ASSESSING ENERGY POVERTY IN ITALY: AN ENDOGENOUS CUT-OFF DETERMINATION

Gloria Polinesi, Maria Cristina Recchioni, Mariateresa Ciommi, Francesca Mariani, Alfonso Carfora

Abstract. In recent years, the key role of energy in individual well-being has drawn the attention of policymakers, institutions, and researchers to the issue of energy poverty. Energy poverty refers to a situation in which households struggle to access or afford essential energy services. The vulnerability of several households has worsened due to the reduction of disposable incomes resulting from the labor market crisis, escalating unemployment triggered by the COVID-19 pandemic, and the increase in domestic energy demand brought about by the extended periods of lockdown.

The expenditure-based approach defines energy poverty as the inability to afford adequate energy services while keeping expenditures within a reasonable level arbitrarily defined. A commonly used cut-off considers household energy-poor if the ratio between energy expenditure - in heating and electricity consumption - and the total expenditure is greater than 10%.

With the aim of investigating the theoretical foundation of this ratio we implement a stratification approach identifying sub-groups of cut-offs at each iteration by approximating their distribution with a sequence of two-component log-normal mixtures. Thus, different cut-offs are not fixed a priori but rather endogenously by the iterative procedure.

Using data from the Household Budget Survey (HBS) provided by the Italian National Institute of Statistics in the years 2019-2022, the stratification algorithm supports the assessment of the percentage of Italian households in energy poverty highlighting differences pre and post COVID-19.

1. Introduction

Energy poverty has emerged as one of the most pressing challenges of the 21st century, representing a critical intersection between energy security, social equity, and sustainable development. This multifaceted phenomenon affects households across both developing and developed countries, transcending traditional economic boundaries and highlighting the universal nature of energy access efforts in contemporary society.

Energy poverty is broadly defined as the lack of access to affordable, reliable, and adequate energy services essential for human well-being and socio-economic development (Bouzarovski, 2014; Zarghami, 2025). This definition encompasses not only the absolute absence of energy access but also situations where households face disproportionate energy costs relative to their income, inadequate energy services that fail to meet basic needs, or unreliable energy supply that disrupts daily activities and economic opportunities.

In Europe, the proportion of the population unable to adequately heat their homes rose dramatically from 6.9% in 2021 to 10.6% in 2023 (EC, 2025), largely driven by the energy crisis following geopolitical tensions and supply chain disruptions. The Italian context provides a particularly compelling case study for examining energy poverty dynamics in developed economies. By the end of 2023, approximately 2.36 million Italian households - representing 9% of the national population - were experiencing energy poverty conditions, marking one of the highest prevalence rates recorded since the inception of systematic data collection in 1997 (OIPE, 2024).

The complexity of energy poverty extends beyond simple access metrics to encompass multiple dimensions including affordability, reliability, quality, and sustainability of energy services. This multidimensional nature has significant implications for measurement approaches, as traditional single-indicator metrics often fail to capture the full spectrum of energy poverty experiences (Kashour and Jaber, 2024). Given the urgency and complexity of energy poverty, there is a critical need for robust, comprehensive, and context-sensitive measurement approaches that can inform effective policy interventions and track progress toward energy equity goals. Accurate measurement of energy poverty is essential for identifying affected populations, understanding the underlying drivers, evaluating the effectiveness of interventions, and ensuring that energy transition policies do not inadvertently exacerbate existing inequalities.

