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REVIEW

Exploring the Complexity of Energy Poverty in the EU: Measure it, Map it, Take Actions

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Abstract
Energy poverty presents a pressing challenge in the European Union (EU), worsened by recent geopolitical events and economic vulnerabilities, particularly highlighted by the COVID-19 crisis. This article explores the complexity of energy poverty within the EU context, emphasizing the necessity to define, measure, and monitor it comprehensively. It reviews the evolution of energy poverty definitions and causes, underlining the multifaceted nature of the issue influenced by factors such as low-income, high-energy prices, and building inefficiencies. Various measurement indexes are examined, and categorized into consensus, expenditure-income comparison, and direct/indirect measurement indicators, offering insights into their advantages and limitations. Furthermore, the work discusses mapping methodologies to pinpoint instances of energy poverty spatially. It also examines best regulatory practices employed by nations, including economic accessibility enhancements and structural interventions like investments in energy efficiency and renewable sources. Finally, the authors propose a novel approach to map energy poverty at municipal granularity in Italy, integrating economic vulnerability and building energy efficiency indices.

Keywords Energy poverty · Energy poverty indicators · European union · Energy efficiency

Introduction

Energy poverty has emerged as an increasingly urgent issue in Europe, especially in recent years after the Covid-19 crisis. Recent political developments – namely, the strong increase in LNG and gas demand and the Russian invasion of Ukraine [1]– have increased economic vulnerabilities among families while leading to significant fluctuations in energy prices, notably for fossil fuels like gas, as well as electricity. Recent data estimates that in 2022, approximately 40 million European citizens across all Member States, accounting for 9.3% of the Union's population, could not heat their homes adequately [2]. This figure marks a sharp increase compared to 2021 when 6.9% of the population faced similar challenges. This increase, due to energy crisis, represents a global trend in 2022 [3].

Consequently, the world is developing initiatives for tackling energy poverty while achieving energy transition. In each case, policies differ due to different needs, for instance in African continent the energy poverty, thus the funding on purpose, relates to access to grid [4]. The European Union is taking steps to establish funds (e.g., the EU Social Climate Fund, established by Regulation EU/2023/955 [5]) to combat energy poverty in Europe and to guide the policies of individual Member States. The concept of energy poverty was first introduced in 2009 in Directive 2009/72/EC [6], where the European Commission emphasized the importance of an energy transition that leaves no one behind, ensuring necessary electricity supply to vulnerable customers and supporting energy efficiency improvements. This concept has been reiterated several times in subsequent years, including in the "Clean Energy for all Europeans package" adopted in 2019 [7] and the "Fit for 55" package in 2021 [8]. A significant contribution to the fight against energy poverty was also made by establishing the Energy Poverty Observatory (EPOV) [9] in 2016, a 40-month project aimed at collecting information on policies and indicators useful to Member

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States for implementation in their legislations. Upon its conclusion in 2021, the project was renamed the Energy Poverty Advisory Hub (EPAH) [10], which offers technical support to States through platforms, online courses, and documentation to effectively implement policies against energy poverty. Thanks to these tools, the EU has gathered not only inspirational cases but also some useful indicators to measure the phenomenon.

Effective policies against energy poverty require a clear framework of "define, measure, and monitor," as emphasized in recommendations published by the European Commission (EC) in 2020 and 2023 [11, 12]. Previous literature review works focused on either of the topics: definition [13] and measurements [14–16]. Instead, the literature lacks a review of monitoring and mapping studies. We believe that a work encompassing all the stages proposed by the EC can be of support to institutions and stakeholders. Here we propose a review on EU definitions of energy poverty, adopted indices, maps of the issue, and finally best practices to cope with the problem. Since EU is on the verge on the topic and hosts a structured system of tools, a review of the activities in EU can create new knowledge that may serve others beyond the EU. Finally, the authors map the economic and energy efficiency-related situation of the Italian territory, to reduce the risk of energy poverty in all municipalities in Italy. This is to give a quantitative example of mapping activities that can help investigating this multifaceted issue.

Definition and causes

Energy poverty manifests differently in various parts of the world, depending on the socio-economic context and regional nuances. In developing nations like in Africa or Asia, the focus lies on the absence of access to essential energy services, such as connection to the electricity grid and/or adoption of modern energy sources for heating or cooking. In developed economies, it is about the inability to afford these services since the availability of such services is not their prime concern [17]. This article concentrates on developed countries, particularly within the EU context, exploring both the causes and indicators of energy poverty.

