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Of smoke and silence: Energy poverty, digital exclusion, and the rural–urban divide in Eastern Europe

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ABSTRACT

Energy poverty remains a persistent socio-environmental challenge in Eastern Europe, deeply rooted in post-socialist legacies of infrastructural neglect, economic inequality, and inefficient energy systems. Despite growing attention to energy poverty, relatively little is known about its heterogeneous profiles and spatial patterns across Eastern European households. This paper uses Latent Class Analysis (LCA) on microdata from six Eastern European countries — Bulgaria, Romania, Hungary, Poland, Slovakia, and Czechia — to identify heterogeneous household profiles and spatial disparities in energy poverty. This methodology captures the multidimensionality of the concept and has been proven effective in other settings. The results highlight a sharp rural–urban divide in energy poverty profiles: rural households are more likely to rely on polluting solid fuels, live in poorly insulated dwellings, and experience digital exclusion, whereas urban households are predominantly affected by high energy costs and limited control over heating due to inefficient district heating systems in multi-unit buildings. Internet access is associated with lower levels of vulnerability, suggesting that basic digital inclusion may help reduce informational barriers. Our findings also confirm an association between energy deprivation and adverse health outcomes. These results highlight the need for multidimensional energy and environmental policies in Eastern Europe, which address both immediate deprivation and the long-term ecological and health implications. Rather than relying on a single deprivation indicator, this study identifies distinct energy poverty profiles, providing a more nuanced understanding of vulnerability and offering evidence to support more targeted, spatially sensitive and socially inclusive energy policies in Eastern Europe.

1. Introduction

Energy poverty, defined as the inability of households to meet their essential energy needs, represents a multidimensional challenge at the intersection of economic, social, and environmental domains. It affects millions across Europe, threatening not only individual well-being but also regional cohesion and long-term economic growth [1]. In 2023, approximately 47 million Europeans were unable to afford adequate heating for their homes, highlighting the pervasive nature of this issue [1,2]. Energy poverty is particularly salient in the context of climate change and rising energy prices, which further exacerbate inequalities between regions and income groups. Addressing this issue requires evidence-based approaches that extend beyond aggregate indicators to account for geographic disparities even within countries.

Among the regions most affected, Eastern Europe, including Bulgaria, Romania, Hungary, Poland, Slovakia, and Czechia, stands out for its distinct energy poverty profile. These countries face intertwined challenges of high energy costs relative to income, outdated infrastructure, and inefficient heating systems [3,4]. Households in these territories may encounter a variety of challenges related to energy poverty, as they move along the urban-rural continuum. Recent findings from the Joint Research Centre [5] indicate that a greater share of energy expenditure is linked to a more significant urban-rural divide, with rural areas being the most negatively impacted. For instance, in countries such as Bulgaria, Czechia and Slovakia, where total expenditure on energy-related services exceeds 9% of total expenditure, the urban-rural gap is more than 4 percentage points. Indeed, rural households in Central and Eastern Europe (CEE) are disproportionately affected by a combination of lower disposable incomes and a building stock characterized by older, larger, and less compact dwellings with substantial

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thermal inefficiencies, as well as limited access to modern energy systems [6,7]. In contrast, urban households generally exhibit higher income levels and greater access to public resources. They may also reside in more recently constructed buildings, which can be better insulated. Nevertheless, energy poverty remains a concern in urban contexts, driven by high energy costs and inefficient centralized heating systems [8,9]. Beyond housing and income characteristics, rural and urban areas also differ markedly in terms of access to digital infrastructure, internet connectivity, and digital skills. These disparities are particularly pronounced in CEE countries, where digital development has progressed unevenly across territories and social groups [10–13]. Recent data on ICT usage by individuals indicates that the discrepancy in internet access between urban and rural areas exceeds the EU average gap (4 percentage points) in all countries examined in this study, with a maximum difference observed in Bulgaria (14 p.p.).[1] Similar evidence is found relating to the gap in information and data literacy skills [14]. On average, CEE rural households show a gap of 10 percentage points with respect to urban households. Such digital gaps may shape households' ability to access information on energy-saving behaviours, public support schemes, and digitalized services such as price comparison tools and smart meters, thereby interacting with traditional drivers of energy poverty.

While previous studies have highlighted the socio-economic and infrastructural challenges of energy poverty in CEE countries, significant gaps remain. For instance, previous research has primarily focused on national averages or local urban-rural dichotomies, neglecting the nuanced, spatial heterogeneities within these categories [15–17]. Moreover, although recent macro-level studies show that internet access and digital development can reduce energy poverty in CEE countries by improving affordability and reducing utility arrears [10,18], little is known about whether basic digital inclusion, approximated here by household internet access, is associated with existing energy vulnerabilities differently across rural and urban areas [12,19]. Additionally, the intersection between energy poverty and health remains underexplored, particularly regarding how different forms of energy poverty are associated with health risks and chronic illnesses, despite growing recognition of their interconnectedness [17,20]. This omission is particularly problematic in contexts where limited digital access may further restrict households' ability to access health-related information, services, and preventive measures [12].

This paper addresses these gaps by employing Latent Class Analysis (LCA) to provide a more sophisticated, multidimensional understanding of energy poverty in CEE countries. We investigate this issue using a methodological approach that has already been proven to be highly effective in identifying distinct latent household groups based on shared characteristics [21,22]. This approach is applied to a set of countries that are similar in terms of historical and structural features. The main advantage of LCA is that it circumvents arbitrary thresholds and captures the complexity of energy poverty more effectively than traditional income-based measures. Unlike traditional approaches that rely solely on income-based metrics, LCA incorporates a broader array of socio-economic and housing-related factors, providing a more comprehensive view of energy poverty than static, one-dimensional measures. Therefore, we aim to assess the flexibility of this technique in interpreting the drivers of energy poverty, to determine its suitability for application in a variety of institutional contexts.

In addition, in the present study, the methodology is applied separately to rural and urban areas. This enables the identification of geographic, climatic, and structural factors that influence energy vulnerability. By explicitly accounting for differences in digital access between rural and urban households, the analysis allows us to explore whether limited digital inclusion is associated with an additional layer of vulnerability alongside more traditional dimensions of energy poverty [12,19]. This distinction provides valuable insights for designing more context-specific and effective policy interventions [23]. The empirical analysis uses microdata from the EU Statistics on Income and Living Conditions (EU-SILC) database,[2] which ensures comparability and robustness across European countries. The dataset covers diverse socio-economic and demographic profiles, building characteristics, and detailed information on self-reported health outcomes. The richness of the survey thus allows us, after identifying the different categories of exposure to energy poverty, to compare health outcomes across the different energy poverty profiles and to discuss how integrated energy, social, and digital policies could better address these vulnerabilities [11,18].

The remainder of this paper is structured as follows. In Section 2, the relevant characteristics of the CEE countries that are associated with energy poverty are presented. Section 3 describes the methodological approach, the EU-SILC data and the specific variables used in the LCA analysis. Section 4 presents and interprets the results, emphasizing significant spatial and demographic differences. A discussion of the current energy policies adopted by the countries and policy recommendations are provided in Section 5. Finally, Section 6 concludes.

2. A sharp rural-urban divide in eastern European countries: Perspectives and research contributions

2.1. Historical legacies, socio-economic disparities and information barriers

CEE countries share some elements of homogeneity due to their common history as centrally planned economies, yet they also exhibit strong differences both between and within nations. In the energy sector, the legacy of past infrastructure design remains evident, presenting significant challenges for these countries as they navigate carbon transition strategies. The shift to renewable energy sources and the introduction of new technologies are likely to impose heterogeneous burdens on households, exacerbating existing inequalities and deprivation rates, as highlighted by Bouzarovski [24]. His concept of 'energy geographies' emphasizes the emergence of deep spatial disparities due to variations in regulatory schemes, institutional cultures, and political interests that have evolved differently at national and local levels.

The average disposable income across the six countries under consideration—Bulgaria, Romania, Hungary, Poland, Slovakia, and Czechia—is below the EU average. For example, in 2022, the EU-27 average disposable income per inhabitant was over EUR 18,000 (in PPS), compared to values below EUR 13,000 for Hungary, Romania, and Slovakia, with Romania recording the lowest in the EU. Poland and Czechia fared better, with values around EUR 15,000. Nevertheless, all six countries have seen significant income growth since 2010, with Romania more than doubling its median real disposable income. While these increases are encouraging, they have not substantially improved income distribution, as evidenced by Romania's high Gini index (37.2 in 2023), the highest in the EU.[3] Rising energy expenditure highlights the growing financial burden on households in times of high energy prices. According to Eurostat data on household budget expenditure, Bulgaria and Romania experienced an 80% increase in mean residential energy expenditure (in PPS) between 2005 and 2020, while Poland and Czechia

[1] See the EU survey on the use of ICT in households and by individuals https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Digital_economy_and_society

[2] The data used in this study are confidential and cannot be shared publicly. Nevertheless, we are open to sharing the Stata do-files and, if needed, to discussing potential options for data access with interested parties on a case-by-case basis.

[3] Eurostat, Income and living conditions, https://ec.europa.eu/eurostat/databrowser/view/ilc_di12_custom_12499743/default/table?lang=en

faced a 40% rise.

