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Geospatial energy poverty assessment and clustering for policy prioritization

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ABSTRACT

Energy poverty remains a critical challenge, marked by households struggling to access or afford adequate energy services. Previous research focuses on metrics for investigating energy poverty geospatially. Some of these metrics fail in spotting the vulnerabilities, considering average values in a territory. Moreover, the connection between energy poverty assessment and policy proposal is often missing. This paper presents a geospatial analysis of energy poverty in a developed country, focusing on Italian municipalities, using a novel multiparameter indicator to measure both economic and energy vulnerabilities. Building on previous research, the indicator integrates economic indices reflecting income-to-cost ratios and energy indices based on building efficiency and age. It concentrates on the critical tails of the distribution of incomes and buildings, to avoid being misled by mean values. Through clustering, the study identifies municipalities in three categories: highly vulnerable, energy poverty-relevant, and nonvulnerable. Each cluster highlights the socioeconomic and energy challenges faced by households, offering tailored policy recommendations. In particular, the energy poverty-relevant cluster includes 85 % of Italian municipalities and shows a clear correlation between low-performance building share and economic situation of poorer households. The findings suggest the importance of targeted interventions, including direct financial aid for the most vulnerable, energy efficiency incentives for middle-tier municipalities, and nonfinancial measures for better-performing areas (where barriers to energy efficiency could be regulatory, instead of economic). This approach allows policymakers to optimize public expenditures while addressing both immediate and structural drivers of energy poverty.

1. Introduction

Energy poverty is an increasingly urgent issue (European Commission, 2020), (European Commission, 2023), (IEA, 2024). It shows up with differences in various parts of the world, ranging from the difficulty or impossibility of accessing essential energy services in developing countries (Sy and Mokaddem, 2022) to the inability to afford these services in developed ones (Cong et al., 2022a). Focusing on this latter side of the coin, a series of events in the early 2020s (i.e., Covid-19 crisis, increase in LNG demand and Russian war in Ukraine (ACER, 2021)) has dramatically increased energy costs in EU: users unable to keep their homes adequately warm were 30 million (6.9 %) in 2019 and 42 million (10.6 %) in 2023 (European Commission). This has stimulated a reaction from the EU (European Commission, 2020), (European Commission, 2023).

Energy poverty has been extensively studied in scientific literature, with findings indicating that it is influenced by a variety of factors affecting households. The primary factors include low household income, high costs of goods in the local area, regional energy prices, poor energy efficiency of buildings and appliances (EPAH, 2020), and, more recently variables such as the climate policy development of the country experiencing energy poverty (Bouzarovski et al., 2021). In particular, there is not only a nexus between energy inefficiency and energy poverty (Li et al., 2021), but a clear correlation as improvements in energy

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efficiency reduce energy poverty and income inequality[1] (Dong et al., 2022). On the other hand, it is well known that poor households are often unable to afford any energy efficiency investment (Boemi and Papadopoulos, 2019), (Schleich, 2019). The propensity to improve energy equipment or efficiency is higher for middle-class incomes (Cayla et al., 2011).

Various indices have been developed to measure energy poverty, which can be grouped in three main categories: indicators based on the consensus or self-assessment approach, indicators comparing energy expenditure and income, and indicators derived from direct or indirect measurements (Campagna et al., 2024a), (Romero et al., 2018), (Faiella and Lavecchia, 2021), (Balletto et al., 2023), (Eurostat). Direct measurements may include assessing the internal temperature of the home, while indirect measurements can involve identifying households with delayed bill payments. It is important to say that, among the broad range of indicators, multi-variable indexes and those that can rely on public data are particularly valuable. They allow for the consideration of multiple aspects of the problem and are advantageous due to their scalability and applicability to a larger user base. For instance, multi-variable indexes adopted in the literature include: low-income high-cost (LIHC) indices, considering both income and costs of a household; minimum income standard (MIS), comparing the energy costs of a household and their residual income after covering households and other needs; indices considering both economic and energy efficiency situations of a household (Romero et al., 2018), (Campagna et al., 2024b).

In addition to investigating and quantifying energy poverty, research should focus more on correlating poverty and environmental studies with policy measures, to participate in creating effective policies (Primc and Slabe-Erker, 2020). Indeed, correctly targeting poor households with the right policy could be the key to having an impact on energy poverty mitigation (Schleich, 2019). This paper addresses that gap by providing a method for grouping municipalities according to levels of energy poverty, using a multiparameter indicator that captures both economic and energy-related vulnerabilities. This enables differentiated policy targeting tailored to the specific needs of each group. The approach developed here offers a concrete tool for designing and delivering effective policies that address this group while optimizing public expenditures.

1.1. Policies for energy poverty mitigation

Energy poverty is typically addressed by two main categories of policies: social and energy policies (Bollino and Botti, 2017). Social policies concern support schemes for low-income households and include financial aid, which largely relies on public expenditures to cope with short-term emergencies (e.g., energy bill assistance). For example, in France, the 'Chèque Énergie' program provides households with vouchers to pay their bills (Ministère de la Transition écologique and énergie), and in Italy, the 'Bonus Sociale' offers discounts on energy bills (ARERA). Energy policies are typically structured as energy efficiency schemes, implemented through subsidies and tax reductions and/or financing mechanisms that also involve energy system operators (e.g., financial support schemes promoting investments in energy efficiency). For instance, Germany's 'KfW Energy Efficiency Program' provides low-interest loans for energy efficiency renovations (KfW), and Italy's 'Superbonus 110 %' scheme provides tax incentives covering up to 110 % of the costs of energy efficiency renovations (AdE). Energy policies are usually mainly motivated by environmental and decarbonization reasons and therefore can fail to direct support to vulnerable households. Indeed, 'Superbonus 110 %' has stimulated investment in energy upgrades, but it has also faced criticism for favoring higher-income households: they are more likely owners than renters, capable of covering upfront costs before reimbursement, and with a large enough taxable income to benefit from the whole deduction (Roventini, 2021). Oppositely, social policies target vulnerable households, but they can be too costly and may have limited effects in the medium to long term (Primc and Slabe-Erker, 2020). Furthermore, it is worth noting that other non-financial policies, such as energy information and regulatory simplification, can foster the adoption of energy efficiency and sustainability measures even without direct economic subsidy (Daniele et al., 2023), (Economidou et al., 2020). Effective examples of energy information policies are energy efficiency labelling, for instance US' Energy Star Program and EU's Ecolabel (EPA), (EU, 2017). Regulatory simplification can be applied for instance to historical building, to streamline the permitting process while balancing historical value and energy efficiency (Panakaduwa et al., 2024). In addition, collective energy initiatives such as energy communities or cooperative self-consumption schemes can provide additional benefits. These measures lower energy costs for vulnerable households while simultaneously fostering investment in renewable energy and energy efficiency (Campagna et al., 2024b), (Dedović et al., 2024). This approach has also been highlighted in the EU Recommendation 2023/2407 on energy poverty (European Commission, 2023), which emphasizes the role of energy communities in addressing energy vulnerabilities. The results of this study are considered in this context to assess whether and when simplification can be an effective solution for different income categories (Brown et al., 2020).