The phenomenon of energy poverty in Europe has evolved significantly since the 1990s, leading to various definitions. While these definitions are generally similar, they exhibit nuanced differences. Boardman made the initial attempt at a definition in 1991 [18], identifying a family as experiencing energy poverty when they allocate a portion equal to or exceeding 10% of their earnings to maintain an adequate home temperature. This threshold was derived from historical data analysis concerning the English population. However, such a parameter may not be universally applicable across diverse geographical and temporal contexts in Europe [19]. Subsequently, in 2014, Bouzarovski [20] defined it as "The inability of a household to access socially and materially necessitated levels of energy services in the home", and several other definitions and indices have emerged, aiming for a more comprehensive and precise identification of at-risk families. Further details will be presented in the following paragraph. Nevertheless, the issue is multi-layered and intertwined with various factors, including those specific to each country or geographic region. Recognizing this diversity, the EU has adopted a broad definition applicable to all Member States: "People unable to ensure sufficient levels of heating, cooling, and lighting in their homes to maintain a decent standard of living and safeguard their health" [21]. This often leads vulnerable families to voluntarily decrease even drastically their energy consumption to alleviate expenses, significantly impacting the health of its members. This phenomenon is termed hidden energy poverty in the literature [22, 23]. In this case, consumers have low-energy bills, making it more complex to identify them with traditional indicators. Hidden energy poverty in Mediterranean countries could be more probable than in Northern European countries due to the warmer temperatures, making these practices more sustainable [22].

The reasons for energy poverty can be many and this also means that its nature can vary. It can be shown as the inability to access energy (or enough energy), but also as a set of conditions where individuals or households are unable to adequately heat/cool or provide other required energy services in their homes at an affordable price [24]. EPAH ([24, 25]) identifies three main causes of energy poverty:

- low income.
- high energy prices.
- low energy performance of buildings and appliances.

Therefore, in addition to a financially precarious situation, the type of building where people live is crucial, low energy-class buildings impose very high energy expenses to heat them adequately. However, these aspects only constitute the factors that directly influence energy poverty.

Upon closer analysis, indirect factors can also be highlighted, placing certain families at a higher risk. These aspects are of a sociodemographic, geographical, or cultural nature [24, 26]. The geographical area of residence is one of the most important aspects; it can influence both the energy aspect—for instance, living in mountainous areas requires greater energy demand to maintain adequate temperatures—and the economic aspect, considering housing in rural or urban areas. Within the same country, there are often diverse regions that differ significantly, making it challenging to find a single indicator that fits various contexts. EPAH states that the risk of poverty is greater for families that are social aid beneficiaries, social housing tenants, people living in rented homes, people with low levels of education, or ethnic minorities [24]. The composition of the household is also important—single parents, pensioners, families with people with disabilities, or young students in rental apartments. In addition to the above-described vulnerability factors, those related to the building also have an impact, as highlighted by [26], such as the period of construction, materials used, type of dwelling (single-family, small villas, condominium), title of occupancy of the property (rental/ownership), and finally, the type of municipality of residence (metropolitan city, suburbs, municipalities under and over 50,000 inhabitants). All these variables can increase the probability of high energy expenses and/or low income.

Measurement indexes

Energy poverty occurs at the domestic level, which makes it challenging to identify and quantify its diffuse effect properly, and to collect punctual data. The most used indicators are reported by EPOV. The aim is to contribute to a common understanding, but not to finally define energy poverty. They are a suggestion for Member States. Each of the indicators may have advantages and disadvantages and be more or less suitable for a specific context. They can be divided into three different categories: indicators based on the consensus or self-assessment approach, indicators comparing energy expenditure and income, and finally those based on direct or indirect measurements [27]. The most widely used ones are listed below, a complete and more comprehensive table can be found in the EPOV reports [28].

Regarding the consensus indicators they are based on self-reported assessments of indoor housing conditions, and the ability to attain certain necessities relative to the society where a household resides. They are based on EU Survey on Indoor Living Conditions (EU-SILC) [2]. This extensive survey features microdata that are calculated relatively straightforwardly from the share of households responding 'yes'. Some of the questions are for example: "Can your household afford to keep its home adequately warm? In summer? In winter?". This kind of indicator is very straightforward and easy to measure through, but also depends on individual preferences, thus making it subjective (Table 1).

Then there are indicators based on the comparison of energy expenditure and household income with absolute or relative threshold values. The most important indices belonging to this category are the 2M, M/2, and Low Income High Cost (LIHC) index. The first two were reported by the EU [28], and the third is well-established in the literature [25].

