

# A Multidimensional Analysis of Energy Poverty in the EU: Exploring Complex Drivers and Cross-Dimensional Impacts

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Energy poverty remains one of the key obstacles to sustainable development, directly affecting households and increasingly influencing business operations as well. The research investigates the relationship between energy poverty and greenhouse gas (GHG) emissions in the EU, addressing the often-overlooked connection between social vulnerability, environmental impact, and local climate policy. The study utilizes EU-level indicators to assess energy poverty across member states and develops the Energy Poverty Integral Index (EPII) to quantify it through multidimensional socioeconomic indicators. Building on this, the authors introduce the Energy Poverty and Emissions Index (EPEI), a novel, three-dimensional composite index that integrates (1) energy poverty (via the EPII), (2) residential GHG emissions, and (3) participation in the Covenant of Mayors (CoM), a proxy for local climate policy engagement. By bringing these components together, the EPEI offers a new perspective for examining the intersection of energy deprivation, carbon intensity, and policy responsiveness across the EU. This makes it possible to identify country profiles and policy gaps where high energy poverty coincides with either high emissions or weak climate action. The findings reveal significant correlations between energy poverty and emissions in several EU-27 countries, with strong positive relationships in the Netherlands, Lithuania, and Romania. In contrast, some member states exhibit inverse patterns. Cyprus, Italy, and Germany stand out with the highest energy poverty rates. The study contributes by proposing a standardized framework that links energy poverty to environmental and governance dimensions, supporting more targeted and just climate-energy policy responses in the EU.

## 1. Introduction

Energy poverty, impacting household well-being and social inclusion, lacks a universally accepted definition (European Commission, 2020). It is primarily driven by low income, poor energy efficiency, and high energy prices (Kryk and Guzowska, 2023). Economic shocks, such as energy price crises and the COVID-19 pandemic, further exacerbate the issue (Kryk and Guzowska, 2023). Addressing energy poverty has become increasingly important, given its links to energy security and climate change (Kashour and Jaber, 2024). Historically, one-dimensional indicators, like Boardman's 10 % rule (Boardman, 1991) and the Low Income High Costs (LIHC) index (Hills, 2012), have been used but fail to capture the full multidimensional nature of energy poverty. The European Commission (2020) proposed several indicators, such as heating inadequacy and energy debt, but these only represent isolated parts of the problem. Thomson and Snell (2013) argue that one-dimensional indicators fail to capture the structural aspects of energy poverty. Herrero (2017) also notes that such indicators are insufficient for capturing the full scope of the issue, highlighting the need for multidimensional, synthetic indices (Aristondo and Onaindia, 2018).

Recent indices, such as the Synthetic Multidimensional Energy Poverty Index (SMEPI), integrate multiple indicators to assess energy poverty. These include subjective aspects, like heating difficulties, and objective factors, such as income-based energy expenditure (Kryk and Guzowska, 2023). SMEPI's strength lies in its simplicity and comparability, but it has limitations, such as the lack of regional data and subjectivity (Herrero, 2017). Other approaches, like the Objective Energy Poverty Index (OEPI) and Subjective Energy Poverty Index

(SEPI), distinguish between objective and subjective dimensions of energy poverty. These indices showed weak correlation between the two, leading to differing rankings for EU countries (Wojewódzka-Wiewiórska et al., 2024). The Composite Energy Poverty Index (CEPI) incorporates energy access, availability, and affordability, enabling cross-country comparisons, though it has been criticized for being overly aggregated and not accounting for internal disparities (Khanna et al., 2019). González et al. (2024) also criticize the CEPI for not considering country-specific conditions, such as climate differences and local preferences. The Composite Energy Poverty Index (CEPI), developed by Kashour and Jaber (2024), combines economic and social factors to rank EU countries based on energy poverty, with higher values indicating worse energy conditions. Tovar Reaños et al. (2025) applied a new approach combining a multidimensional index and factor analysis to measure both the extent and intensity of energy poverty, highlighting that both the prevalence and severity of energy poverty should be considered for more effective policy targeting.

The reviewed indices highlight that measuring energy poverty cannot be reduced to a single dimension; it calls for methods that balance breadth with contextual detail. Yet, despite advances, no standardized tool currently exists that systematically incorporates environmental impacts and policy engagement.