To design an appropriate support system, an energy-poverty tariff should be based on indicators that can identify energy poverty, take into account the costs of all energy sources (Bouzarovski and Petrova, 2015) (not just electricity), and be available exclusively to vulnerable consumers, to coherently target and optimize public expenditure (Romero et al., 2018).

To help this process, researchers should combine the examination of energy poverty with the proposal of coherent policies. Indeed, effective policy measures differ depending on how much poverty is experienced and what the main causes of households' energy poverty are in each territory (Primc and Slabe-Erker, 2020). An effective policy scheme should prioritize tailor-made actions at the territorial level by considering local specificities and implementing the following principles.

- Optimize public expenditure by conveying social and short-term policies (e.g., support in paying energy bills) exclusively towards the lowest economic quantiles of the population, who are unable to prioritize energy efficiency investments, even if subsidized.
- Exploit the well-known relationship between increased energy efficiency and reduced energy poverty (Dong et al., 2022), by identifying that part of the population that could afford, if subsidized, energy efficiency actions and would benefit from the consequent cost reduction.
- Assess whether complementary measures, such as regulatory simplification can foster adoption of energy efficiency measures in households that do not show economic issues. For instance, this apply to the renovation of historical buildings, that could take advantage of specific rules for an energy renovation compatible with artistic value conservation (EU, 2019), (Christiernsson et al., 2021).

An example of a comprehensive policy agenda encompassing social, energy and non-costly measures is the Spanish strategy for energy poverty mitigation 2019–2024 (Ministerio para la Transiciòn ecològica, 2019). Indeed, it establishes the periodical computation of energy poverty indicators, it implements social bonuses and incentives for refurbishments, it foresees information and communication campaigns for energy/cost awareness of households.

[1] The relation between increased energy performance and decreased income inequality is explained by the fact that energy efficiency interest increases the wages and the occupation of low to middle class workers (Dong et al., 2022). This is a positive externality often disregarded when considering support policies.

1.2. Geospatial studies on energy poverty with fine granularity

This study aims to contribute to energy poverty research by advancing a municipality-based analysis conducted across a national territory (i.e., Italy) (Campagna et al., 2024b), drawing inspiration from methodologies that have been explored in related works. The references considered are regional or country-wide studies where information on energy poverty is provided with local detail. Considering Italy, the "Osservatorio Italiano sulla Povertà Energetica (OIPE)" is an institutional body proposing yearly reports on the risk of energy poverty in Italy. To assess energy poverty, OIPE adopts an updated version of the LIHC index (Faiella and Lavecchia, 2021), thereby directly considering energy costs. Public data of OIPE are on a regional basis, featuring a value of energy poverty risk for each one of the 20 Italian regions. Other studies adopted finer granularity. For instance, study (Mulder et al., 2023) conducted a detailed spatial analysis of energy poverty in the Netherlands, using georeferenced microdata to identify vulnerable households through affordability, energy quality, and participation in the energy transition. Their use of household-level data allowed for high precision but relied on comprehensive national databases, which may not be equally accessible in all countries. Similarly, the Energy Poverty Vulnerability Index proposed by (Gouveia et al., 2019) integrates socioeconomic factors, climate considerations, and building energy performance to map heating and cooling vulnerabilities across Portugal and was later adapted to analyze energy poverty in Switzerland (Pfoster, 2024). Recent investigations have identified clusters of high energy poverty in rural Canada (Riva et al., 2024) which are often associated with older housing, low socioeconomic status, and poor energy efficiency. Similarly, a regional vulnerability analysis in Poland was conducted in (Karpinska et al., 2021), combining household-level energy poverty indicators with district-level socioeconomic and environmental data, highlighting areas where interventions are most needed. This approach relied on a combination of public data and building surveys, but it required extensive regional datasets to assess energy demand gaps accurately. Data availability plays a crucial role in shaping methodologies, as access to detailed microdata or regional datasets varies widely across countries. Consequently, methodologies may need to be adapted to accommodate differences in data availability and granularity.

1.3. Scope and significance of this study

The aim of this paper is to improve an existing geospatial multiparameter energy poverty indicator to make it suitable for providing a clear connection between the indicator's value and the suggested policy for that territory. Thus, the work aspires to bridge the research gap, highlighted in the literature (Primc and Slabe-Erker, 2020), between assessment of energy poverty and proposition of a mitigating energy policy. To achieve this, the proposed energy poverty indicator is used to cluster vulnerable households across municipalities based on their economic conditions (i.e., based on households' income/cost ratio). Then, we assess whether interest in energy efficiency measures as a tool for reducing energy poverty is greater or lower in specific income/cost ranges. Based on these findings, a set of targeted policies is proposed to maximize positive impact across different economic situations, including social policies, energy-poverty mitigation policies and other nonfinancial nudges. The energy poverty indicator can therefore be used by policymakers to prioritize different actions in different municipalities. This approach is demonstrated through a national case study involving Italy and its nearly 8000 municipalities.

The remainder of the paper is structured as follows. Chapter 2 outlines the proposed methodology for the energy poverty indicator. Chapter 3 presents the main results of applying this indicator to Italian municipalities and correlates the indicator with the optimal policy agenda. Chapter 4 draws conclusions.

2. Methodology

The methodology updates a previous study (Campagna et al., 2024b) to find a new ranking and a clustering of municipalities useful for defining tailor-made social and/or energy policies in a territory. According to the literature review, the proposed indicator considers both the economic situation of households and the condition of poverty resulting from the energy costs they face. We target those users (1) who have a low ratio between incomes and costs for durable goods, confronted with (2) the energy performance of their households adopted as a marker of energy-related costs. This is (1) to avoid false positives and (2) to focus on vulnerable users experiencing more significant energy costs. In contrast to the broader, less targeted mapping approach proposed in the previous study (Campagna et al., 2024b), this methodology integrates granular economic and energy indices into a clustering framework. This ensures not only precise identification of vulnerabilities but also actionable, cluster-specific, policy interventions that address both immediate economic burdens and structural inefficiencies.