The 2M index considers households in energy poverty when the share of energy expenses in total income $\left(\frac{s_{e,i}}{Y_i}\right)$ is more than two times the national average value $\left(2\left(\frac{\sum_{i=1}^{n} s_{e,i}}{\sum_{i=1}^{n} Y_i}\right)\right)$. The energy expenses in this case and also in the following ones are considered the expenses associated with the building and not, for example, mobility expenses. This indicator aims to capture the burden that energy bills put on households relative to their disposable income, using the national median as a reference point. However, it has some limitations: it is unable to identify hidden energy poverty, since it does not consider at risk who reduces their costs living in discomfort (e.g., not keeping its house warm enough) and, on the contrary, it could be misleading in considering energy overconsumption, since it considers at risk every household that spends more than necessary (e.g., keeping very high indoor temperature in winter). In addition to this, the threshold value is relative, which means that it can change over time, for example because of policies or rising energy prices, making the results vary greatly, and the national scale on which this threshold value is measured may not be representative enough for all geographical areas.

The M/2 index, on the other hand, places those households with an absolute value of energy expenditure ($s_{e,i}$) less than half the national median reference value at risk $\left(P50\left(s_{e,i}\right)\right)$. In this case, therefore, the objective is to capture the underconsumption of energy services, thus including the phenomenon of hidden energy poverty, not detected by the 2M index. Even in this case, however, it is possible to identify some cases of 'false positives' or 'false negatives' and

Table 1 2M, M/2 and LIHC index comparison

	2M	M/2	LIHC
Formulation	$\frac{s_{e,i}}{Y_i} > 2\left(\frac{\sum_{i=1}^{n} s_{e,i}}{\sum_{i=1}^{n} Y_i}\right)$	$s_{e,i} < P50(s_{e,i})$	$[s_{e,i} > P50(s_{e,i})]\ U\left(Y_i - s_{e,i}\right) < y^*$
Advantages	Identifies where there is a low building energy efficiency	Considers hidden energy poverty	No false positive cases
Disadvantages	No hidden energy poverty, considers people that consume more than necessary	Considers people with high efficiency and people whose bill is included in the rent	No hidden energy poverty
Reference	[28]	[28]	[25]

depend on a relative value that may vary over time and may not be sufficiently representative because information on the distribution within the country is lost. Some households may have very low or no energy expenses because they are included in the total rent or flat has high thermal efficiency and state-of-the-art appliances. In both cases, the M/2 index would identify them in energy poverty.

LIHC was created in 2011 [25] to overcome some of the limitations of the previous indices, while not solving them completely. It identifies low-income but high-expenditure households; in fact, it requires the fulfilment of two conditions: an energy expenditure above the national median value ($s_{e,i} > P50(s_{e,i})$) and an income net of energy expenditure below a threshold value ($(Y_i - s_{e,i}) < y^*$). This threshold value identifies a household in poverty and is set by Eurostat at 60 percent of the median national equivalised income. Thanks to this indicator, households with high incomes but poor building efficiency or poor behaviour are no longer considered at risk. On the contrary, however, as in the case of 2M, households with hidden energy poverty cannot be identified. To overcome this problem, a more articulated revision of the LIHC index is proposed in [26]. The risk of energy poverty can occur either with the two conditions of the classical LIHC index just seen, or with the occurrence of zero heating expenditure and an equivalent total expenditure below the median threshold. The latter indicator was adopted by Italy as a measure of energy poverty in the National Recovery and Resilience Plan. As can be seen, this type of indicator is more objective than the indices seen above, but not necessarily more accurate or more faithful to reality. It certainly presents more difficulties in collecting data, as not all European countries have databases with a wealth of information on incomes and especially on energy expenditure.

A third category of indicators is based on direct or indirect measurements. The former measure physical variables to determine the adequacy of energy services, e.g. the internal temperature of the dwelling. In this case, however, it is very difficult to determine the exact minimum heat requirement, as it may vary depending on the specific habits of the country or region, making the requirement arbitrary. Indirect indicators, on the other hand, measure energy poverty through related factors such as arrears in bill payments, the number of supply suspensions and the quality of housing (dwellings with leaks, dampness or rotting) [11].

The indices analysed so far are called single indicators [19], to distinguish them from other so-called composite indicators. The latter, recently proposed, are a combination of the former and try to emphasise the multidimensional aspect of energy poverty, for instance, it has been already highlighted that both energy/efficiency and economic reasons can motivate energy poverty [29]. Compared to the former, they are much more complex and so far, there is fewer applications to real contexts. The most recent studies include [30], which combines both energy expenditure data and subjective household data in Greece and [31], which proposes a new energy poverty measure for the EU with the Composite Energy Poverty Index (CEPI). It proposes to combine consensual, energy expenditure and income indicators and direct and indirect measurements into one index. For what concerns identification of hidden energy poverty, composite indicators include an index aimed to overcome both the issues of M/2 index and the revision of LIHC. The proposed index places a household in hidden energy poverty when their energy expenditure is below a fixed threshold, they are in a poverty situation, and they live in a dwelling that is not well-insulated [32]. These studies usually have a regional or national granularity. Yet, a smaller granularity (e.g., the municipality) would be beneficial to consider that energy poverty risk changes widely even in small territories, e.g., in cities and suburbs, or in valleys and elevated mountain locations [33].