*Table 1. Comparison of Selected Energy Poverty Indices (Source, Dimensions, Aggregation)*

Index Name (Abbreviation)	Dimensions (Examples)	Aggregation Method	Reference
Objective and Subjective EP Index (OEPI, SEPI)	OEPI: objective burdens (energy price, cost-to-income ratio, poverty risk); SEPI: subjective deprivations (cold home, debt, poor housing conditions)	Composite indices (calculated separately), equal or alternative weighting	(Wojewódzka-Wiewiórska et al., 2024)
Composite Energy Poverty Index (CEPI)	Access (electricity, clean fuel); Availability (energy supply per capita); Affordability (energy consumption per capita)	Two-step aggregation: weighted average of dimensions → difference from reference country	(Khanna et al., 2019)
Multidimensional Energy Poverty Index (MEPI)	Access to modern energy (electricity, clean cooking); multiple deprivations	Alkire–Foster method (double threshold): headcount (H) × intensity (A)	(Nussbaumer et al., 2012)
Synthetic Multidimensional EP Index (SMEPI)	Affordability and housing: e.g., heating difficulties, energy debt, income-based energy expenditure, low consumption, energy use per capita	Standardized indicators with equal weighting	(Kryk and Guzowska, 2023)
Low Income High Costs (LIHC) indicator	Income and energy cost dual criteria (low income + high energy bill)	Threshold-based categorization (energy-poor if both criteria met; depth based on remaining income)	(Hills, 2012)

Different indices define and measure energy poverty from different perspectives, each with advantages but also disadvantages. Multidimensional indices offer a broader view than single indicators, but interpreting these values is challenging due to subjective decisions in selecting indicators, weights, and normalization methods (Sareen et al., 2020). Most indices focus on social and economic dimensions, ignore the environmental impact of energy consumption, and climate policy efforts. This gap is particularly relevant in the context of the EU's climate policy and the 2050 climate neutrality goal. Balancing energy poverty reduction with decarbonization is crucial, as energy subsidies or price reductions could conflict with climate goals by promoting fossil fuel use, while carbon pricing or a lack of green investments could increase household burdens without adequate social safety nets. No index currently integrates these factors. To address this, the EPEI index was developed, linking energy poverty indicators with greenhouse gas emissions and climate policy engagement, offering a three-dimensional view of energy poverty, ecological footprint, and climate policy responses. This index allows for comparison of EU member states over multiple timeframes, aiding the evaluation of trends across all three dimensions and improving understanding of how climate mitigation actions, like participation in the Covenant of Mayors, interact with energy poverty.

## 2. Materials and methods

To address the data gaps related to energy poverty, it is essential to gather, standardize, and harmonize data across the EU27 based on EU directives and standards. The study focused on the years 2011, 2016, and 2021, as reliable and consistent data were available for these years. Key indicators for the analysis included electricity prices for household consumers, per capita energy consumption, and the proportion of the population unable to provide adequate heating. Electricity prices are crucial for understanding energy affordability, especially for low-income groups. Per capita energy consumption is an important metric for assessing a country's overall energy efficiency and consumption patterns. The proportion of the population unable to heat their homes reflects a key aspect of energy poverty, indicating a failure to meet basic energy needs. After standardizing the data, Euclidean distances for each indicator were calculated, leading to the creation of a dimensionless index representing national-level electricity prices, energy consumption, and heating inadequacy. The procedure for calculating the Energy Poverty Integral Index (EPII) was adapted from Oliinyk et al. (2023).

Eq(1) was used for standardization of initial data with different units and dimensions in order to reduce them to a single metric scale, where:  $Z_{ij}$  is the standardized value of the  $i$ -th indicator of the  $j$ -th EU member state ( $i=1,2,\dots,n$ ;  $j=1,2,\dots,m$ ) in a given year;  $\bar{x}_i$  the arithmetic mean value of the  $i$ -th indicator across all EU member states in a given year;  $\sigma_i$  is the standard deviation value of the  $i$ -th indicator. Both the mean and the standard deviation were calculated separately for each year (2011, 2016, 2021) across all EU member states, ensuring that the EPII reflects relative positions of countries within a given year and allows changes to be tracked over time.

$$Z_{ij} = \frac{x_{ij} - \bar{x}_i}{\sigma_i}, \quad (1)$$

Coordinates of the reference point  $M(M_1, M_2, \dots, M_n)$  were calculated as the maximum values of each indicator among the EU member states.

$$M_i = \max_j(Z_{ij}), \text{ where } i = 1, 2, \dots, n. \quad (2)$$

Eq(3) calculates the Euclidean distance ( $d_j$ ), which shows the distance of the indicators relative to a given reference point.

