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SCIENCE FOR POLICY BRIEF

Identifying energy vulnerability in Europe: a multidimensional index for policy action

HIGHLIGHTS

- → We propose a multidimensional framework combining building energy performance and adaptive capacity.
- → Building energy performance varies across EU regions, influenced by local climate and building characteristics.
- → Urban areas show higher energy vulnerability when considering adaptive capacity in addition to building energy performance.
- → We call for greater support for local and regional authorities to monitor energy vulnerability more regularly and granularly.

"The best time to plant a tree was 20 years ago. The second best time is now." – Chinese Proverb

ENERGY POVERTY & VULNERABILITY

Energy poverty is a pressing challenge in the European Union (EU), affecting over 45 million households in 2023, or 10.6% of the EU's population, who reported being unable to adequately heat their homes [1]. This marks a significant rise from 6.9% in 2021, largely driven by soaring energy prices and geopolitical instability, including Russia's aggression against Ukraine [2]. **Energy poverty** reflects the **current inability** of households to meet basic energy needs, driven by a combination of high-energy prices, socio-economic disparities, and insufficient energy efficiency in the building stock [3].

Complementary to energy poverty, **energy vulnerability** refers to the **risk factors** that predispose households to become energy poor [4]. Energy vulnerability describes the intersection of three dimensions: (i) *exposure*, or the degree to which households face energy-related risks like thermal discomfort at home; (ii) *sensitivity*, which reflects how severely households are impacted by such risks; and (iii) *adaptive capacity*, or the ability of households to mitigate these impacts through resources, behaviour, or technological measures [5]. Vulnerable groups—such as elderly residents, low-income families, and renters in urban areas—are particularly at risk due to higher exposure and sensitivity, and socially structured limited adaptive capacity [4].

In a context where climate change exacerbates these risks for the most vulnerable, policymakers must move beyond reactive measures and focus on preventive actions to address energy poverty [6]. Therefore, to enable timely interventions, it is key to identify not only **households** at higher risk of energy poverty, but also the **underlying risk factors**.

A multidimensional approach is needed

The EU's diverse geographical, socio-economic, and climatic conditions make the manifestations of energy poverty highly variable across EU [7]. This complexity thus requires a multidimensional approach to assess energy poverty and vulnerability [8]. Two dimensions are particularly key in assessing households' **risk** to become energy poor:

1. Building energy performance:

The energy performance of residential buildings reflects the extent to which buildings meet energy efficiency standards and adequate indoor conditions [9]. The energy performance gap—the difference between modelled energy demand (optimal conditions) and actual energy consumption—captures inefficiencies in the built environment that exacerbate exposure to energy poverty [10]. Thus, poorly performing buildings, which fail to maintain adequate thermal comfort, underline the material households' exposure and sensitivity to energy vulnerability.

2. Adaptive Capacity:

Adaptive capacity reflects households' ability to respond to energy challenges, influenced by both objective factors (e.g., income, housing tenure) and subjective dimensions (e.g., perceived ability to act) [11]. For instance, higher-income households are generally better equipped to invest in cooling or heating systems and address thermal discomfort compared to renters or households with non-negotiable energy needs [12].

At the same time, the fact that energy vulnerability manifests differently across EU highlights the need for an assessment at the regional level [13]. Such an approach would better enable policymakers to identify context-specific risk factors and design tailored solutions. As an example, energy vulnerability in urban areas may be linked to dense populations, exacerbated spatial socio-economic disparities, and common rental status, all of which expose households to a specific risk: summer energy poverty [14]. This form of energy poverty reflects the challenges vulnerable households face in achieving adequate cooling and maintaining thermal comfort during increasingly frequent and intense heatwaves, driven by climate change [15]. Therefore, addressing energy vulnerability requires targeted, multidimensional interventions that specifically tackle the risks posed by the specific contexts.

METHODOLOGY

This brief summarises the main steps of the development of an Energy Vulnerability Index (EVI), a multidimensional framework that integrates building energy performance and adaptive capacity.

Energy Performance Gap Index (EPGI)

The Energy Performance Gap Index (EPGI) quantifies the gap between the energy required for optimal building functionality and comfort, referred to as final energy demand (FED), and the actual energy consumed by households, known as final energy consumption (FEC). This index sheds light on inefficiencies in residential energy performance that contribute to thermal discomfort and, thus, exposure and sensitivity to thermal discomfort.