Economic disparities further contribute to varying experiences of energy poverty between rural and urban households. Rural areas generally report lower average incomes, higher energy costs relative to income, and limited financial resources to invest in energy efficiency improvements [25]. Dokupilová et al. [6] confirm these findings, noting that rural households in CEE countries frequently depend on polluting solid fuels and reside in poorly insulated dwellings, amplifying vulnerability to energy poverty. In contrast, urban residents may face higher absolute energy costs but benefit from better access to social safety nets and subsidies designed to alleviate energy poverty [23]. Characteristics of the residential building stock further contribute to this divide. The socialist era left behind two legacies: massive, prefabricated multi-apartment buildings in urban centres, and a neglected, self-constructed rural housing stock. Following the 1989 transition, the mass privatization of these assets transformed 'energy-poor tenants' into 'asset-rich but income-poor homeowners', creating a significant barrier to collective energy retrofitting. Table A in appendix summarizes the main characteristics of the building stock in the selected countries. In terms of building types, single-family dwellings dominate (in the EU the proportion is 68% with a higher share of multi-family houses, 24%) and more than 40% of the housing stock was built before 1970 (the EU average is 51% for the same period). Notwithstanding some similarities, scholars have identified a north-south divide in terms of tenure structure which can be dated back in pre-state socialist times with a path dependence in more recent decades. In Poland, Czechia and Slovakia territories urban and industrial centres developed before WWI with a government support for collectively owned housing, while in the southern countries such as Bulgaria, Romania and Hungary home ownership was clearly supported [26]. These differences persisted also during the Soviet times and after the restoration of property rights. Moreover, in general there is also a different distribution of building types between the rural and urban locations within each country, with detached houses prevailing in rural areas. Comparative analysis reveals diverging trajectories in building efficiency. In particular, Czechia and Slovakia have implemented renovation programs financed with public funds, which have facilitated the thermal renovation of their urban prefabricated stock. Conversely, in Romania and Bulgaria, the fragmentation of district heating systems and the lack of integrated renovation policies have led to 'energy-inefficient islands', where urban households often resort to individual, inefficient heating solutions. As regards rural dwellings, Hormigos et al. [5] find that around 30% of households have undergone at least one renovation improving energy efficiency in the period 2017–2022.[4]

Beyond income and housing conditions, rural-urban disparities in CEE countries also reflect unequal access to information, public services, and increasingly digitalized policy instruments. Consumer engagement is not fully exploited because of a lack of digital literacy and understanding of how energy systems work [27]. Recent studies emphasize that limited digital access can reinforce existing socio-economic inequalities, particularly in rural areas, by constraining households' ability to obtain information, navigate administrative procedures, and adopt energy-efficient practices [11,18,19]. The level of internet access, digital skills, and use of e-government in CEE countries is summarized in Table 1. Although the infrastructure gap (i.e. internet access) between urban and rural areas is closing across the CEE region, the skills gap (i.e. digital literacy) and low usage of e-government services for accessing information and applying for support remain critical barriers, particularly in rural areas of Romania and Bulgaria. These prevent the transition to dynamic energy markets, leaving vulnerable households unable to respond to price signals and benefit from market liberalisation.

2.2. Environment, climate and energy infrastructure

Despite economic growth, several characteristics contribute to increasing the fragility in the region and create further disparities. Environmental pollution, particularly exposure to fine particulate matter (PM2.5), remains a critical concern. This has direct implications for public health, as regions with higher pollution levels experience increased rates of premature deaths due to respiratory and cardiovascular conditions. For instance, Romania exhibits alarming figures, with some regions recording more than 200 premature deaths per 100,000 inhabitants, while Poland shows significant regional variability (e.g., over 160 in Miasto Kraków compared to under 50 in Koszaliński). Although there has been a 40% reduction in estimated premature deaths from 2005 to 2020 across most countries, this improvement remains insufficient to address the underlying vulnerabilities.

The climate also provides an element of homogeneity across the CEE region: the six countries show an overall average between 2500 and 3700 heating-degree days, although significant climatic heterogeneities exist within each country. For instance, Bulgaria's Sofia averages -0.2 °C in January, while mountainous areas can drop to -4.4 °C. Similar patterns are observed in Slovakia and Czechia, where rural regions experience harsher winters than centres. These disparities exacerbate energy poverty in rural areas, where heating needs are higher, and households are often unable to afford or access efficient energy solutions. The inadequate indoor heating can lead to serious health issues, including higher incidences of respiratory illnesses and chronic cardiovascular diseases, particularly among vulnerable populations such as the elderly and children [7,28,30]. Self-reported health data show an association between poor housing conditions and inadequate heating to worsened health outcomes, further intensifying the social burden of energy poverty [15,28]. Additionally, these health difficulties are also associated with higher healthcare costs and reduced productivity, creating a broader economic impact that extends beyond the affected households. These effects may be exacerbated by limited access to digital health services and information channels in rural areas. This delays prevention, diagnosis, and support, thereby reinforcing the cumulative health and economic burden associated with energy poverty. Moreover, rural areas located in CEE countries record relatively low doctor-to-population ratios, particularly in Romania and Hungary [14].

As regards the heating equipment, the prevalence of district heating (DH) systems is another defining feature of Eastern Europe's energy landscape, stemming from the planned economy era. DH systems are more widespread in these countries than in Western Europe, with shares in heating energy consumption ranging from 10% in Hungary to 25% in Poland. However, the efficiency and regulatory frameworks governing these systems vary widely. For example, Poland's DH infrastructure serves both small towns and larger cities, yet many systems are inefficient and in dire need of upgrading [1]. Similarly, Bulgaria's DH networks cover densely populated urban areas but face challenges in efficiency and regulation. In Romania, after the fall of communism, many households disconnected from the DH systems because these systems did not provide adequate thermal comfort and instead relied on individual gas boilers.

Several characteristics of the energy markets limit consumer engagement and, consequently, the fight against energy poverty. A high level of concentration in the electricity and gas markets is typical of CEE countries. With the exception of Czechia, switching rates are historically very low because contracts are either regulated or flat-rate, or consumers are unable to compare different offers from providers [31]. The natural gas network is well developed in Poland, Hungary and Czechia. While the latter's market is liberalised and switching rates are increasing, the former's markets are highly concentrated and prices are regulated. In Bulgaria and Romania, the natural gas network is only partially developed. Rural households rely on biomass and coal from informal markets, where prices are volatile and difficult to compare [5,32]. Moreover, solid fuels are less efficient and contribute to higher

[4] This finding is confirmed for all households by the results of Eurobarometer on Europeans' attitudes towards EU energy policy (Special Eurobarometer 255 April–May 2024).

Table 1
- Internet access, digital skills and e-government use (%) - 2025.

	Level of internet access		Digital Skills (*)		Use of e-government to request benefits or entitlements		Use of e-government to obtain information	
	Urban	Rural	Urban	Rural	Urban	Rural	Urban	Rural
Bulgaria	97.0	86.6	81.0	63.1	2.2	1.5	20.5	10.2
Czechia	97.3	94.7	94.6	91.2	7.8	3.0	62.3	55.0
Hungary	95.6	90.3	92.0	81.8	18.0	10.8	74.6	54.9
Poland	96.9	95.3	88.8	79.0	15.3	14.7	43.8	29.1
Romania	97.7	93.5	87.3	72.4	2.9	0.8	18.4	8.2
Slovakia	95.1	91.1	90.3	81.1	8.6	6.3	52.5	42.2

Source: Eurostat - ICT usage in households and by individuals.
(*) These skills relate to finding information about goods or services, seeking health-related information, reading online news sites, newspapers or news magazines, activities related to factchecking online information and its sources.

pollution levels and health risks [15,33].

Finally, Ambrose et al. [34] point out that memories of the Soviet era are still strong in these countries, and after decades of rationing and external control of energy use, it is important for households to gain control over their thermal comfort. This effect could explain the shift away from poorly maintained district heating systems towards individual home heating in an attempt to regain a sense of agency. Similarly, traditional heating practices such as wood heating are not only motivated by a lack of alternative infrastructure or economic reasons. Traditional and cultural reasons should not be dismissed, nor should the ability to exercise a personal choice over home heating.

3. Methodological approach

3.1. Latent class analysis

The use of LCA is a valuable tool for identifying distinct profiles of energy-poor households based on socio-economic characteristics and housing conditions. We consider this approach which has proven effective in a variety of contexts, including tropical regions and Mediterranean Europe [21,22,35]. LCA has also been successfully applied in environmental behavior studies to uncover heterogeneous consumer profiles based on psychological and socio-demographic factors, reinforcing its appropriateness for multidimensional energy poverty analysis [36].

LCA's methodological strengths make it particularly well-suited for identifying fuel-poor households. Unlike traditional methods, it allows researchers to uncover subgroups within a population that share similar characteristics, without relying on predefined thresholds for fuel poverty. This is particularly important in contexts where energy poverty manifests in varied and overlapping ways across different socio-economic and geographic groups. LCA captures the multidimensional nature of energy poverty by incorporating various observable indicators to classify households into distinct latent classes. Key advantages of LCA are presented in Collins and Lanza [37].