2.1. Economic and energy indexes

The literature analysis has made it possible to consolidate some variables that most affect the risk of energy poverty for a household: a low income of the household; high expenses for durable goods in the area highlight an area where costs are already generally high for the inhabitants; high energy costs, for example due to old household appliances, a high energy price or low building efficiency; the low efficiency of buildings, as already introduced, is the main cause of an increase in energy costs or the impossibility of having thermal comfort conditions in the home. This often leads vulnerable families to voluntarily decrease their energy consumption drastically to alleviate expenses, significantly impacting the health of household members—a phenomenon termed hidden energy poverty in the literature (Cong et al., 2022b).

We consider within the definition of the indicator:

- low income,
- high costs for durable goods (expenditure stable over time and typical for the territory) and
- low efficiency of buildings.

This is due to many reasons, e.g., the fact that the literature review shows these are among the main reasons for energy poverty and the interest for an indicator based on public data homogeneously available throughout the territory. We develop two composite indices that express the economic and energy efficiency situation of each municipality. The indices are constructed in such a way as to highlight as at greatest risk those situations in which the critical tail of the population is most vulnerable. By critical tail we refer to the lower percentiles of the distribution—those individuals or households far from the average in terms that increase the likelihood of energy poverty, such as poor building efficiency or below-average incomes (see Fig. 1).

The input data and the related public sources are listed in Table 1. These data are publicly available in Italy at the municipal level. The developed energy poverty indices are highly dependent on data available in Italy. Replicating the study in other countries would likely require different datasets, which could lead to the development of alternative indices.

For what concerns the economic index (k_{econ}), it is obtained for each municipality i with the following equation.

$$k_{econ,i} = \frac{tp_i * cdg_i}{ip_i} \quad (1)$$

where for each municipality i, tp_i are the taxpayers in poverty (in %), cdg_i are the average provincial costs for durable goods, ip_i is the average

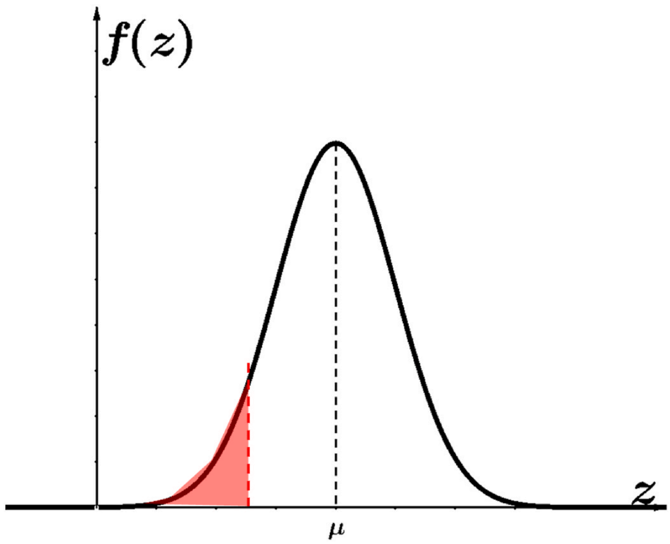

Fig. 1. Exemplification highlighting in red the critical tail in a Gaussian distribution. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Data sources.

Data	Institution	Description	Source
Shapefile Italian municipalities	Istat	Geospatial boundaries and administrative codes for all Italian municipalities	(Istata)
Income distribution	Irpef	Aggregated tax declarations data, including the number of taxpayers by income brackets	(Dipartimento delle Finanze)
Poverty threshold	Eurostat	Relative poverty threshold used to define the low-income population	(Eurostat)
Expenses for durable goods	Findomestic's Observatory	Annual report on average household spending for durable goods, available at the provincial level	Findomestic (2023)
EPCs	Siape – Enea	National EPC database providing average energy performance values by building age class and climate zone	(ENEA)
Building age class	Istat	Census-based statistics on residential building stock distribution by construction period and municipality	(Istatb)

income of taxpayers in poverty. We consider in tp_i those with annual per capita income below the relative poverty line, as defined by Eurostat (10,500 euros in 2021 in Italy) (Eurostat). The index captures financial vulnerability by combining the prevalence of poverty (tp_i), its intensity (ip_i), and local economic pressure (cdg_i). Although cost data are available only at the provincial level, they offer a consistent proxy for territorial differences in living expenses. This formulation highlights municipalities where income fragility is most intensified by high costs of essential goods. Other variables such as housing prices, unemployment rates, debt levels, or social assistance could reflect economic vulnerability, but they are either not uniformly available at the municipal level or are consequences of low income and high living costs. Including them would risk redundancy or a partial view. The selected variables instead offer a direct, scalable, and coherent basis for a practical indicator.

The energy index for each municipality ($k_{ener,i}$) is obtained as below.

$$k_{ener,i} = \sum_{m=1}^{M} q_{\,m,i} * \left(\frac{EP_{gl,nren,m}}{EP_{gl,nren,ref,std}} \right)_i \tag{2}$$

where $q_{m,i}$ is the share of buildings in a certain age class m for the municipality i; $\left(\frac{EP_{gl,nren,m}}{EP_{gl,nren,ref,std}} \right)_i$ is the relative energy performance of a building of the same class with respect to the standard building for that municipality. The standard building is different for each climate zone. M is the number of critical age classes considered. We consider as critical age classes the following three classes: <1945, 1945–1972, 1973–1991>. Buildings from these periods are included because over 80 % of them fall into the lowest three energy performance classes (E, F, G) (Campagna et al., 2024b), indicating poor energy efficiency, after this year the percentage reduces considerably (ENEA). This correlation between construction year and typical energy performance (ENEA) allows us to identify the "critical tail" of the building stock—those most likely to generate high energy costs or inadequate thermal comfort. This structure captures both the prevalence of inefficient buildings and their relative energy demand, offering a proxy for energy-related vulnerability at the municipal level. Other possible variables—such as actual energy expenditure or household energy bills—could, in principle, offer a more direct representation of energy poverty, as done in other indicators. However, these approaches face significant limitations. First, energy bill data is not uniformly available across municipalities or countries. Second, in many cases, energy costs are included in rental agreements, making individual consumption data inaccessible or distorted. Moreover, these indicators may fail to detect hidden energy poverty: households that limit energy use to reduce expenses can appear non-vulnerable, while high consumption may be mistaken for need. They can also be skewed by overconsumption unrelated to actual vulnerability (Campagna et al., 2024a). For these reasons we rely instead on structural factors like building age and relative efficiency, consistently available and strongly correlated with energy needs.