Energy poverty measurement has evolved through three distinct methodological frameworks, each offering unique perspectives on household energy deprivation. The expenditure-based approach employs quantitative indicators examining the relationship between household energy expenditure and income levels, including the widely-used 10% threshold rule, the Low Income High Cost (LIHC) indicator combining high energy costs with low disposable income (Hills, 2011), and adaptations incorporating vulnerability components (Faiella and Lavecchia, 2015). Recent applications have explored hidden energy poverty across EU countries (Menyh'ert, 2024) and micro-level elasticity relationships between energy prices and poverty status (Bardazzi *et al.*, 2024). The consensus-based approach captures subjective experiences through household surveys, addressing energy poverty's multidimensional nature by incorporating indicators such as heating difficulties, bill payment delays, and perceived energy discomfort. This methodology can adopt either a union approach (considering at least one indicator) or an intersection approach requiring simultaneous deprivation across multiple dimensions, with scholars increasingly favoring multidimensional composite indicators (Marchand, 2019; Simionescu, 2024). The direct measurement approach evaluates energy services against established benchmarks using objective temperature and consumption data (Okushima, 2019), providing empirical evidence while potentially overlooking contextual variations in energy needs (Sy and Mokaddem, 2022). This methodological diversity reflects the scholars' ongoing debates regarding optimal quantification approaches. Expenditure-based methods offer objectivity and income poverty connections but may overlook energy rationing behaviors. Conversely, consensus-based indicators capture multiple deprivation dimensions but can be influenced by demographic and cultural perception biases. This methodological complexity underscores energy poverty's multidimensional nature, situated at the intersection of economic, social, and housing well-being dimensions

This paper addresses this methodological challenge by proposing a novel analytical framework that advances beyond traditional energy poverty measurement approaches. Our research introduces a hybrid methodology that integrates statistical modelling techniques with socioeconomic analysis to overcome the limitations of arbitrary threshold selection that characterizes existing literature.

The core innovation lies in the development of a two-phase analytical process. Initially, we employ advanced statistical procedures to identify natural breakpoints within energy spending patterns, moving away from conventional fixed percentage rules. Subsequently, we incorporate broader household consumption patterns to construct a comprehensive poverty assessment that reflects both energy-specific vulnerabilities and general economic constraints.

This integrated approach represents a methodological advancement in energy poverty research, offering a more empirically grounded and contextually sensitive measurement tool.

2. Methodology

The first step in our approach involves the determination of endogenous cut-off points for energy expenditure. Rather than relying on a fixed threshold - such as the widely used 10% rule - we adopt a data-driven method that accounts for heterogeneity in household spending behavior. Specifically, we implement an iterative stratification procedure based on two-component log-normal mixture models, which allows for the identification of distinct segments within the energy expenditure distribution. These captures underlying subpopulations and provide a theoretically grounded means of determining cut-off values that are internally consistent with the observed data.

In the second stage, we use these endogenously derived thresholds to estimate the incidence of energy poverty. This estimation is conducted in conjunction with information on total household expenditure, focusing on households whose overall consumption falls below 60% of the national median. By combining relative economic constraints with energy expenditure cut-offs, our method offers a nuanced and regionally sensitive measure of energy poverty. This dual-criteria approach ensures that both affordability and social inclusion considerations are reflected in the final energy poverty indicator.

2.1. Determination of the endogenous cut-offs

The recent iterative stratification procedure applied to household incomes by Mariani *et al.* (2022) can be adapted to analyze the left-hand tail distribution of the ratio between energy expenditure and total expenditure (see Polinesi *et al.*, 2025).

Under the assumption that this ratio can be approximated by a univariate log-normal mixture, in the first iteration, the stratification procedure identifies the so-called change point and divides the ratios into two distinct groups: ratios that are smaller than or equal to the change point and ratios that are larger than the change point.

The change point is the threshold where the leftmost component of the mixture dominates the rightmost component to its left and is dominated by it to its right. This indicates that a structural change in the distribution occurs. In each subsequent iteration, the procedure approximates with a lognormal mixture the right group of returns from the previous iteration, appropriately shifted. It identifies the change point associated with this right group and then, it splits this group into two sub-groups.

The procedure stops when it fails to find a new change point or when the new change point is larger than the median of the ratios.

In its first iteration, the procedure identifies the first change point a^1 to split the set of all ratios $\mathcal{S}_n = \{y_1, y_2, \dots, y_n\}$ into two disjoint groups: the left group $\mathcal{K}_1 = \{y \in \mathcal{S}_n \,\wedge\, y \in (0, a^1]\}$, composed of ratios smaller than or equal to the threshold value, and a right group $\mathcal{R}_1 = \mathcal{S}_n \setminus \mathcal{K}_1$, composed of ratios larger than the threshold value.