Final Energy Demand (FED) represents the energy needed for heating, cooling, ventilation, domestic hot water, and lighting under standardized indoor conditions and prevailing climatic circumstances. This metric is derived from national cost-optimal methodology reports[1], which use the concept of reference buildings to model typical national building typologies employing either steady-state or dynamic energy simulations [16]. Reference buildings are defined based on representative characteristics such as geometry, thermal envelope quality, technical systems, and operation conditions. For the present

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[1] EU countries' cost-optimal reports (2013 - 2018 - 2023), Available at: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en

study, data on FED is aggregated from building to regional levels (NUTS1) using a bottom-up approach.

Final Energy Consumption (FEC) refers to the empirical energy usage by households, sourced from Eurostat's energy balance statistics [17]. This dataset offers a comprehensive overview of energy consumption across Member States, covering heating, cooling, and other essential energy services in the residential sector. We adjusted the end-uses included and used a top-down methodology to disaggregate national-level data (NUTS0) to the regional level (NUTS1), accounting for variations in regional housing stocks, demographics, and energy use patterns.

We adopt the approach from Gouveia et al. [10] to assign classes to the gap. That is, we standardised each percentage gap (from 0% to 100%) into a sub-index (classes) ranging from 1 to 20.

The EPGI is, thus, calculated as:

$$EPGI = 1 + \frac{EP_{gap,i} - EP_{gap,min}}{EP_{gap,max} - EP_{gap,min}} \times (20 - 1)$$

Regions with high EPGI values indicate significant energy inefficiencies, suggesting a gap between the theoretical energy performance of buildings and actual household energy use, and thus higher exposure to risk of becoming energy poor.

Capacity to Adapt Index (CAP)

The Capacity to Adapt index (CAP) measures households' ability to alleviate thermal discomfort and manage energy-related challenges. This index encompasses both objective factors (e.g., income levels, housing quality) and subjective factors (e.g., perceived ability to act) [11].

The data for CAP development is sourced from Eurostat's 2020 Household Budget Surveys (HBS), which provide microdata on household income, expenditures, and other socio-demographic characteristics at the NUTS1 level. Covering 22 EU Member States, the 2020 HBS dataset serves as a basis for analysing adaptive capacity across regions. Additionally, it enables an initial urban analysis, as in some countries, certain NUTS1 regions correspond to metropolitan areas.

The selected variables to construct CAP include, amongst others, residence geographical dispersion, income levels, housing costs, household composition, socio-demographic factors, expenditure patterns (e.g. medical services, education), and skills.

Following the approach of Gouveia et al. [10], we applied a segmented linear approach. Particularly, we divided each variable's distribution within NUTS1 regions into five equal segments based on percentiles. Next, we created a categorical variable, "class", for each variable to standardize the data for categorization into risk classes (we assigned a risk classification value between 1 (minimum risk, i.e. high adaptive capacity) and 5 (maximum risk, i.e. low adaptive capacity)). The NUTS1 average for each classified variable was then computed. Finally, to generate the final CAP index, we assigned each variable a weight based on its relevance to adaptive capacity - as assessed by the expert judgments of two researchers.

Energy Vulnerability Index (EVI)

The EVI is calculated for each NUTS1 and is defined as the average of the Energy Performance Gap Index (EPGI) and the Capacity to Adapt (CAP) index, reflecting the balance between a household's sensitivity and exposure to thermal discomfort and the ability to adopt measures to alleviate thermal discomfort:

$$EVI_{urban} = \frac{EPGI + CAP_{urban}}{2}$$

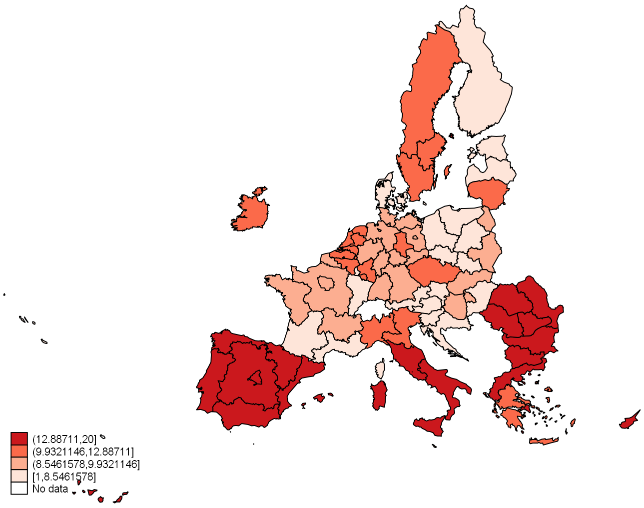
MAIN RESULTS

The analysis shows major differences in energy performance and vulnerability across Europe, highlighting context-specific challenges in energy consumption and adaptation between regions and urban areas. The Energy Performance Gap Index (EPGI) measures inefficiencies in aligning energy demand with consumption, while the Energy Vulnerability Index (EVI) incorporates socio-economic and behavioural dimensions, offering a broader perspective on energy vulnerability.