$$d_j = \sqrt{\sum_{i=1}^n (Z_{ij} - M_i)^2}, j = 1, 2, \dots, m \quad (3)$$

The index of the Energy Poverty Integral Index (EPII) was calculated, which reflects the alternative measure of energy poverty in the EU member state ( $j$ ) with the formula

$$EPII_j = 1 - \frac{d_j}{d_0}, \quad d_0 = \bar{d} + 3s, \quad s = \sqrt{\frac{\sum (d_j - \bar{d})^2}{n-1}}, \quad (4)$$

where:  $EPII_j$  is the representation of the given level of energy poverty in each EU state ( $j = 1, 2, \dots, m$ );  $\bar{d}$  is the arithmetic mean of the corresponding Euclidean distances;  $s$  is the standard deviation of the corresponding Euclidean distances. The index EPII compares the Euclidean distance of the EU state position ( $d_j$ ) in the indicator space from the maximum to that distance ( $d_0$ ), which is considered unusually large, representing a hypothetically ideal state.

The analysis of the primary and secondary data showed a stable yet varied low-energy poverty state between the three selected years. Malta exhibited a negative result during the taxonomic analysis for 2016 and 2021, but due to its negligible level, it was considered as 0 for the continuation of the investigation. The dataset analysis revealed a stable, low-energy poverty state across the examined period with minimal fluctuations. Because the indicators were standardized year by year, the EPII not only compares the relative position of EU member states at a given point in time but also makes it possible to evaluate how these positions shift between 2011, 2016, and 2021. The procedure for calculating the Energy Poverty Integral Index (EPII) ensures that the various dimensions of energy poverty, electricity prices, energy consumption, and heating access are captured and quantified in a way that allows for cross-country comparisons within the EU. Moreover, integrating the Covenant of Mayors initiative into the analysis adds a layer of relevance, as it allows the findings to be contextualized within the broader climate policy framework at the local level.

There is no single indicator system or set of indicators that can universally measure energy poverty across the EU. Therefore, this work proposes the creation of a specific composite index based on selected indicators, providing a unique and systematic method for evaluating and comparing energy poverty across EU member states.

### 3. Results

The average value of the calculated index value was 0.3525 in 2011, 0.3778 in 2016, and 0.4222 in 2021, which represents a low value, but a growth rate was experienced during the period under review, along which can be reduced to a constant increase in the level and risk of energy poverty (Table 1). Between 2011 and 2021, the average change in the energy poverty index (EPII) for EU-27 countries showed a 40.9 % increase. This growth was not consistent throughout the decade. During the first half of the period (2011–2016), the average increase was +20.9 %, while in the second half (2016–2021), the growth slowed significantly to +9.71 %. These trends reflect a deceleration in the pace of changes in energy poverty across member states in the latter half of the examined timeframe. The analysis highlighted notable variations among EU-27 countries. Between 2011 and 2021, Luxembourg (+100.6 %) experienced the most significant growth in energy poverty, with its index more than doubling during this period. Estonia (+82.6 %) and Greece (+64.9 %) followed as the second and third highest increases. Notably, Greece's surge was concentrated in the first half of the period (+60.4 %), while Luxembourg saw its most dramatic rise in the second half (+71.4 %). Estonia maintained steady growth across both intervals, with increases of +36.8 % in 2011–2016 and +33.5 % in 2016–2021.