After computing $k_{econ,i}$ and $k_{ener,i}$ for each municipality, they are normalized to have values in the interval [0, 1] where values close to one indicate high risk of economic or energy vulnerabilities. Indeed, the indexes are mainly used to compare with each other instead of in absolute terms.

$$k_{ener,i} = \frac{k_{ener,i} - \min\left(\mathrm{k_{ener,i}}\right)}{\max\left(k_{ener,i}\right) - \min\left(\mathrm{k_{ener,i}}\right)} \tag{3}$$

$$k_{econ,i} = \frac{k_{econ,i} - \min\left(\mathrm{k_{econ,i}}\right)}{\max\left(k_{econ,i}\right) - \min\left(\mathrm{k_{econ,i}}\right)} \tag{4}$$

2.2. Clustering municipalities

To extract the most from the considered indexes, we aim to link the real-world situation of the municipalities in a territory with the corresponding set of applicable policies. Energy poverty affects households differently depending on their economic conditions. We aim to cluster the municipalities in a territory based on economic conditions, exploiting the previously described $k_{ener,i}$ of each municipality. To assess the impact of energy costs for households in different economic conditions, we look for a possible correlation between k_{econ} and k_{ener}. Therefore, we apply a piecewise linear regression (Pilgrim, 2021) to return $k_{ener,i}$ as a function of $k_{econ,i}$ to assess the correlation between these two variables. Piecewise linear regression has already been used in the literature to model the relationship between energy intensity/consumption and economic factors, in studies analyzing both intra- and international data (Liu et al., 2016), (Deichmann et al., 2019), (Liao and Cao, 2018). This methodology receives as input 2-dimensional data (i.e., $k_{ener,i}$ and $k_{econ,i}$ for each municipality) to be linearized and the desired number of segments. It returns the breakpoints of the segments, in the desired number, minimizing the error metrics in approximating the data (i.e., the RMSE). This method is preferred over a simple linear regression as it allows us to capture variations in the relationship across different ranges of economic conditions, which may exhibit non-uniform trends. Furthermore, compared to more complex machine learning models, it provides interpretability and clarity in identifying thresholds and transition points between distinct clusters of municipalities. This choice ensures the analysis remains accessible for policy implications while adequately reflecting the heterogeneity of the data. In particular, as per the previous literature review presented in Chapter 1 and in Section 1.1, we expect three relevant ranges for the economic coefficients and three consequent behaviors.

- For a subset of municipalities (the economically most vulnerable), economic issues are predominant in the critical tail of the population, e.g., those characterized by high costs for durable goods coupled with low incomes. While energy costs are a contributing factor, they do not represent the primary financial burden for these households. These households have insufficient purchasing power to prioritize investments. In this context, social policies (e.g., bill assistance) are likely to be the most appropriate for this group of municipalities.
- For another subset of municipalities (referred to as "energy poverty-relevant municipalities") the critical tail presents economic conditions in a mid-range, always considering both income levels of low-income households and durable goods costs in the area as per k_{econ}. In this range, two situations coexist: energy costs are relevant in the household financial balance, and a portion of households are willing to invest in energy efficiency (Cayla et al., 2011). The critical tail may benefit from support schemes to reach the financial capacity to invest in improving buildings' energy performance, which could enhance economic outcomes in the medium to long term. We consequently assume a possible correlation between k_{econ} and k_{ener} in this range: better building efficiency results in better economic conditions, since it reduces household costs (that are at the numerator of k_{econ})
- Another subset of municipalities (nonvulnerable municipalities) shows better economic conditions even in the tail, for instance given by a smaller share of low-income households and/or below-average durable goods costs. In these cases, low energy performance of buildings could be due to non-economic barriers, e.g., either no interest in energy efficiency or the presence of ancient buildings and regulatory constraints on refurbishment. This subset of municipalities can be further divided into two groups: the first one with good economic conditions but low energy performance of buildings (low-performance nonvulnerable municipalities); the second group with both good economic and energy indexes (on-target nonvulnerable municipalities). The first could benefit from non-financial schemes to improve the overall energy performance of the municipality. The latter one does not need any specific support policy for energy efficiency.

One or more clusters can belong to each of these sets: as better presented in paragraph 3.1, a sensitivity analysis is proposed for the piecewise linear regression used for clustering, varying the segment number. Each segment defines a cluster; one or more segments define a set. Considering each municipality's membership in a specific economic coefficient range, and thus to a cluster, we rank the municipalities in each cluster as per the following rule-based mechanism.

- For clusters with vulnerable municipalities, the rank is based on $k_{econ,i}$. The higher the economic index, the higher priority for intervention in that municipality.
- For the energy poverty-relevant municipalities, the rank is based on an axis with an angular coefficient equal to the one of the linear function $k_{ener} = f(k_{econ})$. The rank is higher for a municipality with a higher level on that axis (see Fig. 2). In this cluster, we specifically look for a correlation between economic and energy-related conditions, to assess the extent of the need for energy poverty mitigation policies.
- For nonvulnerable municipalities, the rank is based on $k_{ener,i}$. Within clusters of nonvulnerable municipalities, policymaking should indeed prioritize (non-costly) actions where there is lower energy performance.

This ranking is used for comparison with literature, and it is attached to the main text.

3. Results

The proposed methodology is applied to Italy, where the total number of municipalities in 2024 is 7896. However, the publicly available data are based on the 2020 data, which includes 7903 municipalities (Presidente della Repubblica, 2000). Therefore, in eqs. (3) and (4), $i = 1, \ldots, 7903$ and 7903 energy and economic coefficients $k_{ener,i}$ and $k_{econ,i}$ are computed. The normalized coefficients,as explained previously (see eqs. (3) and (4)) are presented in the scatter plot in Fig. 3. Fig. 3(a) shows each municipality highlighting three macro-areas of Italy: North (4412 municipalities), South (2253 municipalities), Islands (768 municipalities). The scatter plot shows similar trends, although the northern region shows more scattered behavior in both directions. In particular, the municipalities with a larger economic coefficient (highlighting economic vulnerabilities) are predominantly located in the North, although these are few. Anyway, a large share of municipalities in the northern area has lower economic coefficient than any municipality in the South or Islands group. This indicates typically better economic conditions in the northern zone, with some outliers reflecting both extreme vulnerabilities and very favorable conditions. We see a similar situation for the energy coefficient, with the northern zone showing both the maximum and the minimum values. While the northern and southern groups show energy coefficients close to zero, the islands zone does not present $k_{ener,i}$ lower than 0.2. Furthermore, Fig. 3(a) presents the centroids of the three groups, weighted by the number of taxpayers in each municipality. North zone's centroid shows slightly lower values for both economic and energy coefficient compared to Islands and South groups.