In the second iteration, the procedure considers the subset $\mathcal{R}_1$, obtained in the first iteration. It identifies a new threshold value $a^2 > a^1$, and splits $\mathcal{R}_1$ into two disjoint groups: the left group $\mathcal{K}_2 = \{y \in \mathcal{S}_n \,\wedge\, y \in (a^1, a^2]\}$ and the right group $\mathcal{R}_2 = \{y \in \mathcal{S}_n \,\wedge\, y \in (a^2, +\infty)\}$. In the k-th iteration, the algorithm proceeds similarly to the first two iterations, by identifying the threshold a^k and dividing the set $\mathcal{R}_{k-1}$ into two groups: $\mathcal{K}_k = \{y \in \mathcal{S}_n \,\wedge\, y \in (a^{k-1}, a^k]\}$ and $\mathcal{R}_k = \{y \in \mathcal{S}_n \,\wedge\, y \in \left(a^k, +\infty\right)\}$.

The vector of unknown parameters for the density functions associated with the two mixture components $\Theta_k = (\pi_k, \mu_{1,k}, \mu_{2,k}, \sigma_{1,k}, \sigma_{2,k})'$ is estimated using the return in the set $\mathcal{R}_{k-1}$ through the expectation maximization (EM) algorithm (see Dempster *et al*., 1977). Note that $\pi_k \in [0,1]$ is the mixing weight representing the a priori probability that the point $x = y - a^{k-1}$, $y \in \mathcal{K}_{k-1}$, for $k = 1,2,\ldots$, belongs to the first component[1]. The change point a^k of the mixture is determined using the following rule:

$$a^k = \min\{y \in \mathcal{R}_{k-1} \wedge \pi_k f_{1,k}(y - a^{k-1}) = (1 - \pi_k) f_{2,k}(y - a^{k-1})\}, \qquad (1)$$

where $f_{1,k}(x)$ and $f_{2,k}(x)$, $x \in \mathbb{R}_+$, are the log-normal densities of parameters $\mu_{1,k}$, $\mu_{2,k}$, $\sigma_{1,k}$, $\sigma_{2,k} \in \mathbb{R}$ associated with the two mixture components. As already specified, at step k the change point represents the smallest point where the leftmost component is equal to the rightmost component.

The change point a^k is the frontier of the two groups $\mathcal{K}_k$ and $\mathcal{R}_k$ at the k-th iteration, and, broadly speaking, a^k divides the sample into two subsamples with non-homogeneous distributions. The procedure stops when a new a^k cannot be determined (i.e., Eq. (1)) does not admit any solution.

2.2. *Estimation of the energy poverty indicator*

In the second stage of the analysis, we estimate energy poverty using a joint condition that reflects both relative spending effort and overall economic constraint. The indicator is defined in terms of two key components of household consumption:

- X, representing energy expenditure, and
- Z, representing all other expenditures.

Specifically, we consider the share of energy expenditure relative to total consumption, $\frac{X}{X+Z}$, and compare it to an endogenously determined threshold, identified as the complement to one of the first change point a^1 (i.e., k=*1*) of the stratification procedure. At the same time, it assesses the household's total expenditure $X + Z$ relative to the national median *m*.

A household is classified as energy poor if it satisfies the double condition:

$$\frac{X}{X+Z} > a^1 \wedge X + Z < m \qquad (2)$$

[1] Hereafter we assume $a^0 = 0$.

This definition captures households that are simultaneously burdened by disproportionately high energy costs and have limited overall spending capacity. By combining these two criteria - excessive energy burden and low total expenditure - the indicator provides a refined, behaviorally informed measure of energy poverty.

Specifically, our indicator accounts for how people adjust their energy consumption in response to their financial constraints, rather than simply assuming that all households have similar energy needs or consumption patterns.

3. Data and results

This study investigates energy poverty of Italian households at regional level by drawing on data from the Household Budget Survey (HBS) conducted by ISTAT over the period 2019-2022. The HBS provides detailed information on household consumption patterns across Italy, capturing changes in both the level and composition of spending. It incorporates key social, economic, and geographic variables, allowing for a detailed analysis of household behavior. The survey plays a central role in producing official estimates of relative and absolute poverty, as well as in calculating inflation indicators based on expenditure categories. By combining consumption data with socio-demographic characteristics, the HBS serves as a vital source for understanding economic conditions and informing both public policy and market strategies.

