including less incentive for landlords to invest in energy efficiency compared to homeowners who would directly benefit from such improvements. Moreover, individuals with disabilities, especially those reliant on electric medical devices or those who struggle with thermoregulation difficulties in the absence of heating or cooling resources, exhibit heightened vulnerability to the repercussions of energy insecurity [1]. These findings highlight the profound challenges faced by ADPs in terms of EB and their daily lives, compounded by their existing physical health conditions.

3. *Most severe issues in built environment, perceived thermal discomfort, and heating insecurity.* This study identified that the most prominent concerns for ADPs are all related to inadequate temperatures. Most ADPs reported homes that were too cold, requiring extra clothing, blankets, or hot water bottles for warmth. They often adjusted their home temperatures inadequately to reduce energy consumption. Moreover, according to our correlation analysis, the perception of thermal discomfort is strongly related to the energy-saving behaviors. These results underscore the critical challenges of thermal comfort within the built environment, which is closely linked to energy expenses. During the COVID-19 pandemic, extended home stays exacerbated these issues, especially for ADPs. Previous studies have revealed that approximately 2 out of every 5 people with disabilities could not afford their energy bills, leading them to cut essential household expenses, like medicine or food, putting them at risk of further insecurities [23]. Recognizing the primary concerns of ADPs is instrumental in enhancing our comprehension of their essential needs, their responses to poor housing quality and energy poverty.
4. *Concentrated disadvantages in housing issues.* The effects on the interactions of high-risk EB and homeownership, as well as assistance-dependent status are investigated to reveal the compound challenges. The results reveal that, regardless of whether ADPs have a HEB or not, they faced more challenges than non-ADPs. This underscores the greater predictive significance of assistance-dependent status over EB in issues related to the built environment, heating insecurity, and perceived thermal comfort. Furthermore, it is suggested that renters experienced higher EB compared to homeowners

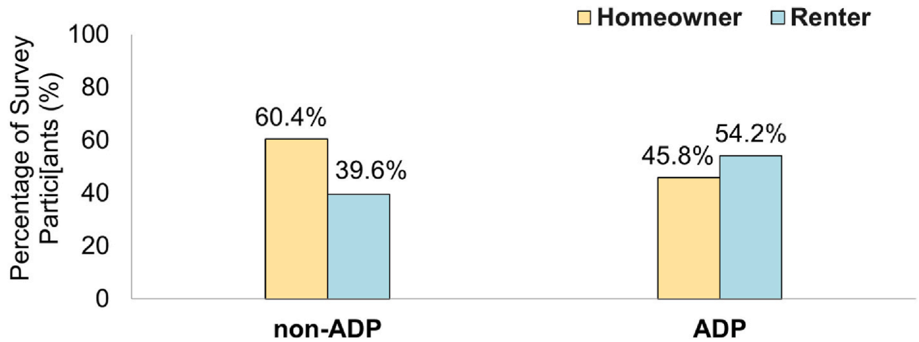

Fig. 11. Proportion of ADPs/non-ADPs across homeownership status.

[1]. By combining assistance-dependent and home ownership status, it becomes apparent that renters among the ADPs face the most adverse conditions among the three key variables. These findings pinpoint ADPs with higher EB and those who rent their homes as the most vulnerable populations concerning housing quality and overall well-being.

Furthermore, the discovery that ADPs are more likely to experience higher EB and live in poorer conditions is of paramount importance. Their trade-off behaviors, such as having to choose between paying energy bills and purchasing food, medicine, or other necessities, and maintaining their homes at unsafe or uncomfortable temperatures, which compromises their quality of life, can put individuals at greater health risks, especially during the COVID-19 pandemic [24,29]. Given that ADPs already grapple with preexisting physical illnesses, it becomes imperative to mitigate these additional health risks and ensure the provision of healthy and safe living conditions for vulnerable demographics, thereby advancing the goal of equity within the built environment.