Fig. 3(b) shows a density chart of the scatter plot. Darker shading indicates more values fall within a range of $(k_{econ,i}, k_{ener,i})$.

The density chart shows that most municipalities fall inside a narrow interval of small k_{econ}, between 0.10 and 0.25, and a slightly wider interval of (generally) large k_{ener}, between 0.6 and 0.95. Considering that these are normalized values, they show that most of the municipalities have a similar economic situation for vulnerable households, with few municipalities showing a significantly tougher situation. The opposite for energy efficiency, where few municipalities highlight very good conditions in a general panorama of low performance.

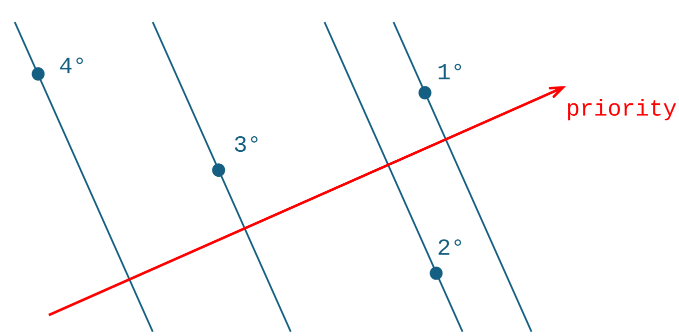

Fig. 2. Ranking criterion for energy-poverty relevant clusters.

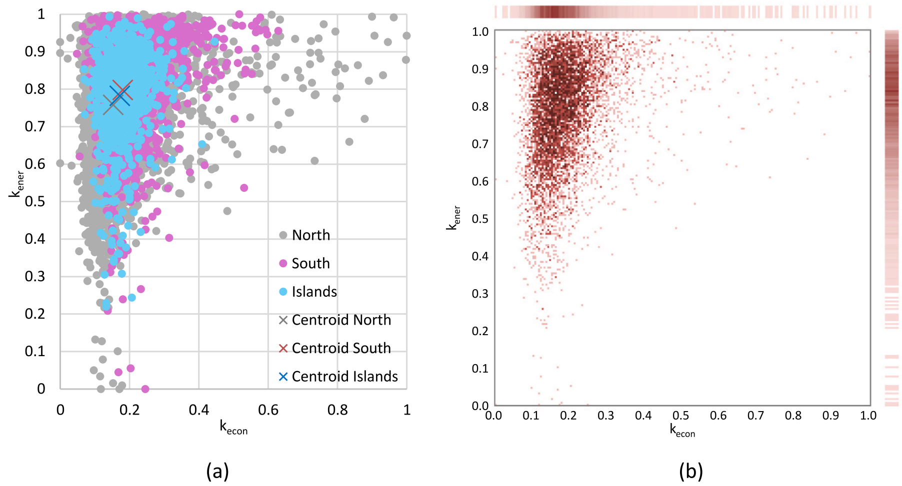

Fig. 3. (a) Scatter plot for economic and energy indices for all Italian municipalities, and (b) density chart of the scatter plot (0.005 bins are considered on both axes).

3.1. Clustering municipalities

To assess possible correlations between $k_{econ,i}$ and $k_{ener,i}$, we apply piecewise linear regression to the data. The linear fitting is performed to return an increasing set of clusters, starting from N = 1. The loop stops when the additional point does not modify the trend. The results are shown in Fig. 4. Input data are the blue dots, the piecewise linearization is in read, with the breakpoints between segments represented as red dots. From subFig. 4(b)–subFig. 4(d) we see a flat segment typically representing the economically most vulnerable cluster. Instead, ascending segments represent the energy-poverty relevant clusters where a clear relation between energy and economic situation is present. Other segments represent the nonvulnerable clusters. Adding a further point (N = 4, subFig. 4(d)) to the 3-segments piecewise linearization (N = 3, subFig. 4(c)) does not significantly modify the outcome: it adds a new breakpoint separating two energy poverty-relevant clusters. Therefore, it can be considered robust. The breakpoints for the four clusters are reported in Table 2. We highlight that the aim of piecewise linearization is not to represent quantitatively the data, but to identify how relevant energy (in)efficiency is as a driver for different economic situations of the vulnerable population.

It is worth noting that none (or few) of the economically most vulnerable municipalities is nonvulnerable energy-wise. Therefore, we sometimes refer to this clusters of municipalities as "most vulnerable" throughout the paper.

Table 2 presents quantitatively the breakpoints previously shown as red dots.

The proposed clustering is based on the range of the economic index only. Different correlations between economic index and energy efficiency index justify the breakpoint positions. The piecewise linearization shows that municipalities with a high economic index (>0.324) hardly show a correlation between economic and energy index. The angular coefficient of the last segment (from breakpoint N to 1) is close to zero from 2-segment cluster on. This indicates municipalities with

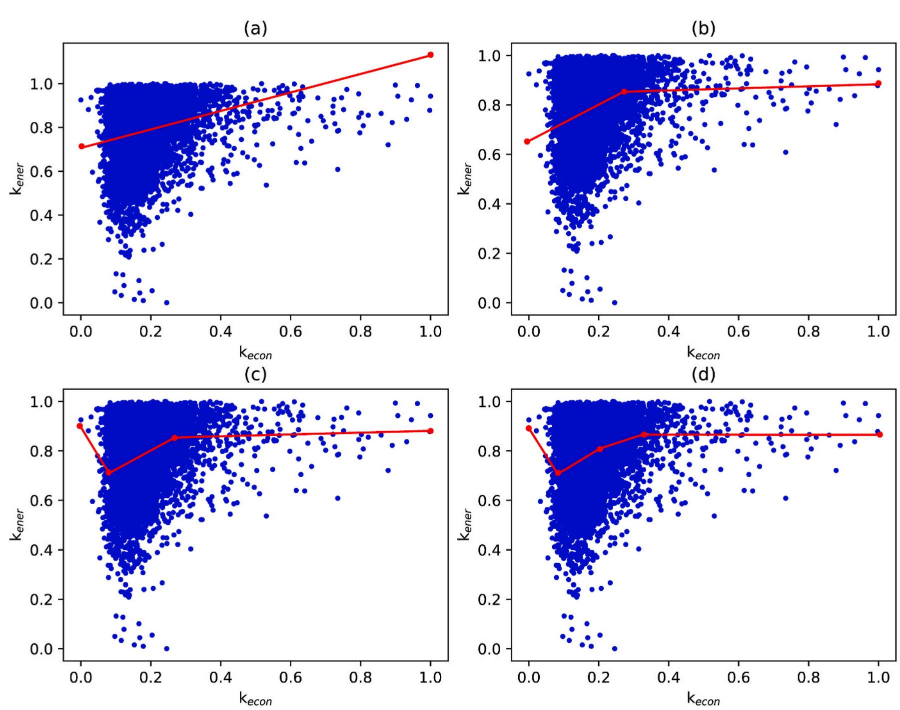

Fig. 4. Piecewise linearization for (a) 1 to (d) 4 segments.