More formally, LCA is used to identify unobserved subgroups of households sharing similar response patterns across a set of observed indicators. The approach assumes that the joint distribution of these indicators can be explained by a finite number of latent classes, within which responses are conditionally independent. Each latent class therefore represents a distinct configuration of socio-economic, housing, energy, and digital access characteristics.

In our application, households are classified into latent classes based on a set of indicators capturing residential energy efficiency and affordability. In addition, class membership probabilities are modelled as a function of observed covariates using a multinomial logit specification. This allows us not only to identify distinct energy poverty profiles, but also to examine how household characteristics influence the likelihood of belonging to each latent class.

Model estimation is conducted using maximum likelihood methods. The optimal number of latent classes is determined by combining standard information criteria, including the Bayesian Information Criterion (BIC) and the Akaike Information Criterion (AIC), with considerations of interpretability and parsimony. The model with the lowest BIC and AIC values is selected as the best-fitting model [38,39]. This approach ensures that the selected model provides a meaningful and policy-relevant typology of energy poverty profiles. The model is summarized in Fig. 1.[5]

3.2. Data

This study aims to identify fuel-poor households in CEE countries, with a focus on the differences between rural and urban areas compared to the overall sample, which includes Bulgaria, Romania, Hungary, Poland, Slovakia, and Czechia. The empirical analysis is based on microdata of the EU Survey of Income and Living Conditions (EU-SILC) [41]. We rely on the 2019 EU-SILC wave to avoid the structural disruptions introduced by the COVID-19 pandemic and the subsequent energy crisis. This choice allows us to identify the structural drivers of energy poverty beyond short-term fluctuations and crisis-specific shocks.

The EU Survey of Income and Living Conditions is used in many studies to investigate energy poverty in European countries. As well-known in the related literature, this survey has some pros and cons for our research question [42]. In particular, EU-SILC allows comparative analysis across several countries because the questionnaire and the definitions of variables are largely shared at the EU level but, on the other hand, it does not provide the flexibility needed to capture territorial specificities. As this survey is not specifically designed to evaluate energy poverty, only consensual indicators are available while expenditure-based measures cannot be computed. On the other hand, the dataset contains information on the location and type of housing, health status, family composition and other socio-demographic characteristics that may help to identify energy vulnerable households. As already discussed in Section 2, CEE countries share some common infrastructural problems, building inefficiencies, high levels of poverty and specific hidden aspects of energy poverty linked with abnormally low energy expenditures [43]. Moreover, they differ from other EU countries in terms of the energy mix, energy dependence, and household attitudes. However, different forms of energy poverty characterize these countries [8]. For example, low income and affordability problems are particularly relevant in Poland while the obsolete energy infrastructure and inefficient building stocks are important energy poverty drivers in Romania. As described in Section 2, there is also a divide between rural and non-rural areas, which mimics a difference in dwelling type and level of economic development. In this paper, to define a household according to its location we use the Degree of Urbanization provided by EU-SILC. This variable classifies all local administrative units into three

[5] A detailed formal presentation of the LCA model and estimation procedure is provided in the Appendix. For general methodological references, see Collins and Lanza [37] and Nylund-Gibson and Choi [40].

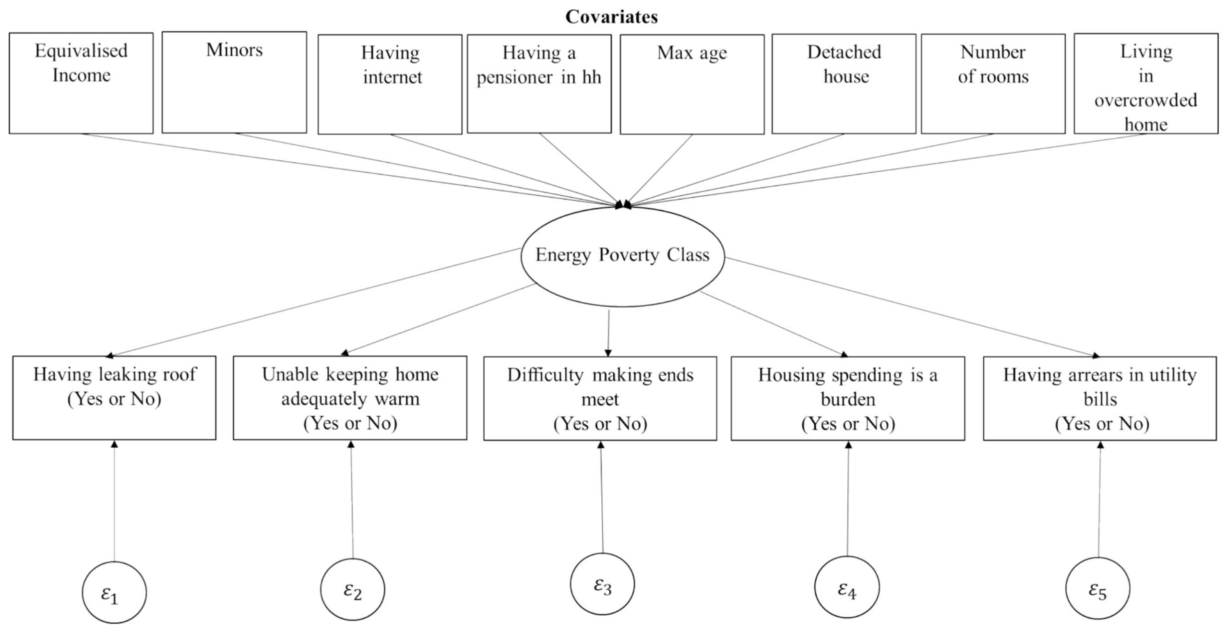

Fig. 1. Path diagram of the LCA model for energy poverty in eastern Europe with covariates.
Note: Energy classes correspond to the latent classes identified through LCA. These classes represent unobserved household profiles of energy poverty and are not directly observable in the data. Class membership is probabilistic and inferred from a set of manifest indicators capturing observed energy deprivation and housing conditions (e.g. inability to keep the dwelling adequately warm, presence of damp or leaking roof). In contrast, covariates (such as income, internet access, household composition, or demographic characteristics) do not define the classes themselves but are included in the model as explanatory variables of the probability of belonging to each latent energy class. They therefore influence class membership without being part of the measurement model.

types of areas: thinly, intermediately, and densely populated.[6] We create a dichotomous rural/non-rural variable where thinly populated areas are identified as rural and the others as non-rural.

For our model, we select self-assessed variables in the EU-SILC database commonly used in micro-level cross-country comparisons to study energy poverty [7,44] and recommended by the European Commission [1]. A set of five indicators is employed as manifest variables to apply the latent class approach. These are: 1) the presence of leaking roofs, damp walls or rotten window frames, 2) the inability to adequately heat one's dwelling in winter, 3) the experience of difficulty in meeting basic living costs,[7] 4) the perception that housing spending represents a financial burden[8] and 5) the occurrence of arrears in utility bills. Energy efficiency is indirectly assessed by indicators 1 and 2, while the remaining variables capture the affordability aspect of energy poverty. These specific indicators are considered essential measures to understand and address energy poverty.

To enhance the robustness of the LCA model, several control variables are included to account for household characteristics that influence energy consumption patterns and energy poverty status. Incorporating these control variables allows the model to capture the multidimensional nature of energy poverty more effectively by isolating the distinct financial, demographic, and structural factors that contribute to household vulnerability. These variables can be broadly classified into two groups: one representing the demographic characteristics of households and the other reflecting financial and material deprivation. In the first group we included the presence of children, household retirement status, and the age of the oldest household member. The presence of children and elderly increases energy required for heating and household activities, thereby heightening vulnerability [45]. Meanwhile, the presence of retired households has two counteracting effects: they alleviate income poverty due to their fixed income, but they also contribute to higher energy demands because they spend more time at home [46].

The second group of covariates includes disposable income (equivalized using the square root of household size as recommended by the OECD), the type of dwelling, the number of rooms, overcrowding and internet access. Disposable income, a critical determinant, allows households to afford energy needs and maintain adequate living conditions [47]. Housing characteristics also play a crucial role: detached homes demand higher energy consumption due to greater exposed surface areas [48], while overcrowded dwellings often suffer from inadequate heating or cooling, compounding fuel poverty risks [49]. Given data constraints in EU-SILC, internet access is used as a parsimonious and widely adopted proxy for basic digital inclusion. Importantly, this indicator captures all forms of connectivity, including mobile access, to assess the possibility of accessing information-intensive digital services. These services are particularly relevant for administrative procedures and energy-related support schemes. Although internet access is correlated with household income and education, it also serves as a proxy for basic digital inclusion and may reflect informational barriers affecting households' ability to access information, apply for subsidies, or engage in energy-saving practices [50,51]. Recently, Yue et al. [13] conducted a panel data analysis showing that the digital divide hampers the reduction of energy poverty, with particularly strong effects in rural areas and low-income countries. Income inequality emerges as a key mediating factor, reinforcing the view that internet access is not merely

[6] Densely populated area: contiguous grid cells of 1km^2 with a density of at least 1500 inhabitants per km^2 and a minimum population of 50,000; intermediate area: clusters of contiguous grid cells of 1km^2 with a density of at least 300 inhabitants per km^2 and a minimum population of 5000; thinly-populated area: grid cells with a density of less than 300 inhabitants per km^2.