As mentioned above, there is probably no suitable indicator for every context and scenario, which is why freedom has been left to each Member State to adopt the one it considers most appropriate. However, it is important to emphasise that the choice of one indicator rather than another has a great influence on the result, as the EPOV Report clearly shows. The European average values, in terms of the percentage of the population in fuel poverty in 2015–2018, in fact range from a minimum value of 6.6% to a maximum of 16.2% [34].

Table 2 below shows the values of various energy poverty indices in European countries, both in absolute and relative terms, creating a hypothetical ranking from the most at-risk country to the least at-risk country. This approach was taken because many indices do not have comparable output values, such as the percentage of the population and absolute index values. It is immediately noticeable how the results change depending on the chosen index, both from the perspective of the individual country and in terms of its relative position compared to other EU countries. For example, analyzing Greece through indices expressed as a percentage of the population reveals that the result varies from 35.6% when considering bill payment delays to 3.8% when considering the LIHC. Similarly, considering the relative position of each country within Europe yields very different results. In the hypothetical ranking, some countries, such as Hungary, Sweden, and Slovakia, can be found both at the top and the bottom of the list depending on the index used.

Mapping the risk of energy poverty

Once the indices for measuring energy poverty are established, a natural next step is their practical application to create a map that not only quantifies energy poverty but also adeptly identifies spatial disparities. This conceptual leap led directly to the initiation of the ENPOR project, funded

Table 2 Comparison of some energy poverty indices among EU countries

	LIHC – Italian NECP version (2010) [35]		2M (2015) [34]		M/2 (2015) [34]		LIHC (2015) [25]		Arrears on utility bills (2018) [34]		Unable to keep home warm (2018) [34]		CEPI (2020) [31]	
COUNTRY	Abs value	#	% pop	#	% pop	#	% pop	#	% pop	Rank	% pop	#	Abs value	#
Austria	-	-	16.0	11	15.0	8	3.0	15	2.4	25	1.6	28	0.238	23
Belgium	0.075	11	13.0	17	9.8	16	3.5	11	4.5	22	5.2	14	0.362	15
Bulgaria	0.157	25	11.5	20	9.4	17	5.8	5	30.1	2	33.7	1	0.642	2
Croatia	0.066	6	12.0	19	7.5	24	4.5	8	17.5	3	7.7	9	0.492	9
Cyprus	0.061	3	12.0	19	13.2	12	2.2	23	12.2	6	21.9	4	0.629	3
Czech Republic	0.064	4	10.8	22	9.2	20	-	-	2.1	27	2.7	22	0.383	14
Denmark	0.065	5	-	-	-	-	3.2	13	5.1	19	3.0	20	0.307	19
Estonia	0.145	23	18.7	5	18.9	5	2.9	17	6.5	15	2.3	24	0.356	16
Finland	0.111	17	22.3	2	29.9	1	2.4	18	7.7	12	1.7	27	0.141	27
France	0.117	18	15.0	13	19.5	4	2.3	20	6.4	16	5.0	16	0.273	22
Germany	0.087	13	17.4	7	17.4	6	3.5	9	3.0	24	2.7	22	0.329	18
Greece	0.094	15	16.3	10	12.8	14	3.8	8	35.6	1	22.7	3	0.655	1
Hungary	0.030	1	9.0	25	9.3	18	7.0	2	11.1	8	6.1	12	0.512	6
Ireland	0.110	16	17.6	6	14.8	9	2.2	21	8.6	10	4.4	18	0.278	21
Italy	0.079	12	-	-	13.6	11	-	-	4.5	22	14.1	6	0.484	10
Latvia	0.075	11	1.7	26	10.7	15	5.8	4	11.6	7	7.5	11	0.409	12
Lithuania	0.155	24	13.9	16	14.4	10	6.4	3	9.2	9	27.9	2	0.502	7
Luxembourg	0.070	8	11.3	21	8.9	22	1.5	21	3.6	23	2.1	26	0.210	25
Malta	0.179	26	20.1	3	16.7	7	-	-	6.9	14	7.6	10	0.297	20
Netherlands	-	-	10.7	23	4.4	26	2.5	15	1.5	28	2.2	25	0.142	26
Poland	0.090	13	16.3	10	19.5	4	6.2	4	6.3	17	5.1	15	0.440	11
Portugal	0.125	6	15.1	12	6.8	25	3.1	12	4.5	22	19.4	5	0.572	4
Romania	0.122	7	16.9	8	1.8	27	6.4	3	14.4	4	9.6	7	0.549	5
Slovakia	0.059	25	9.3	24	7.9	23	7.3	1	7.9	11	4.8	17	0.355	17
Slovenia	0.069	20	13.9	16	8.9	22	4.7	6	12.5	5	3.3	19	0.385	13
Spain	0.119	8	14.2	14	13.0	13	2.3	19	7.2	13	9.1	8	0.493	8
Sweden	0.074	18	28.7	1	24.3	2	2.3	17	2.2	26	2.3	24	0.225	24
UK	0.139	5	18.8	4	9.2	20	-	-	5.4	18	5.4	13	-	-