Table 2
Breakpoints location (k_{econ}) for the proposed piecewise linearization.

Clustering	Breakpoint 1	Breakpoint 2	Breakpoint 3	Breakpoint 4	Breakpoint 5
1-segment (N = 1)	0	1			
2-segments (N = 2)	0	0.270	1		
3-segments (N = 3)	0	0.080	0.269	1	
4-segments (N = 4)	0	0.083	0.203	0.324	1

significant economic issues in the vulnerable tail of the population. This cluster does not see an improvement in vulnerable households' energy efficiency conditions correlated with an improvement in economic conditions. This is because energy efficiency is not a priority for the lowest incomes. Moving towards the left in the diagram, we find a cluster with better economic conditions, and with visible correlation between economic and energy conditions: there is direct proportionality between k_{ener} and k_{econ}. In this cluster, the higher energy performance of buildings is generally related to lower economic vulnerability for the population below the relative poverty threshold. This correlation is already explored in the literature and consistent with the definition of energy poverty: higher energy efficiency leads to lower energy costs, in turn improving the economic situation and reducing energy poverty (Dong et al., 2022). This is generally the largest cluster, including 85–90 % of the municipalities (clusters from N = 2 on). For N = 3 and 4, a further cluster appears where energy performance shows inverse proportionality with economic situation. With low economic coefficients (<0.083), energy performance generally decreases with improving economic conditions. This phenomenon is not explained by the literature. The set of municipalities in this cluster is limited (around 120–200 municipalities respectively for N = 3 and N = 4), 1–2 % of total municipalities, mainly belonging to the Northern part of Italy. Additionally, this cluster shows wide variability in k_{ener}, ranging from 0.2 to 1. Therefore, we can state that for municipalities with a good economic situation (even for the vulnerable part of the population) improving energy efficiency is not a clear driver.

The clustered scatter plot for N = 3 is presented in Fig. 5. This is used as the basis for the following discussion. Economically most vulnerable municipalities (red dots) are 813, representing 10 % of Italian ones, differently distributed in North (9 % of the North municipalities belong to this cluster), South (15 %) and Island areas (6 %). Energy poverty-relevant municipalities (yellow) are 6971, accounting for 88 % of all in Italy. These vast majority shows a clear correlation between energy efficiency and socio-economic situation of most fragile citizens. A minor

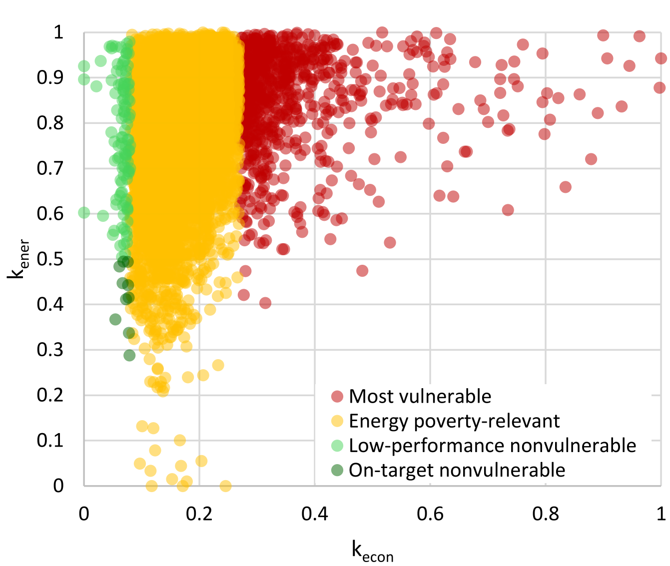

Fig. 5. Italian municipalities' clustering based on N = 3 piecewise linearization.

part of these municipalities (261) already has k_{ener} below 0.5 (high energy efficiency): possibly, the impact of massive energy efficiency investments on these municipalities is reduced. For the remaining municipalities, measures for reducing costs by improving energy efficiency can be effective. Indeed, considering the proposed linearization, a municipality with better energy efficiency has generally lower economic issues. Nonvulnerable municipalities (green) are a minor part (120), corresponding to less than 2 % of Italian ones. We recognize 11 municipalities in Italy "on target" (dark green), with relatively low economic issues for the most critical part of the population and with above median energy efficiency ($k_{econ} < 0.08$ and $k_{ener} < 0.50$). This does not mean that there is no vulnerability in these cities, since individual conditions are not captured by the analysis. Instead, at a general level, these values of coexisting energy and economic coefficient highlight a possible target for other municipalities. These municipalities are presented in a separate subcluster. The rest of nonvulnerable municipalities are "low performance". Most of them are in the North zone (100 out of 109).

In Fig. 6, we provide a map of Italy highlighting municipal clusters. It is apparent that economically most vulnerable cities are mainly located in mountain regions (Alpine Lombardy, Trentino, Piedmont, Emilian Apennines, Abruzzo and Molise Apennines) and inner areas (in Tuscany, in the Po delta, Basilicata and Sicily, and diffusely all over the other regions). Instead, low vulnerability is shown generally in flatlands and in the surroundings of the largest metropolitan cities, particularly in the central-northern regions: see Milan, Bologna, Trieste areas. These areas could benefit from lower costs with respect to the cities, with high shares of commuting to the cities.

As already introduced, the Italian territory was previously analyzed following a similar procedure, based on k_{econ} and k_{ener} arbitrarily combined and weighted (Campagna et al., 2024b). The result of the previous study was a ranking of the Italian municipalities from the most to the least critical. A coherent ranking of priority is developed for the obtained clustering, considering:

- the municipalities in the red cluster as the most critical, ordered by descending k_{econ};
- the municipalities in the yellow cluster as the following ones, ordered as illustrated in Fig. 2 in paragraph 2.2;
- the municipalities in the green cluster as the last ones, ordered by descending k_{ener}.