[7] We have created a dummy variable set to 1 for all households that have experienced any degree of difficulty in making ends meet. We have adopted a broad definition by grouping three response categories (great difficulty, difficulty, and some difficulty) to capture a wider spectrum of financial strain relevant for identifying energy vulnerability, rather than restricting the measure to the most severe cases.

[8] The variable is set to 1 for all households for which housing costs are either a heavy or slight burden. We have combined households reporting both a "heavy" and a "somewhat" burden, with the aim of capturing intermediate forms of vulnerability that are central to the latent class approach.

a proxy for socio-economic status but rather can be associated with the exposure to energy poverty. We therefore interpret this variable as a proxy for basic digital inclusion that may also reflect informational barriers associated with household vulnerability, particularly in rural areas.

3.3. Housing and socio-demographic characteristics: Descriptive patterns and potential drivers of energy poverty

Descriptive patterns in housing conditions and socio-demographic characteristics across countries and territorial contexts found in our dataset are presented in this section. These patterns are not interpreted as causal effects, but rather as potential structural factors of the cross-country and rural–urban differences in energy poverty profiles later identified through the latent class analysis.

The proportion of households residing in sparsely populated regions is observed to range from 36% in Bulgaria and Czechia to 42% in larger countries such as Poland and Romania, as evidenced in our data. On average, there is a greater prevalence of buildings exhibiting poor quality in rural areas, with Hungary displaying the highest value of the indicator.

Overall, the characteristics of the building stocks previously described affect the energy efficiency of the dwellings and the energy demand of households. This conclusion is also supported by the high share of households unable to keep the house adequately warm, which is generally higher than the EU average in 2019 (6.9% according to Eurostat), especially in rural areas, with values above 30% in Bulgaria. A problem of affordability of energy expenditure is captured by the remaining three indicators presented in Table 2. In particular, a large majority of households have difficulties in making ends meet, especially in the southern Eastern Member States, while the problem is less severe, although well above the EU average (6.5%), in Poland and Czechia. Housing expenditure is indeed a somewhat greater cost burden for households living in rural areas, who also have to cope with arrears on their utility bills. However, in Poland, Slovakia and Czechia, only a small proportion of households are unable to pay their bills, although practices of self-restriction in energy consumption and the use of traditional cheap solid fuels help to explain this finding and expose families to the phenomenon of hidden energy poverty [15]. This information is measured using household expenditure data available in a comparative format for EU Member States in selected years (EPAH website). In 2015, the latest year of available data, 14.6% of EU households report energy expenditure below half of the national median: in the CEE countries, Poland and Romania show results above this value, at 19.5 and 16.8% respectively. While in theory this finding may indicate high energy efficiency standards, it could also be a sign of households that are dangerously under-consuming energy.

Regarding the variables selected for the multinomial logit in the latent class approach, Table 3 shows the descriptive statistics for the whole sample.[9] As expected, equivalised income is higher in the northern countries, while demographic characteristics are more similar: the proportion of families with children ranges from 23% in Bulgaria and Hungary to 30% in Poland and Slovakia, and the maximum age of the family members is between 60 and 64 years. The average share of detached houses is higher in Hungary and Romania, while the number of rooms is around 3–3.5. The problem of living in overcrowded dwellings affects 10% of families in Czechia and Hungary, whereas this figure more than doubles in the other countries. Finally, internet access was particularly low in Bulgaria and Romania, although the situation has improved in recent years, as shown in the previous section. Nevertheless, there is evidence of a persistent rural–urban gap.

Taken together, these cross-country differences in housing quality, affordability constraints, and digital access point to distinct

Table 2
Manifest variables - descriptive statistics.

	BULGARIA						CZECHIA						HUNGARY					
	rural ($N = 2650$)		non-rural ($N = 4690$)		whole ($N = 7340$)		rural ($N = 3146$)		non-rural ($N = 5560$)		whole ($N = 8706$)		rural ($N = 2581$)		non-rural ($N = 4316$)		whole ($N = 6897$)	
Variable	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
Having leaking roof	0.160	0.367	0.089	0.285	0.115	0.319	0.079	0.269	0.066	0.248	0.070	0.256	0.273	0.445	0.209	0.406	0.233	0.423
Unable keeping home adequately warm	0.362	0.481	0.329	0.470	0.341	0.474	0.030	0.170	0.033	0.178	0.032	0.176	0.082	0.274	0.060	0.237	0.068	0.252
Difficulty making ends meet	0.907	0.290	0.837	0.370	0.862	0.345	0.443	0.497	0.420	0.494	0.428	0.495	0.798	0.402	0.721	0.449	0.749	0.433
Housing spending is a burden	0.928	0.258	0.911	0.285	0.917	0.276	0.897	0.304	0.857	0.350	0.872	0.335	0.881	0.324	0.802	0.399	0.831	0.374
Having arrears in utility bills	0.253	0.435	0.252	0.434	0.252	0.434	0.013	0.112	0.017	0.130	0.016	0.124	0.131	0.338	0.084	0.278	0.102	0.302

	POLAND						ROMANIA						SLOVAKIA					
	rural ($N = 8331$)		non-rural ($N = 11{,}485$)		whole ($N = 19{,}816$)		rural ($N = 3073$)		non-rural ($N = 4170$)		whole ($N = 7243$)		rural ($N = 2066$)		non-rural ($N = 3520$)		whole ($N = 5586$)	
Variable	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
Having leaking roof	0.130	0.337	0.088	0.283	0.106	0.307	0.151	0.358	0.054	0.226	0.095	0.294	0.095	0.294	0.033	0.179	0.056	0.230
Unable keeping home adequately warm	0.062	0.241	0.062	0.241	0.062	0.241	0.113	0.316	0.088	0.283	0.098	0.298	0.104	0.305	0.077	0.267	0.087	0.282
Difficulty making ends meet	0.598	0.490	0.515	0.500	0.550	0.498	0.800	0.400	0.753	0.431	0.773	0.419	0.726	0.446	0.676	0.468	0.695	0.461
Housing spending is a burden	0.953	0.213	0.938	0.241	0.944	0.230	0.934	0.248	0.941	0.235	0.938	0.241	0.887	0.316	0.878	0.328	0.881	0.323
Having arrears in utility bills	0.063	0.243	0.055	0.228	0.058	0.234	0.126	0.332	0.160	0.367	0.146	0.354	0.085	0.280	0.072	0.259	0.077	0.267

Source: EU SILC 2019, authors' calculations.

[9] Details on rural/urban data are available in appendix (Table B).

Table 3
Descriptive statistics for covariates, 2019.

Variable	Obs	Mean	Std. Dev.	Min	Max
BULGARIA					
Equivalized income	7,340	5,277.042	6,335.479	20.73	242,936.3
Minors	7,340	0.233	0.423	0	1
Having a pensioner in hh	7,340	0.514	0.5	0	1
Max age	7,340	64.491	13.373	18	81
Detached house	7,340	0.457	0.498	0	1
Number of rooms	7,340	3.032	1.161	1	6
Living in overcrowded home	7,340	0.236	0.424	0	1
Having internet	7,340	0.502	0.5	0	1
CZECHIA					
Equivalized income	8,706	10,833.757	5,950.845	89.87	185,018.8
Minors	8,706	0.27	0.444	0	1
Having a pensioner in hh	8,706	0.422	0.494	0	1
Max age	8,706	60.002	15.72	21	81
Detached house	8,706	0.389	0.488	0	1
Number of rooms	8,706	3.524	1.249	1	6
Living in overcrowded home	8,706	0.104	0.306	0	1
Having internet	8,706	0.756	0.43	0	1
HUNGARY					
Equivalized income	6,897	6,403.169	5,139.581	0	190,138.53
Minors	6,897	0.225	0.418	0	1
Having a pensioner in hh	6,897	0.49	0.5	0	1
Max age	6,897	62.631	13.892	20	81
Detached house	6,897	0.676	0.468	0	1
Number of rooms	6,897	3.564	1.071	1	6
Living in overcrowded home	6,897	0.113	0.316	0	1
Having internet	6,897	0.64	0.48	0	1
POLAND					
Equivalized income	19,816	8,047.835	5,113.087	0	105,035.6
Minors	19,816	0.298	0.457	0	1
Having a pensioner in hh	19,816	0.392	0.488	0	1
Max age	19,816	60.039	15.599	17	81
Detached house	19,816	0.431	0.495	0	1
Number of rooms	19,816	3.054	1.333	1	6
Living in overcrowded home	19,816	0.276	0.447	0	1
Having internet	19,816	0.741	0.438	0	1
ROMANIA					
Equivalized income	7,243	4,669.367	3,053.909	0	42,154.441
Minors	7,243	0.219	0.414	0	1
Having a pensioner in hh	7,243	0.463	0.499	0	1
Max age	7,243	62.387	14.276	19	81
Detached house	7,243	0.611	0.487	0	1
Number of rooms	7,243	2.829	1.023	1	6
Living in overcrowded home	7,243	0.233	0.423	0	1
Having internet	7,243	0.453	0.498	0	1
SLOVAKIA					
Equivalized income	5,586	9,173.567	4,038.921	9.63	38,524.359
Minors	5,586	0.301	0.459	0	1
Having a pensioner in hh	5,586	0.423	0.494	0	1
Max age	5,586	60.784	14.113	23	81
Detached house	5,586	0.419	0.493	0	1
Number of rooms	5,583	3.252	1.236	1	6
Living in overcrowded home	5,583	0.243	0.429	0	1
Having internet	5,586	0.724	0.447	0	1

configurations of vulnerability. The latent class analysis builds on these patterns to jointly examine how such characteristics combine at the household level and shape heterogeneous energy poverty profiles across countries and territorial contexts.