*Table 2: Results of integral index and Euclidean distance calculation*

State	Euclidean distance: 2011	Euclidean distance: 2016	Euclidean distance: 2021	EPII <sub>j</sub> : 2011	EPII <sub>j</sub> : 2016	EPII <sub>j</sub> : 2021
Belgium	4.77	4.51	4.05	0.3502	0.3734	0.4148
Bulgaria	4.43	3.89	3.67	0.3975	0.4601	0.4699
Czechia	5.06	5.26	4.76	0.3108	0.2699	0.3117
Denmark	5.05	4.83	4.19	0.3131	0.3291	0.3946
Germany	4.58	4.41	3.90	0.3765	0.3873	0.4361
Estonia	6.17	5.62	4.89	0.1604	0.2194	0.2929
Ireland	4.81	4.24	3.68	0.3453	0.4118	0.4682
Greece	4.60	2.89	2.66	0.3733	0.5989	0.6154
Spain	4.04	3.34	1.81	0.4500	0.5357	0.7384
France	5.26	4.80	3.90	0.2832	0.3334	0.4354
Croatia	5.43	4.79	4.62	0.2609	0.3341	0.3315
Italy	3.68	3.25	3.19	0.4986	0.5486	0.5380
Cyprus	2.61	3.28	2.09	0.6453	0.5450	0.6972
Latvia	4.75	4.39	4.37	0.3527	0.3906	0.3681
Lithuania	4.08	3.88	3.55	0.4440	0.4610	0.4866
Luxembourg	6.13	5.81	4.62	0.1654	0.1936	0.3318
Hungary	4.77	5.15	5.10	0.3501	0.2844	0.2619
Malta	3.66	4.59	3.95	0.5022	0.3625	0.4281
Netherlands	5.11	4.94	4.76	0.3045	0.3138	0.3122
Austria	5.33	5.16	4.89	0.2747	0.2830	0.2935
Poland	4.66	4.80	4.49	0.3656	0.3328	0.3503
Portugal	3.02	2.21	2.13	0.5893	0.6932	0.6918
Romania	4.84	4.27	3.60	0.3413	0.4068	0.4789
Slovenia	5.28	4.76	4.44	0.2812	0.3382	0.3578
Slovakia	4.63	4.56	4.06	0.3695	0.3669	0.4126
Finland	6.26	6.16	6.02	0.1472	0.1450	0.1292
Sweden	5.41	5.17	4.48	0.2639	0.2825	0.3517

Several countries, including Hungary, Malta, and Finland, saw significant reductions in energy poverty, with Hungary experiencing the largest decrease of -25.2 % between 2011 and 2021. This decline was sharp in the first half of the period (-18.8 %) and continued at a slower pace in the second half (-7.9 %), driven primarily by targeted energy policies, such as significant price reductions. Hungary's ranking improved from third place in 2011 to 17th in 2016, and to 24th in 2021, demonstrating the impact of national policies, economic conditions, and global events like the COVID-19 pandemic on energy poverty trends. While countries like Luxembourg and Estonia faced rising challenges, Hungary made notable progress in reducing energy poverty. This research introduced the Energy Poverty and Emissions Index (EPEI) to explore the link between energy poverty and greenhouse gas emissions. It found a positive correlation between higher energy poverty levels and increased emissions, driven by higher energy consumption, which leads to greater carbon emissions (Öztürk, 2015). By comparing EPII values with carbon emissions from household activities in EU member states (Figure 1), diverse patterns emerge. For example, Germany, France, Italy, Spain, and Poland emitted over 50 Mt of greenhouse

gases in both 2011 and 2021, despite having an EPII value below 0.5, indicating varying impacts of energy poverty across countries.

The comparative analysis of household greenhouse gas emissions and the calculated values reveals a weak negative correlation compared to the EU-27 average. A strong positive correlation was found in the Netherlands (0.9975), Lithuania (0.9957), and Romania (0.9936), indicating a strong link between energy poverty and residential GHG emissions. Hungary showed a moderately strong negative relationship (-0.8944), while Denmark (-0.9973), Finland (-0.9991), and Poland (-0.9999) exhibited a strong negative correlation, highlighting the lack of a uniform relationship between energy poverty and carbon emissions across the EU.

Further investigation is needed to explore this relationship, as many economic and social factors, such as class disparities, may contribute to these variations. Figure 2 compares the 2021 data on greenhouse gas emissions and the population covered by the Covenant of Mayors.

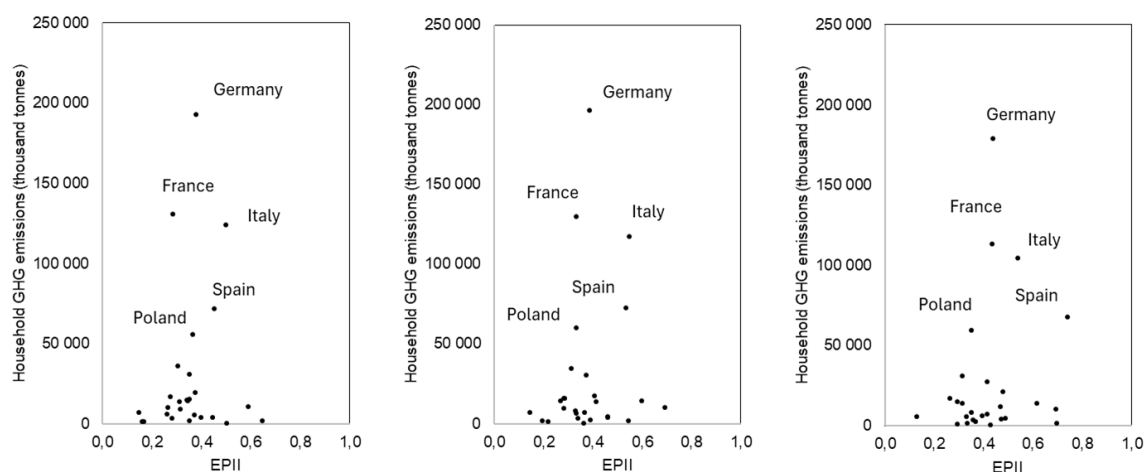


Figure 1: Comparison of calculated energy poverty index values and greenhouse gas emissions (a: 2011, b: 2021) Data from: EUROSTAT, own edited