In this section, we also present the results for the energy poverty indicator defined in Eq. (2), separately for the four years considered. First, following Eq. (1), we compute the endogenous cut-offs at the regional level (Table 1). Then, we illustrate the values of the headcount ratio by highlighting differences between pre and post COVID-19 (Figure 1) and its spatial distribution across regions (Figure 2).

Table 1 shows that the endogenous cut-offs are generally consistent with the ten percent rule (Boardman, 1991). This rule defines a household as being in energy poverty if its energy expenditure exceeds 10% of its income (or total expenditure), where the 10% threshold represents the minimum energy required to achieve a basic level of comfort. However, the endogenous cut-offs derived from Eq. (1) vary both across regions and within the same region, highlighting that policy guidelines should be tailored to the specific characteristics of each area.

Table 1 - *Endogenous cut-offs according with Eq. (1) for each region by year.*

	2019	2020	2021	2022
Piemonte	0.117	0.134	0.12	0.157
Valle d'Aosta	0.106	0.135	0.106	0.123
Lombardia	0.08	0.092	0.086	0.087
Trentino-Alto Adige	0.07	0.094	0.08	0.112
Veneto	0.122	0.094	0.083	0.112
Friuli-Venezia Giulia	0.122	0.08	0.086	0.093
Liguria	0.063	0.078	0.077	0.069
Emilia-Romagna	0.078	0.091	0.086	0.119
Toscana	0.08	0.082	0.082	0.092
Umbria	0.085	0.092	0.10	0.103
Marche	0.093	0.08	0.098	0.119
Lazio	0.092	0.098	0.093	0.103
Abruzzo	0.104	0.111	0.111	0.136
Molise	0.127	0.112	0.098	0.223
Campania	0.089	0.083	0.089	0.102
Puglia	0.102	0.109	0.124	0.116
Basilicata	0.128	0.154	0.095	0.139
Calabria	0.098	0.099	0.121	0.157
Sicilia	0.104	0.10	0.11	0.114
Sardegna	0.135	0.072	0.093	0.109

Figure 1 shows the fraction of households in energy poverty, as defined by Eq. (2). Notably, the Southern regions exhibit higher values. Overall, the share of households in energy poverty has decreased - the national average declined from 11.2% in 2019 to 10.7% in 2022 - highlighting regional disparities before and after the COVID-19 pandemic. This trend is consistent with the estimates presented in the latest energy poverty report for Italy (OIPE, 2024), which indicate that the proportion of energy-poor households fell from 8.5% in 2019 to 7.7% in 2022.

Figure 1 – *Fraction of households in energy poverty according with Eq. (2) for the years 2019 (red circle), 2020 (green circle), 2021 (cyan circle) and 2022 (purple circle). The graph shows the difference between the values of 2022 and those of 2019.*