4. Results

4.1. Identification of households affected by energy poverty, vulnerable households and sufficient households

Based on the existing literature, we adopted a multiple-class typology of exposure to energy poverty. Indeed, previous research on this topic has shown that a binary classification of energy poverty tends to overlook the existence of varying degrees of risk and exposure. In particular, it fails to adequately capture the condition of a large segment of the population experiencing vulnerability—households that, while not currently affected by energy poverty, are at risk of falling into energy poverty following even minor shocks. This approach is consistent with the concept of a continuum or scale of energy poverty, as proposed by Charlier and Legendre [53].

The selected manifest variables enable the model to effectively classify households into three distinct energy poverty categories, according to the standard information criteria mentioned in the methodology section. Fig. 2 and Table C in the appendix—each presenting panels for the six countries studied—display the marginal effects of the manifest variables across the three latent classes. The results indicate that differences between classes are strongly dependent on the nature of the variable. For those directly linked to living standards—such as housing and subsistence costs—the effects tend to be consistent across countries and urbanization levels, particularly for the vulnerable and energy-poor households. The burden of housing costs is significant for energy-poor and vulnerable households in all countries and locations. By contrast, the energy-sufficient class shows lower shares, particularly in Hungary and Slovakia, as well as in urban areas of Bulgaria. As previously discussed, residential energy represents a large proportion of the household budget in the CEE countries. Difficulties in making ends meet, a common trait among the vulnerable and energy-poor, are markedly less prevalent among energy-sufficient households, with the notable exception of rural Bulgarian households—where 54% report such difficulties, compared to just 12% in urban areas. Finally, arrears on utility bills are the last considered indicator of energy expenditure affordability. This manifest variable distinguishes energy-poor households from the other two classes in both rural and urban areas. Despite regulated prices for electricity and natural gas in most CEE countries, affordability issues arise and contribute to explaining this phenomenon although arrears are negligible for energy-poor households in Czechia, where markets are liberalised and consumers can switch energy

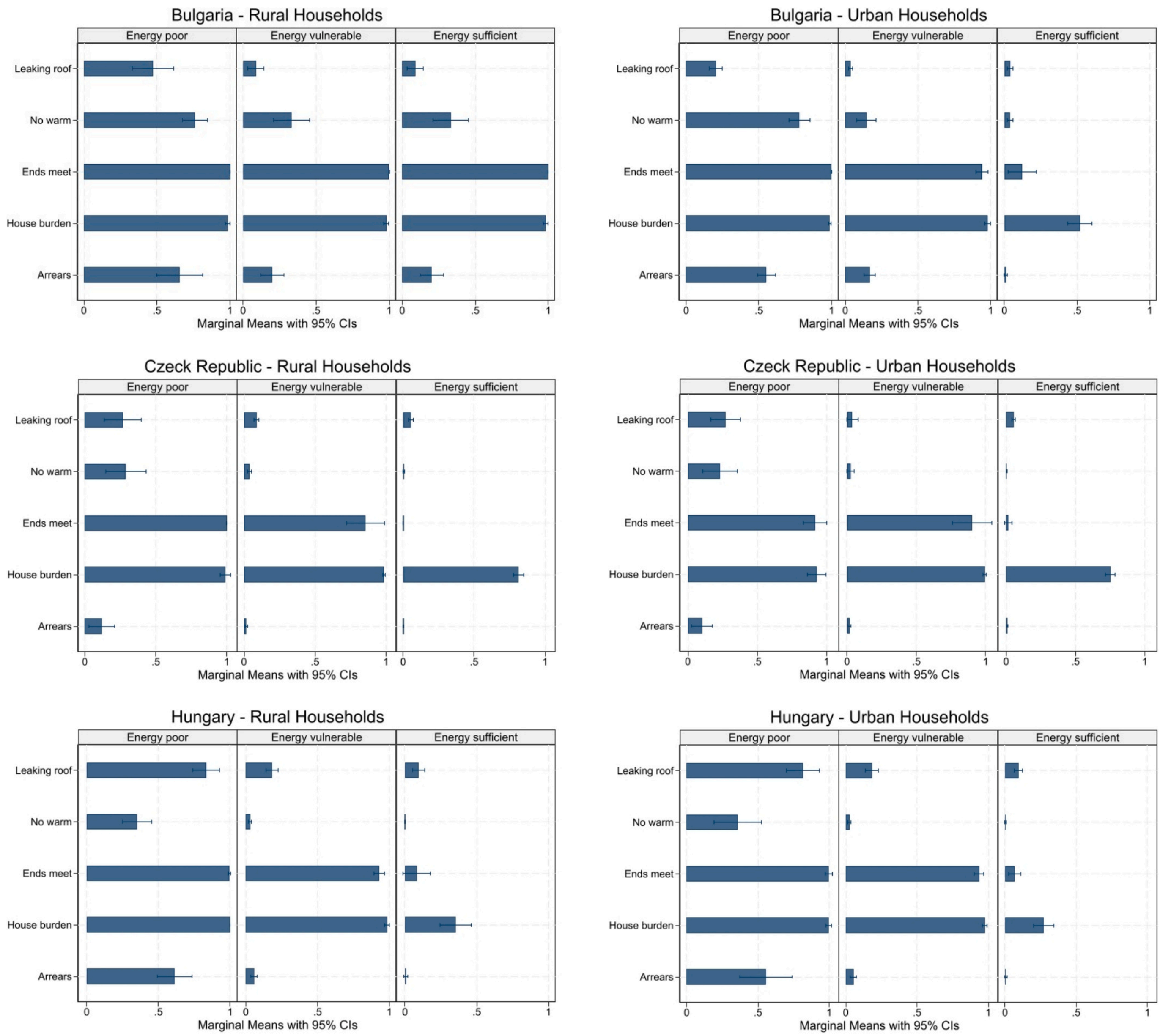

Fig. 2. - Manifest variables: marginal effects across countries and locations.

providers.[10]

The second group of indicators helps to capture the energy efficiency of households and is the most effective in distinguishing energy-poor households from the other two classes, as well as identifying the rural-urban divide. A significant share of energy-poor households in rural areas report roof leaks and/or dampness in their homes, with the difference between rural and urban areas ranging from 10 to 20 percentage points in Romania, Bulgaria, and Slovakia. Most of the rural building stock consists of detached houses, which are privately owned and difficult to maintain in good condition. In multi-family buildings, several barriers exist in terms of collective decision-making processes, low disposable income of homeowners and lack of standards for existing heating equipment and of information on public support schemes [54]. Our results show that the poor quality of buildings is a highly distinguishing characteristic of energy-poor families in Hungary, regardless of where they live. Notwithstanding that a very large proportion of households are owner-occupiers (about 90%), poor housing conditions are persistent as in 2024 Hungary stands out with the lowest renewal rate compared with other EU member states due to a lack of resources, information, motivation and skills [55].

The inability to keep the home adequately warm is a consistent marker of energy poverty across all the countries studied. However, its significance is influenced by differences in heating infrastructure. This variable exhibits notably strong marginal effects in Bulgaria, despite the fact that the average temperature in this country is higher than in other CEE countries. Notably, 76% of households affected by energy poverty

[10] The latent class model was also estimated using a stricter definition of the manifest variables 'difficulty making ends meet' and 'housing costs as a burden', assigning a positive value only to households experiencing very serious difficulties. The energy sufficient class's marginal effects for these variables are lower for some countries, as expected. However, overall estimates remain consistent for both the three-class structure definition and the additional covariates' effects. The results are presented in Tables E and F in the Appendix.