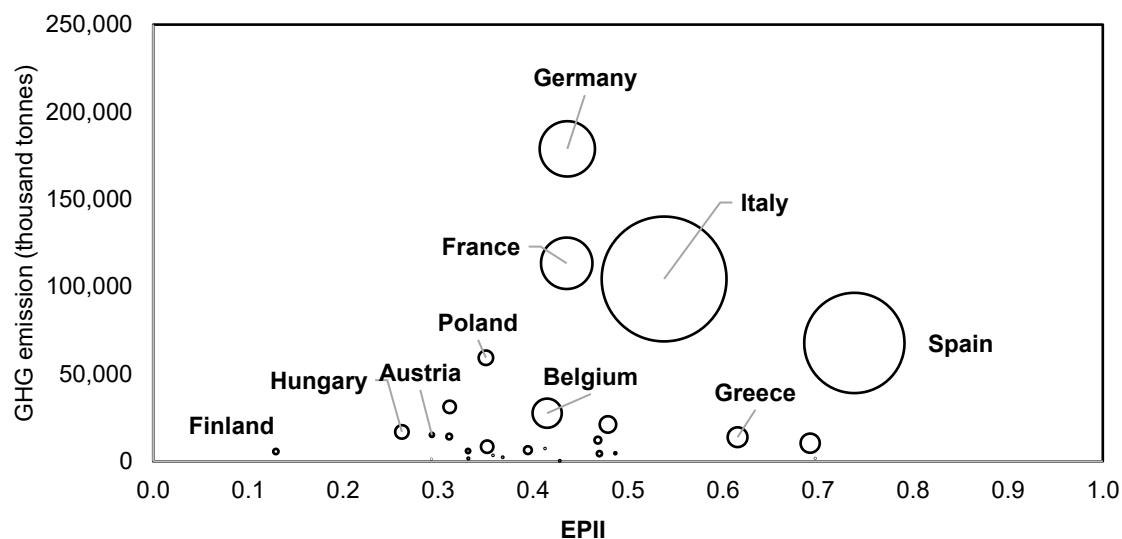


Figure 2: Comparison of calculated energy poverty index values, GHG-emissions and population covered by the Covenant of Mayors. Data from: EUROSTAT, own edited. Note: the size of each circle represents the size of the population covered by the Covenant of Mayors

#### 4. Conclusions

This paper examined the links between energy poverty and greenhouse gas emissions across EU member states. To capture different dimensions of this relationship, we developed the Energy Poverty and Emissions Index (EPEI), which combines three elements: socioeconomic indicators of energy poverty (through the EPII), household-level GHG emissions, and local climate governance, measured by participation in the Covenant of Mayors. The index makes it possible to analyze how energy deprivation, carbon intensity, and institutional engagement interact within the EU context. The results show significant but uneven correlations between energy poverty and emissions, with notable contrasts in countries such as the Netherlands, Lithuania, and Romania. The findings also confirm that energy poverty is a persistent problem, distributed unevenly across member states and aggravated by recent crises, including the COVID-19 pandemic and the energy price shocks. The EPEI framework highlights situations where high levels of energy poverty coincide with both elevated emissions and limited climate engagement, offering a clearer basis for targeted policy action. Future research should examine more closely the relationship between energy poverty and progress toward carbon neutrality, taking into account regional diversity, socioeconomic conditions, the expansion of renewable energy, efficiency improvements, and the impact of external shocks. Interdisciplinary approaches will be needed to design strategies that address both social vulnerability and environmental pressures in an integrated way. Although the present study focused on EU member states, the approach behind the EPII and EPEI could be applied more widely. With appropriate changes to indicator choice, normalization procedures, and the proxies used for local climate policy, these indices could be adapted to non-EU contexts. This opens possibilities for comparative research on energy poverty, emissions, and governance readiness at a global scale, contributing to a better understanding of how just energy transitions can be achieved in different regions.

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