Energy performance gap

The EPGI (Fig. 1) suggests notable energy inefficiencies especially in Southern and Mediterranean European countries, where regions exhibit the largest gaps between energy demand and consumption. High EPGI values, particularly in Spain, Portugal, Italy, and parts of Eastern Europe like Romania and Bulgaria, signal widespread challenges in achieving thermal comfort. For instance, Spain's Canarias (20.00) and Centro (16.60) reflect substantial energy performance gaps due to unmet cooling needs and outdated building stock. Similarly, Portugal and Italy feature prominently among countries with an EPGI above 12.8, pointing to systemic issues such as inadequate thermal envelopes, insufficient ventilation, and unmet demand for cooling or heating.

Figure 1 – Energy Performance Gap Index by NUTS-1



Source: JRC.

These regions' high cooling demand correlates with climatic conditions such as hot summers and mild winters, compounded by insufficient energy allocation for cooling. Mediterranean regions frequently exceed the EU average for cooling degree days, with values ranging from 141 to 549 compared to the EU mean of 127 [18], further illustrating unmet needs. Notably, the cooling share in total energy consumption in these countries remains low, suggesting a mismatch between demand (needs) and energy supply (abilities).

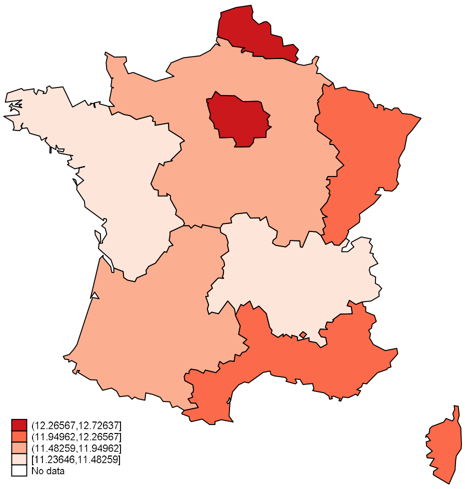
On the other hand, Northern and Central European regions have lower EPGI values reflecting more efficient energy systems and buildings. In France, Île-de-France (7.03) and other regions like Nord-Pas-de-Calais (9.18) and Est (8.31) are associated with moderate energy performance gaps. Countries like Austria, Slovenia, Slovakia, and Denmark similarly report lower EPGI values, likely benefiting from more advanced building standards and higher rates of energy efficiency renovations. Nordic regions also perform relatively well, as modern heating technologies and improved building insulation mitigate the effects of harsher climates.

The regional differences in EPGI are influenced by several factors. First, regions with older building stocks—often constructed before the introduction of energy efficiency regulations—face significant challenges. Many of these buildings are poorly insulated, with outdated heating and cooling systems that fail to meet current energy demands. In the EU, the annual building renovation rate was at only 1% in 2020, exacerbating energy inefficiencies. Second, climatic conditions amplify energy performance gaps, with Mediterranean regions and countries such as Romania and Bulgaria facing greater difficulty in maintaining energy consumption in line with calculated energy demand. Without targeted interventions, these gaps are expected to widen as climate change progresses.

Energy vulnerability index

When considering the EVI, which incorporates both the EPGI and the CAP, urban areas exhibit a heightened vulnerability compared to the other regions in the country. Due to data limitations, we start by exemplifying the EVI for three metropolitan areas, with the plan to explore this at NUTS3 level in future research.

Figure 2 – Energy Vulnerability (Urban) Index in France

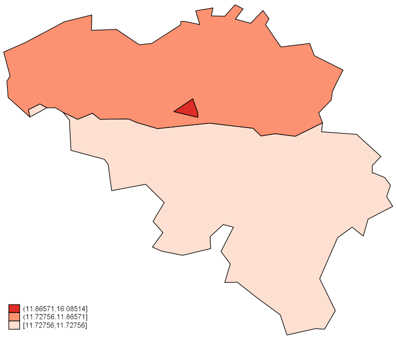


Source: JRC.

In France, Île-de-France (Fig. 2), despite its relatively low EPGI of 7.03, exhibits an urban EVI of 12.73, highlighting increased vulnerability driven by spatially induced socio-economic disparities. As an example, high living costs and widespread rental housing in metropolitan areas limit residents' capacity to adopt energy-efficient measures, while dense urban environments exacerbate thermal discomfort, particularly during hot summers. Similarly, in Belgium (Fig. 3), Brussels' urban EVI of 16.09 exceeds its EPGI of 12.40, highlighting the compounded challenges of rental housing, income inequalities, and limited individual control over building efficiency upgrades. In Madrid (Fig. 4), the urban EVI of 16.80 reflects higher vulnerability compared to an EPGI of 15.11, driven by significant urbanization pressures, including increased cooling needs during summer months and the persistence of energy inefficiencies in densely populated areas.