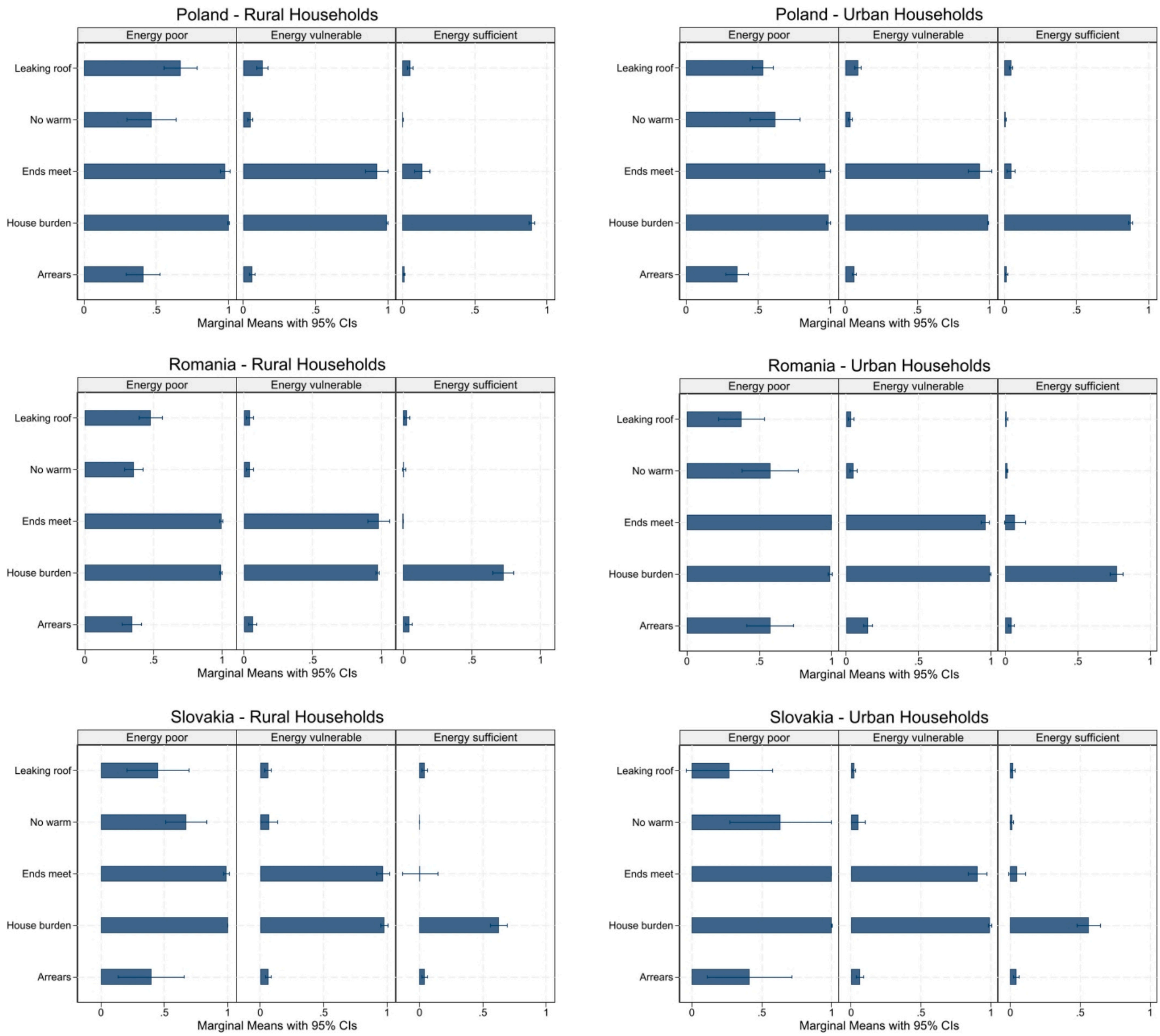

Fig. 2. (*continued*).

and even 6% of the energy-sufficient households in rural Bulgaria report being unable to maintain adequate indoor temperatures. In Romania, this issue is more pronounced in urban areas than in rural ones among the households affected by energy poverty (57% vs. 36%). In both countries, the gas network is underdeveloped, and families rely on single stoves and biomass, unable to warm large spaces. The same finding is observed in Poland. The poor quality of apartment blocks and multi-family houses, coupled with the inefficiencies of district heating systems in urban areas, help to explain this finding.

4.2. *The role of individual attributes in the class membership*

The variables selected as covariates are associated with household membership in the three groups, establishing a ranking based on their level of difficulty in accessing energy, and classifying them as affected by energy poverty, energy vulnerable, or energy sufficient both in urban and rural areas, as summarized in Table 4.[11]

In our findings, two variables stand out as being statistically significant for all countries: disposable income and internet access. Low income and limited digital inclusion are associated with a higher likelihood of belonging to the energy-poor class. Demographic variables and housing conditions have mixed effects across countries and locations and do not always contribute to identifying which class a household belongs to.

As expected, income exerts an important and unidirectional influence in all countries, with a negative correlation between an increase in income level and the probability of being classified as vulnerable or as households affected by energy poverty. The income effect is more pronounced for rural than for urban households in the case of Bulgaria, while in the other cases there seems to be no regularity.

[11] Detailed parameters and standard errors are presented in Table D in the appendix.

Table 4
The role of covariates: impact on the likelihood of belonging to a class.

	URBAN	RURAL
Disposable income	DECREASES probability of EP and vulnerability.	DECREASES probability of EP and vulnerability
Having children	MIXED EFFECT and not always statistically significant: less vulnerability in BG and PL.	MIXED EFFECT and not always statistically significant: less vulnerability in BG, more vulnerability in CZ.
Having a retired member	DECREASES probability of EP and vulnerability when statistically significant.	DECREASES probability of EP and vulnerability when statistically significant.
Max age within the household	Prevalence of an INCREASING EFFECT on probability of EP and vulnerability, not always statistically significant.	INCREASES probability of EP and vulnerability in CZ, DECREASES poverty in BG, not clear in other countries
Detached house	INCREASES probability of vulnerability, when statistically significant.	INCREASES probability of vulnerability, when statistically significant (low level of significance)
Number of rooms	DECREASES probability of vulnerability, when statistically significant.	DECREASES probability of vulnerability, when statistically significant.
Living in overcrowded dwellings	INCREASES probability of vulnerability, when statistically significant.	INCREASES probability of vulnerability, when statistically significant.
Having internet access	DECREASES probability of EP and vulnerability.	DECREASES probability of EP and vulnerability.

Note: EP stands for energy poverty.

The second variable that is associated with class membership is the binary indicator of whether or not there is an internet connection for personal use. In all countries, the direction of the impact of this variable coincides with that of income, and the significance of the impact remains the same. Furthermore, in most cases the effect appears to be more important in the rural areas than in the urban ones. This suggests that, while having an internet connection is indeed associated with a higher income, it also provides access to valuable information, such as investment opportunities in energy efficiency and the associated public subsidy systems, in all countries. This type of information may in fact be more difficult to find in less densely populated areas, which is why the impact of access to information on energy poverty is greater in rural contexts.

The presence of minors in a household does not make the same significant contribution in all estimates. In urban contexts, for example, it is not a reliable indicator of energy poverty, while it is associated with poverty or vulnerability in rural ones and especially in Bulgaria and Czechia. In Polish rural areas, on the other hand, it is associated with a better-off status.

The presence of elderly people has two distinct effects. On the one hand, the presence of pensioners tends to have a positive effect on the energy poverty status. This may be explained by the fact that social benefits help to cover family expenses, as well as by the fact that a person who has been in the formal labour market tends to find it easier to acquire information and make efficient choices. The importance of social protection payments, beyond the generic income variable, has also been highlighted by Spandagos et al. [56], who, using a different approach based on machine learning estimation, find this variable to be very important in describing energy poverty in EU countries. On the other hand, the presence of very old people tends to have a negative impact on well-being, although this is not always statistically significant. In the urban context, where pensioners often live in old multi-family buildings, the presence of the elderly always increases energy poverty and vulnerability, and this effect is particularly significant in Bulgaria, Poland and Romania. In rural areas, on the other hand, the effect appears to be for an intermediate state (vulnerability), with no specific effect on poverty or energy sufficiency in Hungary and Poland, and a more pronounced impact on the likelihood of being affected by energy poverty in Bulgaria and Czechia.

The group of variables related to housing characteristics all have a clear effect, as expected.[12] For detached houses, the effect is clearly an increased probability of vulnerability and poverty status. This effect is more significant in urbanised areas than in rural ones, which is related to the fact that detached houses are more common in the latter. This effect appears particularly strong (and significant) in urban contexts in Romania and Poland. On the other hand, the variables relating to house size and per capita space (number of rooms and living space considered 'crowded') are proxies for the state of general affluence and therefore always have a clear effect on the state of energy poverty. In general, these variables tend to have a more pronounced effect in urban contexts.

5. Discussion

5.1. Energy poverty and public health: Emerging challenges and responses

The identification of distinct groups of energy-poor, vulnerable, and energy-sufficient households allows us to examine health-related issues, which are known to be a key corollary when analysing phenomena of energy poverty. An ex-post analysis of the characteristics of these groups highlights important differences in self-reported health across the identified energy poverty profiles. Descriptive evidence from the EU-SILC survey indeed shows that households belonging to the groups most exposed to energy poverty systematically report poorer self-assessed health (Fig. 3), regardless of the countries and territorial contexts considered. This descriptive pattern suggests a strong association between housing energy conditions, living conditions, and self-reported health outcomes.

These results are consistent with a well-documented analytical framework in social epidemiology, according to which prolonged exposure to inadequately heated dwellings, polluting heating systems, or situations of thermal insecurity constitutes a significant risk factor for respiratory and cardiovascular diseases, as well as for mental health [30,57]. The observed differences between rural and urban areas are further consistent with this interpretation. In rural areas, reliance on solid fuels, lower housing quality, and household isolation may exacerbate health risks, whereas in urban areas, inefficiencies in collective heating systems and residential density can generate other forms of health-related constraints. The fact that similar health gradients are also observed among so-called "vulnerable" households—and not only among those experiencing the most severe forms of energy poverty—suggests that health disadvantages are not confined to the most energy poor households but are also observed among vulnerable households. In this respect, our findings invite energy poverty to be considered not only as an economic, energy-related, or environmental issue, but also as a central public health concern. Although our empirical analysis does not establish causal relationships, this descriptive association suggests that integrated energy, health and social policies may be relevant, particularly in rural areas and in CEE countries where structural vulnerabilities are most pronounced. The articulation between energy policies, health policies, and social policies thus may represent an important avenue for reducing the cumulative inequalities highlighted by our analysis.