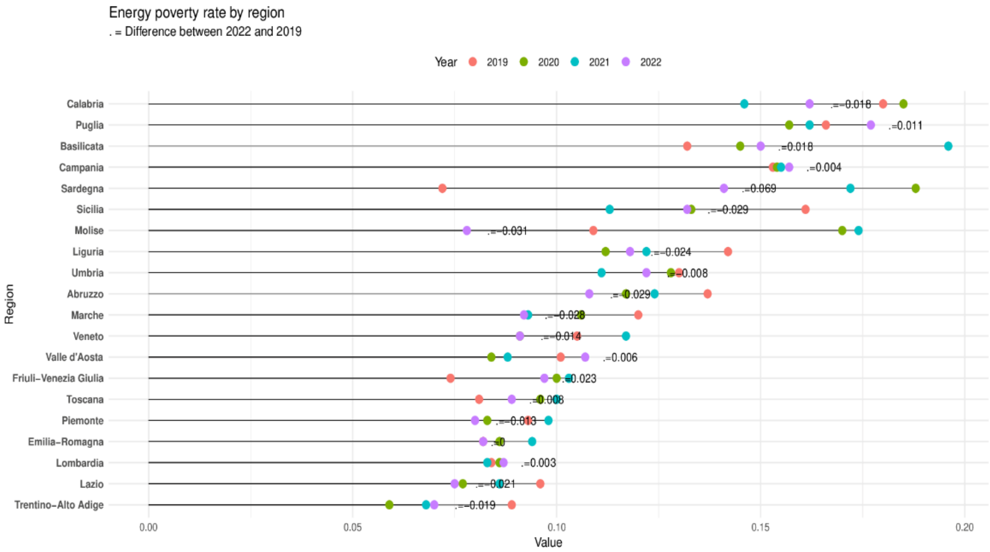
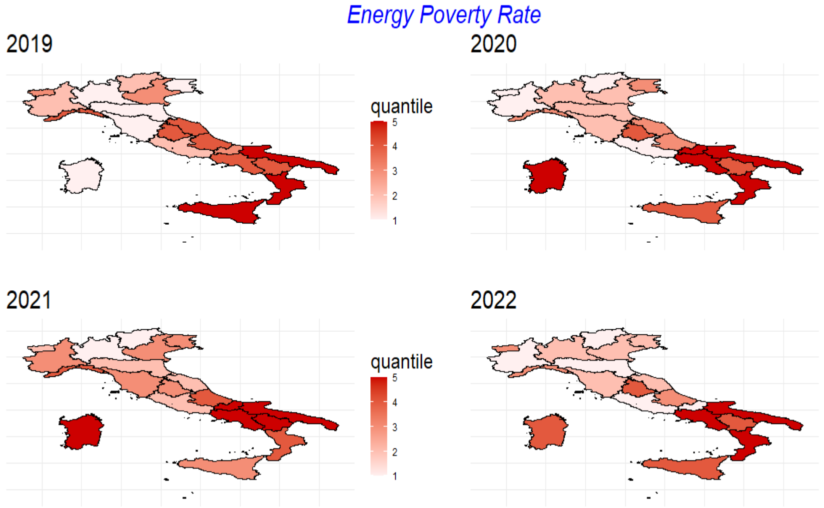


Figure 2 illustrates a geographical representation of how the energy poverty indicator is distributed across the Italian regions over the years 2019-2022. Its values are plotted following a colour scale with darker colours representing higher levels of energy poverty.

A distinct divide between northern and southern regions is evident, supporting the need to develop specific energy poverty reduction strategies for more vulnerable groups. The availability of a local area-level indicator can be a first step towards a national energy poverty dashboard that supports the design of targeted policies to combat energy poverty at the local level (Lavecchia *et al*., 2024).

Figure 2 - *Spatial distribution of households in energy poverty for the years 2019-2022. Darker colours indicate higher level of energy poverty.*



4. Conclusions

Energy poverty continues to represent a significant and persistent social issue, particularly in contexts marked by economic vulnerability and unequal access to resources. Traditional approaches to measuring energy poverty - often based on fixed expenditure thresholds - risk oversimplifying the diverse and complex realities experienced by households.

In response, this study proposes a stratification-based methodology that offers a data-driven alternative to standard benchmarks. By identifying endogenous cut-offs in energy spending behavior, the approach better reflects the heterogeneity in household circumstances and provides more nuanced estimates of energy deprivation.

Our findings reveal that energy poverty levels are consistently higher in Southern Italy, underscoring the need for geographically targeted interventions aimed to reduction strategies.