The newly developed clustering and ranking is considered more suitable for the targets: highlighting where a social or energy policy scheme can improve the (energy) poverty situation of vulnerable households. Indeed, the new ranking gives higher priority to k_{econ}, even when k_{ener} is low (every municipality in the red cluster presents ranking higher than any in the yellow cluster): this choice gives to policymaking a better indication to plan energy-related policies for mitigating economic issues. Indeed, if the household is vulnerable from an economic perspective, a strong policy (e.g., a social policy) is of interest to avoid energy costs (even if low) worsening the already critical household situation. On the other hand, a poorly efficient building that does not represent an issue for the economic situation of the household (belonging to green cluster) can be treated with non-costly policies: obligations, regulatory simplifications, etc. This policy mix could efficiently nudge building improvement in municipalities (or group of

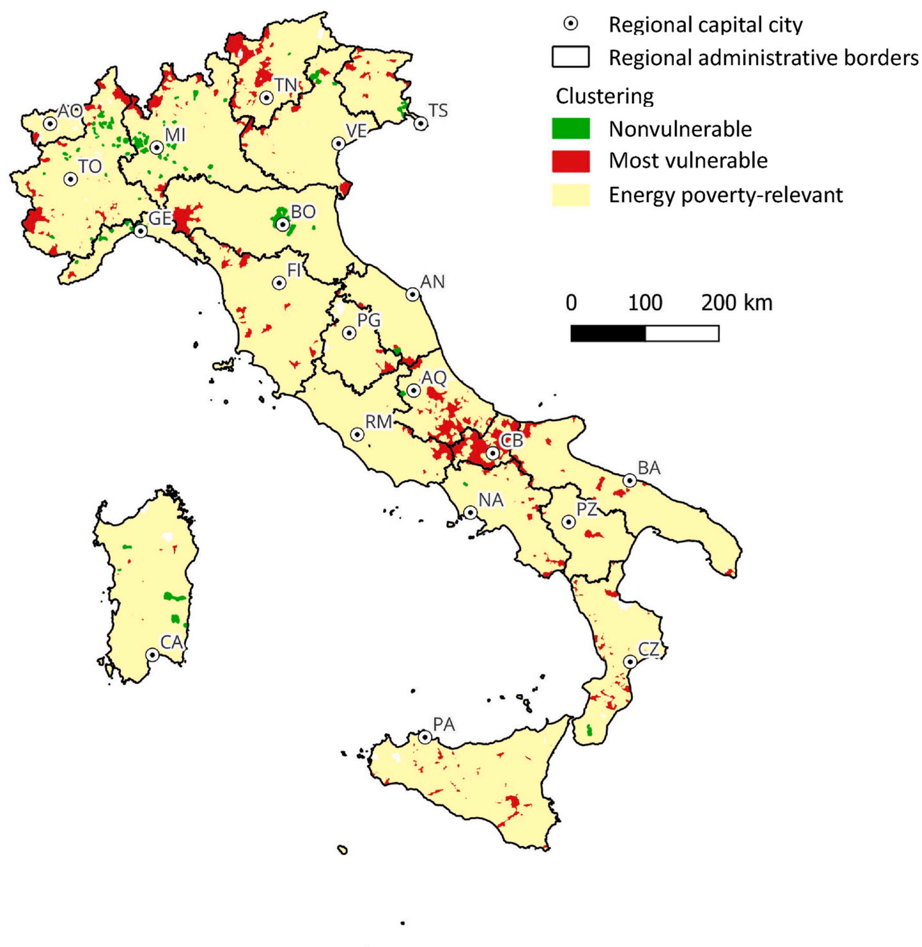

Fig. 6. Italian map showing clusters of municipalities.

households) characterized by much different socioeconomic conditions.

4. Discussion

Findings are compared with existing literature for Italy, adopting the ranking described in paragraph 3.1. As said in the Introduction, OIPE provides yearly report on energy poverty index featuring a regional granularity and considering energy costs, instead of building efficiency (as we do). OIPE results are compared with the average value of municipal coefficients in each region obtained in this study, weighted by population. 5 regions out of 20 show considerable differences between the two analyses, with our study considering lower risk for Basilicata and Sardegna, higher risk for Lazio, Liguria, Toscana. To a certain extent, this could be due to the different role that building efficiency plays in the two studies: a better average efficiency is indeed recorded in Sardegna, while it is worse in Liguria and Lazio compared to neighboring areas. A previous study from Politecnico di Milano (Campagna et al., 2024b) produced a municipal ranking based on similar economic and efficiency indicators. 80 % of municipalities are ranked similarly (with a delta of less than 500 positions out of 8000). Two groups of municipalities present differences: municipalities with above average building efficiency but high economic risk are included in the red cluster, while before they were identified with a low level of risk. Municipalities with very low building efficiency but good economics are now included in the green cluster that proposes non-economic measures. In the previous study, this situation was not considered specifically. These differences are appreciated by the authors, since they increase the application field of this study.

These comparative analyses with literature highlight how this methodology improves the efficiency of social and energy policy mix in two ways. First, it reduces the risk of including overconsuming energy users among the vulnerable users, thus it is better to focus on users with higher energy needs as possibly at risk of energy poverty. This is obtained by considering the building efficiency instead of energy costs. Second, it identifies households with low-energy efficiency and good economic situation and suggests non-costly policies for them.

In doing so, this paper presents a new organic policy agenda for energy poverty mitigation, that is exemplified in the following and in Fig. 7.

In the economically most vulnerable cluster (red), no clear relationship exists between energy efficiency and economics. This suggests that economic issues are mainly caused by other factors not related to energy: e.g., high inoccupancy, high costs for renting or buying houses, low incomes. A targeted policy should ensure that energy costs do not further burden these vulnerable users, providing relief to the critical tail of the population with direct financial measures for an immediate result. These measures include bonuses/discount in the bill, the definition of a special tariff for grid costs and general system charges for vulnerable customers, reducing the VAT on bills. These measures support the movement in a horizontal direction in the scatter plot, towards the left and towards the yellow cluster. These policies have a twofold drawback. On one side, they do not provide a structural reduction of costs in the long run, since no intervention is fostered for the household's envelope or appliances by these measures. On the other side, they are costly. Therefore, this kind of measures (mainly social policies) should be carefully evaluated, dimensioned and reduced or dismissed when