Urban areas thus face several systemic challenges that contribute to heightened energy vulnerability. One critical factor may be the urban heat island effect, where dense construction and limited green spaces lead to higher temperatures and elevated cooling demands [19]. This phenomenon exacerbates energy vulnerability, particularly during heatwaves, and is likely to intensify with climate change. Moreover, urban regions are often characterized by socio-economic inequities, with pockets of extreme poverty coexisting alongside affluence [20]. These disparities limit households' ability to reduce thermal discomfort, as, for example, they are less likely to afford energy-efficient cooling systems.

Figure 3 – Energy Vulnerability (Urban) Index in Belgium



Source: JRC.

Another challenge is the high proportion of rental housing in urban areas, where tenants have limited control over energy efficiency upgrades. This perpetuates inefficiencies, as landlords often lack incentives to invest in energy-saving measures, leaving tenants to face high energy costs [21]. Additionally, urban stress and inequalities, such as limited access to resources or opportunities, can leave residents feeling overwhelmed or powerless [22]. For instance, even if households know that better thermal insulation or using a fan could reduce summer discomfort, they might not act due to perceived lack of control, time, money and competences—even when they could afford it. Mental and social barriers, alongside physical and financial ones, can affect a household's ability to improve thermal comfort.

Box 1: Key concepts

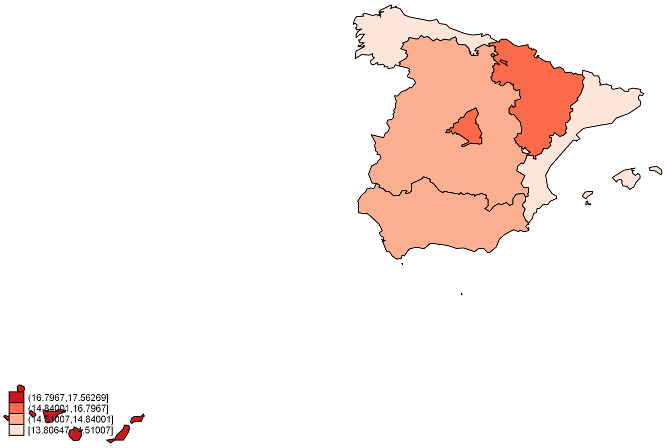
Energy Vulnerability (EV): The risk of households to become energy poor.

Energy Performance Gap Index (EPGI): A measure of the difference between a region's calculated energy demand for optimal building performance and the actual energy consumed. A higher EPGI indicates a larger gap between energy needs and consumption, highlighting areas where energy efficiency improvements are necessary.

Adaptive Capacity (CAP) Index: Evaluates the ability of households to mitigate energy vulnerability by considering both objective (e.g., income,) and subjective (e.g., energy skills) factors that influence how well people can adapt to thermal discomfort. A higher CAP indicates greater vulnerability to thermal discomfort, highlighting the need for measures such as improved landlord regulations and increased energy literacy to empower households to better adapt to changing thermal conditions.

Energy Vulnerability Index (EVI): A holistic index combining the EPGI and CAP. It considers both the energy performance of buildings and the capacity of households to adapt to thermal discomfort.

Figure 4 – Energy Vulnerability (Urban) Index in Spain



Source: JRC.

CONCLUSIONS

We developed a multidimensional framework to guide policymakers in assessing energy vulnerability across EU regions. By integrating building energy performance (EPGI) with adaptive capacity (CAP), the EVI analysis reveals significant disparities across regions and urban-rural divides.

These findings highlight the importance of tailored, region-specific policies rather than one-size-fits-all measures. These include climate-adaptive building renovations, rental market reforms, and programs that enhance both objective and subjective dimensions of adaptive capacity, such as energy literacy initiatives. Addressing the behavioural ad social dimensions of adapative capacity is also crucial, as empowering households with the knowledge and tools to manage their energy use and adapt to thermal discomfort can contribute to reduce the risk to face thermal discomfort. The interplay between technical building performance and socio-behavioural-economic factors highlights the need for holistic interventions targeting both physical infrastructure and energy justice.

To effectively address these challenges, policymakers must invest in recursive data collection frameworks, empowering local and regional authorities to monitor energy vulnerability regularily and granurarly, and adapt policies as conditions evolve. Strengthening regional capacity for detailed, ongoing data collection and analysis is thus critical to creating adaptive, evidence-based solutions that respond to the complexities of energy vulnerability in diverse contexts across Europe.

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DISCLAIMER OR OTHER FINAL DETAILS

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