References

BARDAZZI R., GASTALDI F., IAFRATE F., PANSINI R. V., PAZIENZA, M. G., POLLASTRI C. 2024. Inflation and Distributional Impacts: Have Mitigation

Policies been Successful for Vulnerable and Energy Poor Households? *Energy Policy*, Vol. 188, pp. 114082.
BOARDMAN B. 1991. Fuel Poverty: From Cold Homes to Affordable Warmth. Pinter Pub Limited.
BOUZAROVSKI, S., 2014. Energy Poverty in the European Union: Landscapes of vulnerability, WIREs *Energy Environ*., Vol 3, pp. 276-289.
DEMPSTER AP, LAIRD NM, RUBIN DB. 1977. Maximum Likelihood from Incomplete Data via the EM Algorithm, *Journal of the Royal Statistical Society Series B*, Vol. 39, No. 1, pp. 1-38.
EC-European Commission. 2025. Framing Summer Energy Poverty - Insights and Recommendations for a Resilient Future - *Final Report*, Office of the European Union.
FAIELLA I., LAVECCHIA L. 2015. La Povertà Energetica in Italia, *Politica Economica*, Vol. 31, No. 1, pp. 27-76.
HILLS J. 2011. Fuel poverty: the problem and its measurement. Department for Energy and Climate Change.
KASHOUR M., JABER M. M. 2024. Revisiting Energy Poverty Measurement for the European Union, *Energy Research & Social Science*, Vol. 109, pp. 103420.
KHALID U., SHAFIULLAH M., CHAUDHRY S. M. 2024. Does Conflict Aggravate Energy Poverty? *Energy Policy*, Vol. 194, pp. 114317.
LAVECCHIA L., MINIACI R., VALBONESI P., VENKATESWARAN G. 2024. Energy Poverty Risk: A Spatial Index Based on Energy Efficiency. *Occasional Paper 864*. Banca d'Italia, Roma.
MARCHAND R., GENOVESE A., KOH S.C.L., BRENNAN A. 2019. Examining the Relationship between Energy Poverty and Measures of Deprivation, *Energy Policy*, Vol. 130, pp. 206-217.
MARIANI F., CIOMMI M., CHELLI F.M., RECCHIONI M.C. 2020. An Iterative Approach to Stratification: Poverty at Regional Level in Italy, *Social Indicators Research*, Vol. 31, pp. 1.
MENYH´ERT, B. 2024. Energy poverty in the European Union. The Art of Kaleidoscopic Measurement, *Energy Policy*, Vol. 190, pp. 114160.
POLINESI G., CARFORA A., RECCHIONI M.C., MARIANI F., CIOMMI M. 2025. A New Distributional Based Indicator to Measure Energy Poverty in Italy, *Mimeo*.
OIPE 2024. In FAIELLA I., LAVECCHIA L., MINIACI R., VALBONESI P. (Eds.) La povertà energetica in Italia nel 2022, OIPE.
OKUSHIMA, S. 2019. Understanding Regional Energy Poverty in Japan: A direct Measurement Approach, *Energy and Buildings*, Vol. 193, pp. 174-184.

SIMIONESCU M., CIFUENTES-FAURA J. 2024. Evaluating the Relationship between Income Inequality, Renewable Energy and Energy Poverty in the V4 Countries, *Energy Research & Social Science*, Vol. 115, pp. 103640.

SOTO G., NGHIEM X.-H., MARTINEZ-COBAS X. 2025. Insufficiency of Renewable Energy. How do the Transition to Green Energy Economies and Foreign Direct Investment Affect Energy Poverty in Europe*? Energy*, pp. 135350.

´SMIECH S., KARPINSKA L., BOUZAROVSKI S. 2025. Impact of Energy Transitions on Energy Poverty in the European Union, *Renewable and Sustainable Energy Reviews*, Vol. 211, pp. 115311.

SY S. A., MOKADDEM L. 2022. Energy Poverty in Developing Countries: A Review of the Concept and its Measurements, *Energy Research and Social Science*, Vol. 89.

ZARGHAMI S. A. 2025. The Role of Economic Policies in Achieving Sustainable Development Goal 7: Insights from OECD and European Countries, *Applied Energy*, Vol. 377, pp. 124558.

Gloria POLINESI, Università Politecnica delle Marche, g.polinesi@staff.univpm.it
Maria Cristina RECCHIONI, Università Politecnica delle Marche, m.c.recchioni@univpm.it
Mariateresa CIOMMI, Università Politecnica delle Marche m.ciommi@univpm.it
Francesca MARIANI, Università Politecnica delle Marche, f.mariani@univpm.it
Alfonso CARFORA, Università di Macerata, alfonso.carfora@unimc.it