by the EU Horizon 2020 research initiative. Through this initiative, the "Energy Poverty Dashboard" was conceived. It is a tool designed to spatially pinpoint instances of energy poverty in the private rented sector across Europe. This dashboard serves as a valuable resource for NGOs, civil society, and governing bodies, offering comprehensive information on energy-poor populations, best practices, policies addressing the issue, and a visual representation of ongoing projects in areas of critical need [36]. The dashboard itself is a dynamic, interactive map of Europe, enabling users to observe and compare differences between countries through the previously mentioned indices and track their evolution over time. The indices used include inability to keep home warm, arrears on utility bills, poverty risk, 2M, M/2 and LIHC. Similar to this approach, also [31] produced a map of Europe using the CEPI index, previously mentioned.

While both examples effectively map energy poverty at the State level, facilitating cross-country comparisons, they exhibit limitations in offering nuanced insights into specific critical situations within individual countries. Recognizing this, several countries have established their own energy poverty observatories [34]. These observatories aim to identify and measure the phenomenon within their territories. Italy, for example, has set up the Osservatorio Italiano della Povertà Energetica (OIPE), publishing an annual report on energy poverty and analysing how the phenomenon responds to adopted policies. OIPE adopts the LIHC index in a reviewed version, producing a regional mapping of the Italian territory that offers a macro-level perspective on areas with higher percentages of users in energy poverty [35, 37].

Delving into further detail and increasing granularity, the literature reveals analyses of small territorial segments, primarily focused on cities. In most instances, discussions revolve around municipal or neighbourhood-level maps, drawing on an abundance of data available through detailed local databases. Examples include specific areas in Portugal [38] and the cities of Santiago del Chile [39], Barcelona [40], Bologna [41], and Treviso [42]. In some cases, these analyses have been very helpful to opening the field for interventions by local policymakers in limiting the issue of energy poverty. Only few country maps with municipal granularity have been proposed in literature, yet [43, 44].

These latter studies also show the importance of considering the compresence of multiple factors: for instance, low incomes, harsher climate conditions, energy efficiency lower than average. Energy poverty risk resides where there is simultaneous presence of some (or all) the mentioned conditions. If the research clearly considers the multifaceted nature of energy poverty, do the administrative and regulatory practices to abate it do? Next paragraph will try to address this.

Best regulatory practices

The approach to mitigate energy poverty phenomenon must be comprehensive, employing a multidisciplinary strategy that addresses several facets. One widely adopted strategy by nations involves tackling the problem through enhancing economic accessibility, achieved through measures like tax breaks, social tariffs, energy bonuses, and heating subsidies, coupled with income support initiatives. Countries implementing bonuses for electricity and/or heating include Italy [45], Spain [46], Portugal [47], and the UK [48]. In Spain, since 2022, the "Youth Rental Bonus" has been introduced, providing financial assistance to individuals under 35 with low incomes to support rental payments. Amid the COVID-19 pandemic, some countries chose to suspend disconnections to aid families facing challenges due to sudden energy price hikes, including Austria, Belgium, France, Germany, Greece, Italy, and Ireland [49]. While these interventions offer immediate relief to families, they do not directly impact the marginal cost of energy consumption and lack long-term effects on energy demand. Such measures, crucial in crisis moments, run the risk of fostering dependency on subsidies and fossil fuels, thereby weakening incentives to reduce energy consumption and enhance efficiency. Thus, these measures only consider income/cost as requirements, while they do not act on building performance.