Importantly, Fig. 3 also reveals that the direction and magnitude of rural–urban health disparities differ across countries, suggesting that health outcomes are mediated by country-specific configurations of energy poverty rather than by urbanization alone. In countries such as Bulgaria and Romania, poorer health outcomes among rural energy-poor households are consistent with the strong prevalence of solid fuel

[12] Spandagos et al. [56] also use property characteristics and in particular find a significant effect for the number of rooms and the detached house status for the dwelling.

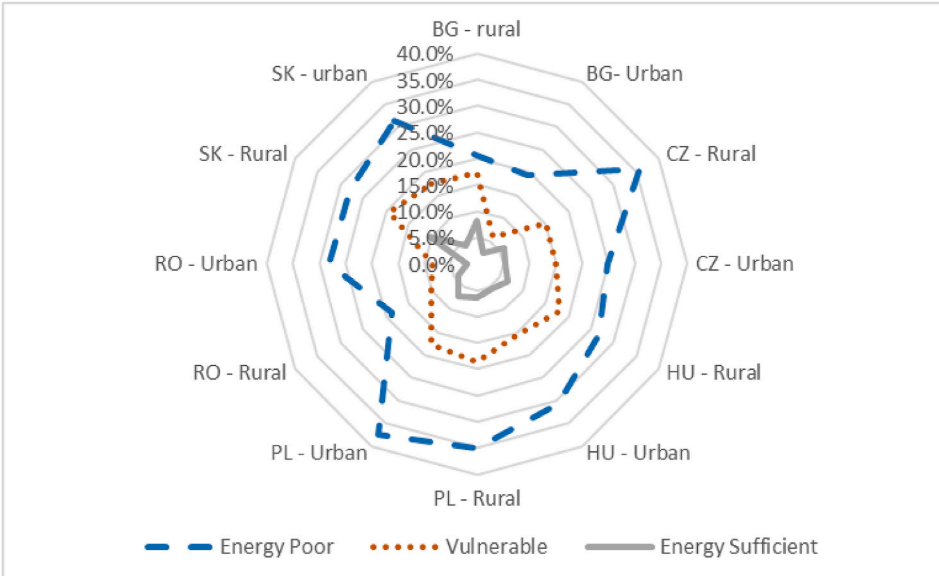

Fig. 3. - Share of households reporting bad and very bad health.

use, poor housing quality, and limited access to services identified in the latent class results. In contrast, in countries where urban energy poverty is more strongly associated with inefficient collective heating systems and dense multi-family housing, such as Poland and Bulgaria, health vulnerabilities may be more pronounced in urban contexts. These patterns highlight that similar levels of energy poverty are associated with different health outcomes depending on the underlying energy systems, housing infrastructures, and exposure pathways identified by the latent class analysis.

5.2. Policies addressing energy poverty: A diverse and fragmented set of measures across countries

Despite growing policy attention to energy poverty across the EU, many CEE countries continue to struggle with designing and implementing interventions that effectively reach the most vulnerable populations. Importantly, given that our empirical analysis relies on EU-SILC 2019 data, the following discussion does not aim to assess the causal effectiveness of existing or recently introduced policies. Instead, it examines the extent to which current policy frameworks appear aligned, or misaligned, with the multidimensional energy poverty profiles identified by the latent class analysis.

When confronted with the results presented in Section 4, this difficulty appears less related to the absence of policies than to the way existing measures are designed and targeted. As illustrated in Fig. 4 and Table G in appendix, a synthesis of ongoing policies in EU shows a persistent reliance on general financial and regulatory instruments, such as energy-efficiency subsidies, thermal insulation standards, and renovation programs, which are typically conceived as nationally uniform measures rather than as responses to differentiated vulnerability profiles

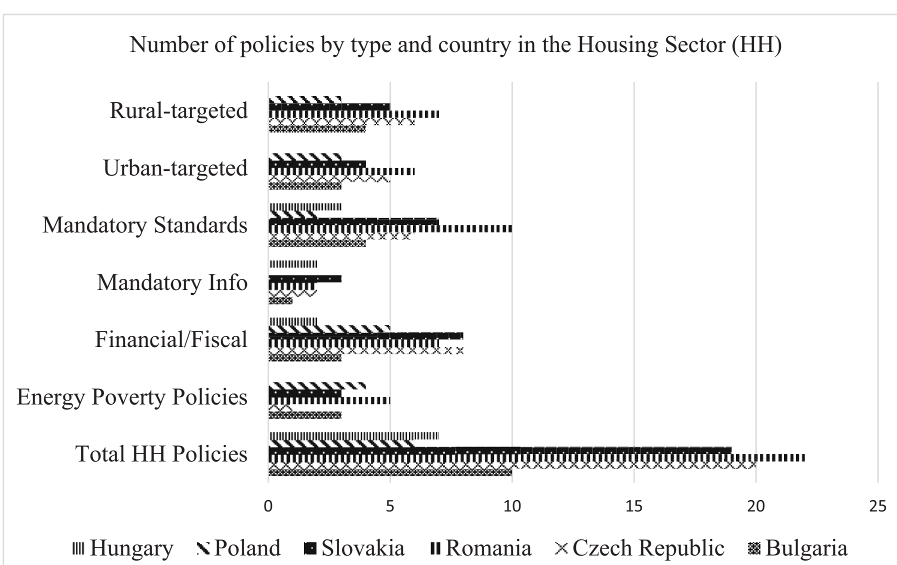

Fig. 4. - Number of policies by type and country in the Residential Sector.
Note: Urban policies include apartment building renovations, district heating upgrades, mandatory certificates in dense areas. Rural policies include single-family home insulation, renewable subsidies for off-grid homes, solid fuel stove replacement. Some policies (especially mandatory standards/info) apply broadly and aren't specific to either context, so urban/rural numbers don't sum to total. Source: Odyssee-Mure website, https://www.measures.odyssee-mure.eu

[42,58,59].

While Romania and Poland have integrated energy poverty concerns into national renovation strategies [15,28], other countries rely predominantly on policy frameworks that are formally inclusive but weakly differentiated in practice, including Hungary and Czechia [17]. In the Hungarian case in particular, the policy inventory compiled by the Energy Poverty Advisory Hub (EPAH) reveals that residential measures primarily target energy performance, building standards, or specific social categories, without explicit differentiation according to spatial context [60]. This absence of rural/urban targeting stands in contrast with our results, which highlight some territorial differences in the mechanisms of energy poverty, especially the accumulation of poor housing quality, lack of financial resources, and limited digital access in rural areas. Similarly, Slovakia, despite having one of the EU's few formal definitions of energy poverty, shows limited responsiveness to spatial inequalities, particularly in its eastern regions [61]. Taken together, these cases suggest that policy design often fails to incorporate the spatial dimension of vulnerability confirmed by the model, rather than reflecting a simple lack of intervention. Beyond differences in policy design, our results suggest that cross-country heterogeneity in energy poverty profiles reflects distinct combinations of structural mechanisms. These include differences in housing stock legacies, energy system configurations, and institutional capacity to reach vulnerable households. For instance, the prominence of rural energy-poor profiles in Romania and Slovakia appears closely linked to the persistence of low-quality housing and reliance on solid fuels, while in countries such as Bulgaria and Poland, urban vulnerability is more strongly associated with inefficiencies in district heating systems and multi-family buildings.

A key implication of the results of LCA is that energy poverty emerges as a cumulative and multidimensional process, which cannot be adequately addressed through single criterion targeting strategies. From this perspective, the policy landscape appears only partially aligned with the structure of vulnerability revealed by the model. While Romania and Poland have more than five measures each that explicitly address energy poverty, many programs in countries like Hungary and Bulgaria lack clear targeting criteria (see Fig. 4 and Table G, Appendix). In addition, the widespread requirement for upfront co-financing in energy efficiency investments constitutes a significant barrier for households belonging to the energy poor and energy vulnerable classes identified in our analysis, for whom liquidity constraints and limited access to information often coexist. As a result, policies that are neutral or progressive in appearance may become effectively regressive in practice, reinforcing exclusion rather than alleviating vulnerability [2,16]. Policies like Slovakia's "Restore the House Light" or Romania's rural solar panel subsidies are exceptions that explicitly prioritize vulnerable households. However, these initiatives remain isolated and are rarely embedded within comprehensive strategies capable of addressing the multidimensional nature of energy poverty highlighted by the model [15,20].