7. Conclusions

This study provided a comprehensive exploration of the profound influence of Energy Burden (EB) and the built environment on individual well-being, with a specific emphasis on Assistance-Dependent Populations (ADPs). By exploring the intersection of EB, housing conditions, and the distinctive challenges encountered by ADPs, this research expands the existing literature on the well-being of vulnerable populations, shedding light on their specific needs in pursuing a safe and healthy living environment. We recognized the intricate relationships between EB, housing, and individual welfare, emphasizing the multifaceted nature of this relationship. Additionally, the research identified critical issues in the built environment, heating insecurity, and perceived thermal discomfort, encompassing living quality, financial concerns, and occupants' behaviors. These findings underscore the essential need to address heating insecurity proactively to alleviate the energy burden faced by ADPs. Consequently, the study highlights the significance of targeted interventions and policy initiatives aimed at enhancing energy efficiency and overall living conditions for ADPs, ultimately promoting sustainability and social well-being within this community.

The current study has certain limitations that may serve as a source of inspiration for future research endeavors. First, it is important to note that the survey data was gathered during the COVID-19 pandemic, a factor that may have amplified the effects of EB and individuals' perception of discomfort regarding their housing quality. Second, this study solely compared the impacts on ADPs and their counterparts, it is expected to conduct further qualitative methods, such as focus groups, interviews, or other methods, to deeper investigate the built environment issues of other underserved communities without internet access. Third, this study primarily focused on different levels of EB without comprehensively investigating income disparities between ADPs and non-ADPs. However, households with varying income levels may experience vastly different impacts from similar EBs. Thus, future research is expected to incorporate income considerations into energy- and housing-related analyses to develop more effective and inclusive solutions. Additionally, policymakers should recognize that interventions aimed at mitigating energy insecurities need to be tailored to the specific needs of lower-income households, as they may face greater challenges in coping with high energy costs. Fourth, this study mainly collected participants' subjective perceptions of the built environment, thermal discomfort, and heating insecurity issues. Our future study aims to conduct a more comprehensive investigation, exploring the objective physical building characteristics (e.g., construction materials, year built, ventilation systems, and conditioning installations) as well as the behaviors of vulnerable populations. Fifth, while this study made an effort to align our sample with the demographic composition as closely as possible, it is important to acknowledge that our sample may not fully represent the broader population. Despite this limitation, our statistical analysis has revealed significant relationships between the groups within our sample size. These findings suggest that within the scope of our study and the participants we were able to access, meaningful patterns and relationships exist, even though they may not generalize to the entire population due to the limitations of our sample. This tailored approach recognizes that differing behaviors and living patterns within these groups can result in distinct energy consumption patterns and specific needs. Moreover, due to the increasing frequency of extreme hot weather conditions during the summer, people may have to spend more time indoors. This is especially true for vulnerable populations such as those with electricity-dependent medical needs or disabilities, who may need to stay indoors for longer periods than others. As a result, this phenomenon underscores the significance of our study in investigating and clarifying critical built environment issues for these vulnerable populations.

To promote energy justice and equity in living conditions, our aim is to advance research on the built environment that leads to the proposal of appropriate housing design, retrofit strategies, and assistance programs for vulnerable populations and underserved communities. These studies are expected to enhance building performance, with consideration given to construction costs, energy efficiency, and overall well-being.

CRediT authorship contribution statement

Wei-An Chen: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. **Chien-fei Chen:** Writing – review & editing, Supervision, Funding acquisition, Data curation. **Mingzhe Liu:** Writing – original draft, Visualization, Investigation, Formal analysis. **Robin Rickard:** Writing – original draft, Investigation, Data curation.

Declaration of competing interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. This manuscript has not been published and is not under consideration for publication elsewhere. All authors have read the manuscript and have approved this submission. The authors report no conflicts of interest. The authors also confirm that any necessary permissions have been obtained.

Data availability

The data that has been used is confidential.

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