Another type of intervention aims to address the structural causes of energy poverty through investments in energy efficiency, renewable sources, and thermal modernization. These initiatives, while yielding long-term impacts, also empower families to take ownership of their consumption patterns and enhance their overall lifestyles. Widely adopted programs include financial support for building efficiency, such as France's "MaPrimeRenov"[50], and Greece's "Energy Upgrade of Buildings" [51]. Commonly seen are also refunds and facilitation mechanisms, like France's "Habiter Mieux Serenite" program [52], offering a 35–50% refund for renovating properties at least 15 years old, or Italy's "Superbonus 110%" for buildings improving their energy efficiency by at least two energy classes [53]. Oppositely with respect to previous set of measures, these ones only focus on energy performance and do not generally consider economic vulnerability of households.

Beyond these general initiatives for the entire population, specific efforts are identifiable for vulnerable families and the improvement of their residences, as in Barcelona [54], or the installation of renewable systems, as in Greece [55]. Additionally, targeted bonuses for low-income families can enable investments in enhancing the thermal comfort of their homes, exemplified by the efficiency voucher in Portugal [56] and the 'Helping Hand' Bonus in France [57]. These measures both consider building efficiency and household economic conditions as a requirement to access the incentive. They are not a tool for planning action on energy poverty at a national level.

The EU recommendation further explores energy communities and self-consumption groups as promising tools for mitigating energy poverty [12]. This solution holds potential for both short and long-term impact. Through energy communities and self-consumption systems, citizens can collectively invest in renewable systems, providing access even to less affluent families and resulting in clean energy access and potential savings on bills through self-consumption or incentives [58]. Notably, the community concept can also elevate awareness among families about energy issues, facilitating access to energy education. Some energy communities have a clear social objective, aiming to alleviate energy poverty, as seen in the example of the energy community in Naples East (Italy), focused on developing a peripheral neighbourhood by supporting investment in systems and providing social assistance [59]. There is a specific interest on energy communities as a tool for mitigating energy poverty. There is also synergy between energy community planning and mapping the energy poverty for planning actions: indeed, maps of distribution power network for energy communities planning have been developed for instance in Italy [60]. Possibly, the same mapping activity could be integrated with an energy poverty risk map. This would identify areas of the network where fostering energy communities could be both compatible with network requirements and helpful to mitigate energy poverty. A possible case study is proposed in next paragraph.

Mapping a country with local granularity: the case study of Italy

In this final section, the authors propose an alternative approach to those analysed in the previous sections, aiming to map a vast territory with fine granularity using public databases. Unlike other studies, the objective was to have a precise view of each municipality without losing the overall perspective of what happens at the regional and provincial levels, using a single data source for the entire territory. Data sources were selected to increase the replicability of the study. Indeed, this kind of information or similar ones are generally diffused by public entities or institutions. The adopted data sources are shown in Table 3.

The idea was developed through the formulation of two indices that assess the two aspects considered most important for energy poverty: the economic sphere and building efficiency. The indices were then applied to the case study at hand, the Italian peninsula, and represented through a map.

The first coefficient (k_{econ}) considers the economic facet of the phenomenon and is formulated as follows:

$$k_{econ,i} = \frac{\%\ taxpayers\ in\ poverty_i * Avg\ provincial\ expenses_i}{Avg\ income\ of\ taxpayers\ in\ poverty_i}$$

The numerator and denominator both hinge on the poverty condition, the percentage of taxpayers in poverty and their average income. The poverty threshold, as defined by Eurostat, stands at 60% of the national equalized disposable income [65]. For Italy, this equates to €10,052 per year per taxpayer in 2022. The final value for each municipality, denoting the number of taxpayers in poverty and their average income, was extracted from the Finance Department of Italy [66]. This quota was then multiplied by the average provincial expenditure for durable goods per capita, available in a public database [67]. In this manner, the resulting indicator captures the cost of living and income ratio, highlighting differences across various territories. For example, in a densely populated city like Milan or Rome, the cost of living and salaries may be high, but just outside the city, the cost-of-living decreases while income remains similar, considering commuters.

The second coefficient evaluates energy efficiency and, consequently, energy bills. This part of the study was more intricate, involving both data retrieval challenges and the complex formulation of the index. Numerous factors, such as climate, building energy efficiency, and energy vector prices, can influence energy bills. The authors opted for the energy performance (EP) indicator, defined as the demand for non-renewable primary energy in kWh/m2/year of the building. This includes all thermal consumption (heating, cooling, hot water, and ventilation). In Italy, every new, renovated, or sold building necessitates an Energy Performance Certificate (EPC or APE in Italian). This certificate utilizes the EP coefficient to assign an energy classification, ranging from A4 (best energy performance) to G (worst energy performance). The EP is then compared to the EP of a reference building ($EP_{gl,nren,rif,standard}$), with identical configuration as the real building but standardized components. This comparison considers factors like the envelope, thermal units, etc., while factoring in the climatic zone associated with the building's location. This information was drawn from statistics in the SIAPE database of ENEA [68] the State research centre on the topic, given the unavailability of raw data. The proportion of buildings constructed before 1991 categorized as "old" and therefore inefficient [69], were considered in the multiplier "$ShareBuildings_{<1991,i}$". The formulation of the energy index, k_{energy}, is provided below:

$$k_{energy,i} = ShareBuildings_{<1991,i} * \left(\frac{EP_{gl,nren}}{EP_{gl,nren,rif,standard}} \right)_i$$

Table 3 Data sources for main input of the study

Data	Source	Notes
Incomes data per municipality	Ministry of economy [61]	This is usually available at a statistical level considering tax declarations
Cost data for durable goods	Private organization observatory [62]	Data related to cost of life can be found in surveys from institutions or other organizations
Building age data	ISTAT, statistical institute of Italy [63]	These data are usually available by statistical institution or land registers
Energy performance data	SIAPE from ENEA, information system on energy performance of buildings [64]	Statistical data on energy performance certificates (EPC) can be available by institutional research centres or land registers

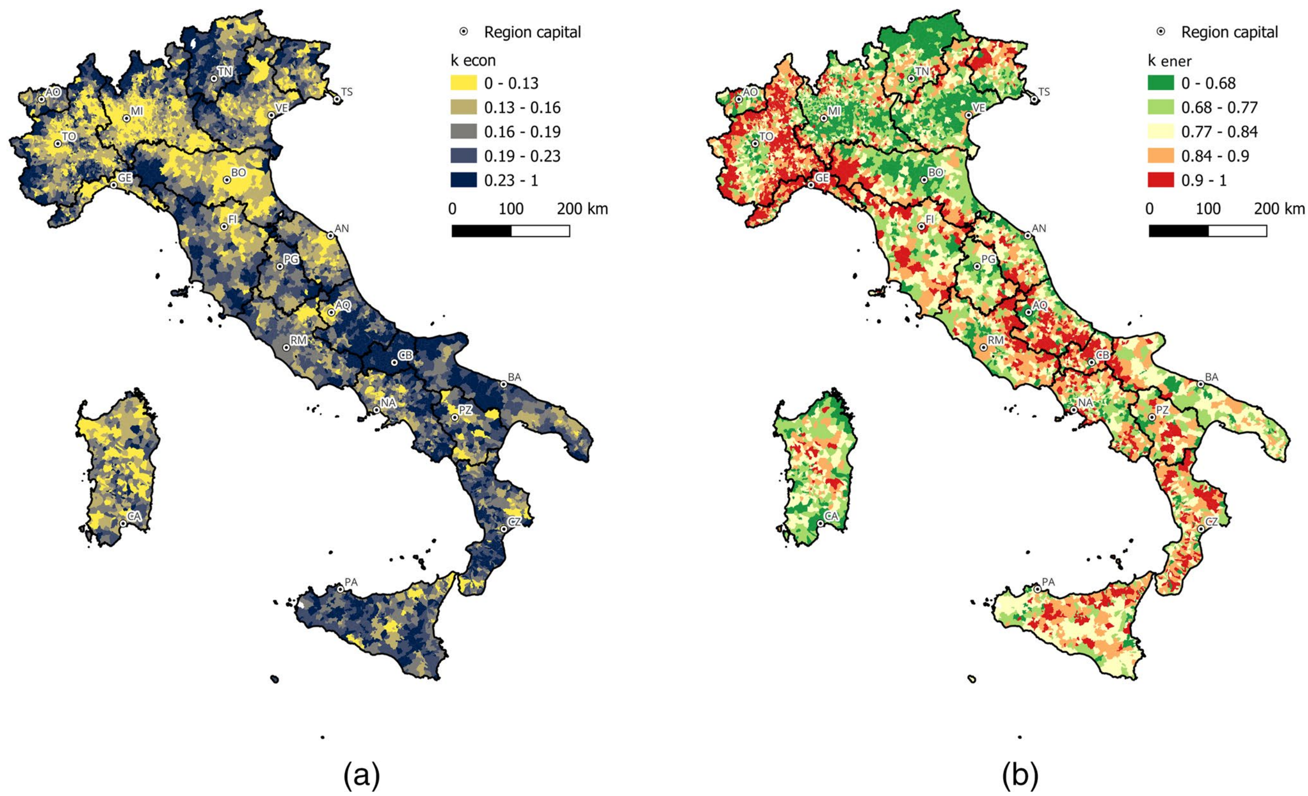

Fig. 1 Economic index (**a**) and Energy efficiency of the buildings index (**b**) for the municipalities in Italy

In Fig. 1, the results of both indices, k_{econ} and k_{energy}, are presented across all 7896 Italian municipalities. For both maps, higher levels show higher vulnerability in terms either of low building efficiency or low incomes/high costs.