Our results confirm rural–urban disparities in the causes and manifestations of energy poverty. While some rural-sensitive programs exist, such as Czechia's "New Green Savings Light" and Poland's "Warm Housing", most national strategies remain urban-centered or undifferentiated in design. This lack of spatial differentiation contrasts with the strong location-specific vulnerability mechanisms revealed by the latent class analysis, and supports the view that spatial and infrastructural factors frequently outweigh income alone as predictors of energy poverty [9,15]. Even in urban contexts where income levels are higher, as in Bulgaria, households often experience poor thermal comfort and high energy bills due to systemic inefficiencies in heat supply and building performance [20]. In contrast, rural households suffer from decentralized and often informal energy arrangements, characterized by high environmental and health costs. These differentiated vulnerability patterns imply that the policy relevance of multidimensional approaches varies across contexts. In settings where energy poverty is primarily driven by rural housing characteristics and solid fuel use, policies focusing on housing renovation and clean heating transitions are likely to be most effective. In contrast, in urban contexts dominated by collective heating systems, system-level interventions targeting building performance and heat supply efficiency appear more critical.

Household internet access appears to be a significant factor associated with the likelihood of being energy-poor in the CEE countries. These findings suggest that policies could strengthen basic digital inclusion by increasing the energy digital literacy and the availability of certified price comparison tools to increase the awareness about price signals and offers of alternative energy providers. Households that are digitally excluded may face greater difficulties accessing the online billing and chatbot functions that energy companies largely use to communicate with customers. Furthermore, they may also be less likely to benefit from financial incentives, which will be taken up by digitally engaged, typically more affluent households. Sovacool et al. [62] argue that low-income households often perceive smart technologies as useless and intrusive. Therefore, 'hard-to-reach households' should be engaged also with dedicated face-to-face services, going beyond internet [63]. One-stop shops have proved to be effective in communicating with people in complex situations. Trained advisors can deliver information in simple language, helping to read energy bills and to gain access to all eligible benefits. Local offices in municipalities and on-site energy audits by energy advisors contribute to engage users. These interventions to tackle energy poverty could also produce health outcomes [64]. Indeed, as suggested in the policy recommendations of the WELLBASED H2020 EU project [65],[13] the team of advisors should also include social workers trained in health issues to promote healthy habits, adapt advice to the health situation of household members and increase awareness about the health problems related to the energy use and dwelling inefficiencies. Similarly, workshops and training sessions for local communities on energy- and health-related topics promote good practices, such as mould prevention, ventilation, and raise awareness of the health impacts of extreme temperatures.

6. Conclusions

Energy poverty is increasingly being recognised as a key challenge for European societies. This is because it not only undermines households' well-being but also highlights the difficulties of the current energy transition.

In the context of rising energy prices, climate pressures, and persistent territorial inequalities, the inability to secure adequate domestic energy services is no longer a marginal issue, but it is a structural driver of social vulnerability and poor population health. These dimensions are particularly salient in the CEE countries, where historical legacies in housing stocks, energy infrastructures and energy market liberalisation intersect with income constraints, unequal access to services, and unequal digital skills.

This paper offers an empirical contribution that relies on the application of LCA to EU-SILC microdata for six Eastern European countries, separately for rural and non-rural areas. This approach allowed us to move beyond single-threshold definitions and to capture energy poverty as a result of overlapping deprivations rather than as a binary condition [21]. Our results consistently support a three-class typology— households affected by energy poverty, vulnerable, and energy sufficient—conceptualising energy poverty not as a set of discrete states, but as a graded continuum of cumulative and overlapping deprivations. One of the main contributions of the analysis lies in revealing the heterogeneity of energy-poor households and the spatial inequalities that structure vulnerability—particularly the sharp divide between rural and urban contexts. However, this rural–urban difference in energy poverty

[13] See https://wellbased.eu/ One of the pilot cities of the project where the programs were implemented is Budapest (Hungary).

cannot be reduced to a single direction or intensity, but rather can be explained by country-specific combinations of income distribution, housing stocks, heating infrastructures, climatic heterogeneity and the diffusion of digital services. Broadly speaking, rural households face cumulative disadvantages related to solid fuel dependence, poor insulation, and digital exclusion, while urban households experience constrained agency within inefficient district heating systems.

By moving beyond income-based approaches, this study underscores the importance of incorporating different dimensions into energy poverty analysis. Two factors stand out for their consistency across all countries: disposable income and internet access. While the central role of income is expected, the strong and systematic association between internet access and a lower probability of being in the energy-poor or vulnerable classes is a particularly policy-relevant result. This finding supports the interpretation that digital deprivation constitutes an additional layer of vulnerability that interacts with traditional drivers of energy poverty. Basic connectivity can affect households' ability to obtain timely information about support schemes and administrative procedures, compare energy offers and access digitalised services that are increasingly important in energy markets. This digital divide is especially evident in rural areas of Bulgaria and Romania, where broadband infrastructure remains limited [16,51]. Karásek and Pojar [9] also note that households lacking internet access are effectively excluded from many online-based support programs. The compounding effects of digital exclusion, low income, age, and housing status reinforce hidden forms of energy poverty that remain overlooked in policy design. These findings are supported by national case studies, which emphasize the importance of multi-dimensional assessments [19,27,63].

Our study reaffirms the association between energy poverty and adverse health outcomes. Exposure to cold homes and indoor air pollution contributes to a range of health issues, including respiratory and cardiovascular diseases and psychological stress. Vulnerable groups such as children, the elderly, and chronically ill individuals—especially in Poland and Romania—are disproportionately affected [28,42,66]. Despite this, health remains a marginal concern in most national policy responses. Integrating health considerations into energy poverty strategies—through mobile medical units, joint renovation-health subsidy programs, or community hubs—could generate significant co-benefits [58]. Significantly, the fact that health disadvantages are not confined to the most severe energy-poor class but are also visible among "vulnerable" households suggests a cumulative dynamic: households may experience health deterioration before reaching the most extreme forms of deprivation. From a policy perspective, this implies that interventions aimed at preventing households from sliding from vulnerability into severe energy poverty may reduce longer-term healthcare burdens. More broadly, the results call for a reframing of energy poverty policies as part of prevention-oriented social and health policy, not simply as compensatory energy-expenditure measures. Indeed, across the countries considered, the policy landscape often relies on broadly defined subsidies, general renovation programs, and regulatory measures that do not fully incorporate the territorial dimension of vulnerability or the informational barriers that may limit the take-up. When considering such non-targeted policies, it is evident that the risk of excluding precisely those households identified as affected by energy poverty or vulnerable households that face liquidity constraints, lower administrative capacity, and, in many rural areas, weaker digital access and competences. This can lead to a paradox in which supposedly progressive measures become regressive in practice, as more affluent and digitally connected households capture a disproportionate share of benefits.

The strength of this research lies not only in its methodological contribution—using LCA to reveal separate household profiles—but also in its policy relevance. It draws attention to the mismatches between household needs and existing national measures. Our findings call for holistic and spatially differentiated policies that link energy, health, and digital access. At the same time, we acknowledge that such interventions inevitably entail fiscal costs and trade-offs, which are particularly acute in CEE countries where public budgets are constrained and redistribution levels remain structurally lower than in Western Europe. Poorly designed programs that fail to account for multidimensionality, territorial disparities, and informational barriers may even exacerbate inequalities if they rely on substantial upfront household contributions. Future work should extend this multidimensional approach to assess the long-term impacts of policy interventions but also their broader fiscal and macroeconomic implications, to improve the targeting and sustainability of support across territorial and socio-economic divides.

These conclusions should be interpreted in the light of the study's data and methodological limitations, most of which are linked to the characteristics of EU-SILC. Despite its rich informational content, EU-SILC was not specifically designed to analyse energy poverty. As a result, it lacks detailed data on household energy expenditure and consumption patterns, indoor thermal comfort, cooling needs, and the intensity and quality of digital use. This also limits the ability to capture potential'hidden energy poverty',as to disentangle affordability from behavioural choices. Moreover, the self-reported indicators used as manifest variables may introduce reporting heterogeneity across cultures and countries. These data limitations also suggest directions for future research. Linking household-level survey data with data on building performance, energy contracts and health outcomes would enable a more precise mapping of energy poverty. Future work could also test whether the typologies identified here remain stable in later EU-SILC waves, particularly after the pandemic phase and the 2021–2023 energy crisis, and could investigate transitions across latent classes over time.

In conclusion, this paper contributes to the literature by demonstrating that energy poverty in CEE countries is best understood as a multidimensional, spatially mediated process with significant public health implications. The LCA approach reveals distinct profiles of deprivation and highlights the importance of both economic resources and digital inclusion in shaping household vulnerability, particularly in rural contexts. These findings call for policy approaches that are integrated across sectors and differentiated across places, combining renovation and clean heating transitions with inclusive delivery mechanisms and explicit attention to health and digital barriers. An appropriate design of such policies is crucial not only for alleviating energy poverty, but also for ensuring that the broader energy transition does not deepen existing inequalities and instead delivers equitable well-being gains across Europe.

CRediT authorship contribution statement

Rossella Bardazzi: Writing – original draft, Visualization, Validation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Dorothée Charlier:** Writing – original draft, Visualization, Validation, Formal analysis, Data curation, Conceptualization. **Berangère Legendre:** Writing – original draft, Visualization, Validation, Formal analysis, Data curation, Conceptualization. **Maria Grazia Pazienza:** Writing – original draft, Visualization, Validation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT-OpenAI in order to improve the quality of the English in which the article had been written. After using this service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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Declaration of competing interest

The authors have nothing to declare.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2026.104953.

Data availability

The authors do not have permission to share data.

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