Economic vulnerability predominantly concentrates in mountainous regions, as depicted in Fig. 1. Elevated k_{econ} values are noticeable along the Alps (at the northern borders) and the Apennines (extending along the entire Italian peninsula from North to South). Furthermore, the number of municipalities exhibiting affluent economic conditions diminishes from north to south. Pronounced economic vulnerability is evident in the regions of Abruzzo, Molise, northern Puglia, Calabria, and Sicily. Regarding k_{energy}, the northwest region of Italy faces the most substantial penalization in terms of energy performance, particularly in the regions of Piedmont and Liguria. The Apennine areas also register significantly high k_{energy} values. Crucially, k_{energy} incorporates energy performance as relative values compared to the reference building in the geographic area. Consequently, the red zones in Piedmont and Liguria underscore lower building performance relative to the high standard set for northern regions. As per what said before, energy poverty is fostered by the simultaneous presence of multiple factors. We can highlight some areas of particular attention for energy poverty risk since both economic and energy performance coefficient are high:

- Alpine subregions, such as eastern Piedmont, northern Lombardy, eastern Trentino-Alto Adige;
- Apennines' regions, such as eastern Liguria, western Emilia-Romagna, southern Marche, southeastern Abruzzo, eastern Latium, western Molise;
- coastal regions, such as river Po mouth in Emilia-Romagna, southern Sicily, northeastern Calabria, around Sibari plain.
- inner regions, especially diffused in southern Peninsula and Sicily;
- generalized risk situations are present in Abruzzo and Molise regions, where most of the territory shows high indices.

Oppositely, another consistent pattern emerges: the Po Valley area (roughly outlined by an imaginary triangle connecting Milan, Bologna, and Venice) consistently displays low values, indicating both a reduced risk of economic poverty and favourable building conditions.

This study extends on the literature on energy poverty in Italy considering the simultaneous presence of multiple risk factors in the same Municipality. Instead, existing indicators, such as LIHC-PNIEC, were not considering both building and economic aspects [70].

Conclusion

As highlighted in this article, energy poverty is a multifaceted issue. In addition to the economic component, the energy aspect is also at play, particularly linked to fluctuations in energy prices. This dynamic has led many families, even if not classified as economically poor, to be at risk of energy poverty in recent years, having to face burdensome bills. Following the latest geopolitical events, the EU, through the October 2023 Recommendation, urges Member States to address this issue through targeted policies. Unfortunately, not all States have yet adopted a national metric to monitor the problem or established observatories, following the example of the Energy Poverty Observatory (EPOV).

Studies conducted so far have reported measurements of energy poverty on a national scale or with detailed information at the municipal or neighbourhoods' level but limited to small areas. Conversely, it is believed that the creation of a metric based on more detailed data at the regional or national level may be more effective for policymakers. An overview, in fact, allows the identification of different risk levels, enabling the definition of targeted policies and the allocation of funds aimed at mitigating energy poverty. Literature generally presents studies on small portion of the territory, characterized by similar features, or oppositely, national studies with national or regional granularity. This is because finding uniform methodologies over a large territory implies a trade-off, possibly losing accuracy of data or of applicability to specific parts of the analysed regions. The importance of using public, uniform data and indicators on a large part of the territory providing details at the municipal level is anyway becoming more and more recognized [43, 44] and a possible further outcome is shown in the proposed case study on Italy. This map, by accepting the use of public, possibly less accurate data (e.g., data based on surveys or older data), returns in the first place a clear indication of where energy poverty risk is relatively higher and where to prioritize actions.

Additionally, using public and general data increases the replicability of the approach. As shown, adopted data come from institutions generally present in every country (e.g., Ministries, fiscal agencies, national research centres) instead of on specific studies.

It is also crucial to delve into multicriteria metrics, which simultaneously evaluate and combine various aspects of energy poverty. For example, the intersection of economic data with energy-related data, such as energy prices and building efficiency initiatives, can provide a more comprehensive perspective. Main indicators, instead, generally focus on either energy data or economic data. The proposed indicators for Italy can be combined for highlighting simultaneous presence of risk factors related to building performance and low-income/high-cost spots and thus shedding a further light on energy poverty.

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Declarations

Competing Interests The authors declare no competing interests.

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