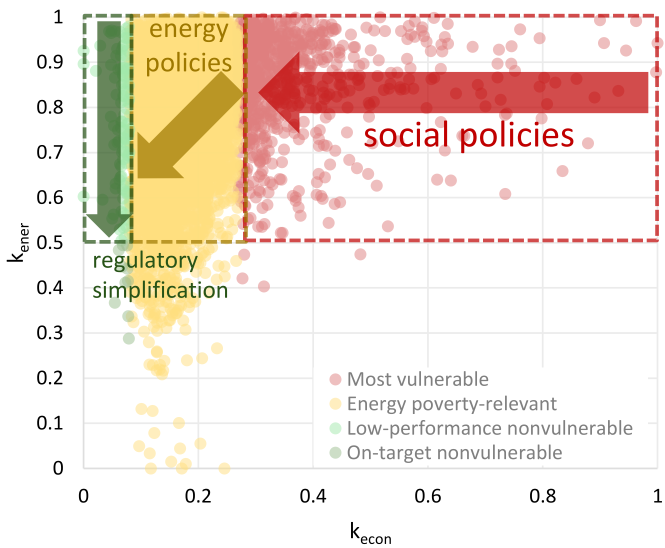

Fig. 7. Policy agenda with tailored mechanisms for each cluster.

possible (Primc and Slabe-Erker, 2020). The red cluster provides an indication on where mainly prioritizing social measures.

In the energy poverty-relevant cluster (yellow), the most populous group, municipalities with higher energy efficiency are generally associated with a better economic situation of critical tails of the population. In the policy agenda, prioritized measures should reduce the burden for families in critical queues by improving structurally the energy efficiency of vulnerable people's homes. Several energy policy schemes stimulate energy efficiency (European Parliament): direct incentives for covering a share (or all) of the investment costs for energy efficiency; tax deductions for money spent for energy efficiency interventions, maybe associated with credit assignment to decrease (even to zero) the financial exposure of the vulnerable households; green loans for guaranteeing low-rate financing for energy efficiency. The proposed measures increase the energy efficiency of the household in a municipality (represented by a downward shift in the scatter plot) and, consequently, reduce the energy expenditure in the long run (indicated by a leftward shift). Therefore, promoting energy policies in this cluster could be an effective strategy.

The nonvulnerable cluster (green) generally shows above-average economic situations, therefore, most of the population does not require strong economic measures, but it could benefit from regulatory simplification or the removal of bureaucratic barriers: measures that allow the downward sliding of the municipalities located in the upper left corner. These are municipalities in which even the critical tail has very low economic coefficient and therefore the low energy efficiency must be traced back to different factors, such as the presence of protected buildings. A coherent framework aimed to simultaneously pursue cultural heritage preservation and environmental targets achievement is the key in these contexts. In case of no strong barriers, the introduction of obligations or high minimum efficiency requirements should be favored, for instance in case of any building renovation. Indeed, from an environmental point of view, there is the highest priority in enabling energy efficiency in economically affluent households.

A lower threshold for the energy efficiency index (e.g., 0.5) could be defined to decrease the priority of intervention for municipalities that already show building energy performance of older buildings significantly above median. See for instance Fig. 7, where the municipalities showing k_{ener} lower than 0.5 are not included in the dashed boxes, indicating that they are possibly not included in the proposed policy schemes.

In general, this study proposes to connect geospatial analysis with policy suggestions. Additionally, proposed clustering technique can be useful for policymaking to better organize action and set local roadmaps for mitigating energy poverty.

4.1. Limitations and recommendations for further research

The limitations of the study include the reliance on Eurostat's relative poverty definitions (Eurostat), which present a single number per country rather than a more comprehensive definition like the Italian institutional one (ISTAT, 2024), more able to represent the complexity of the issue. Therefore, the study can identify the share and average income of citizens below the poverty threshold. This does not allow us to discern between different levels of poverty, that could be fundamental to better address policies. Additionally, the dynamic nature of energy poverty would be better assessed with prompt and yearly updated data, often not available as uniform public data covering the entire territory. As said before, another limitation lies in not considering among the features for the analysis that a relevant part of the population are renters. This reduces the opportunity for investing in energy efficiency with respect to owner-occupied houses.

Future analyses should incorporate summer energy demands, as neglecting cooling needs may underestimate energy vulnerabilities in certain climates. Furthermore, aligning energy poverty mitigation with broader goals such as carbon reduction amplifies the impact of interventions, helping to identify policy synergies.

5. Conclusions

This study assesses energy poverty in 8000 municipalities in Italy and clusters them to propose targeted support and mitigation schemes. The study shows that incorporation of geospatial data regarding building and economic local conditions may enable a more efficient and effective application of specific energy policies to segmented target populations. The clustering for Italy identifies three distinct sets of municipalities that could be involved in three different sets of policies: economically most vulnerable municipalities, where the economic situation of the poorest population segments are the primary interest; energy poverty-relevant municipalities, where improvements in economic conditions appear correlated with energy efficiency; low-performance nonvulnerable municipalities, characterized by widespread inefficiencies in building stock despite favorable economic conditions for lower-income groups.

The study highlights the value of i) integrating geospatial methodologies into energy poverty research, ii) spotlighting the critical tails of the socioeconomic and building efficiency distributions, iii) considering the multifaceted nature of energy poverty developing indicators based on multiple relevant variables, iv) proposing priorities for a tailored policy agenda, rather than including/excluding some parts of the territory from support schemes. The proposed approach ensures that interventions are both equitable, efficient, and effective. The methodology presented can also be adapted to other European countries, provided it is adapted to local data availability and socioeconomic conditions. The use of public and institutional data simplifies the replicability process.

5.1. Policy implications

The proposed clustering approach is useful for the refinement of energy poverty risk assessment and for developing a targeted energy poverty mitigation policy agenda.

For what concerns energy poverty risk assessment, it is shown how, in the considered national case study (i.e., Italy), focusing on building efficiency and on the cost to income ratio of each territory provides valuable results for mapping poverty. We suggest correlating these data for having a better exploration of energy poverty. Additionally, considering building efficiency instead of energy costs can help discerning energy poverty and overconsumption.

Then, we show how a policy agenda should mix social policies, energy policies and non-costly measures. A targeted policy mix is suggested by the distribution of municipalities and by the different relation between economic and energy efficiency situations in each of them. The resulting policy agenda has been exemplified in Fig. 7 and it is below summarized.

- Economically most vulnerable territories require highest priority of actions. Social policies (e.g., bonuses/discounts on the bill, tariff exemptions) should be preferred, since they guarantee effectiveness. Public costs for these policies is high and potentially extended in time, since there is no impact on the causes of high costs.
- Where building and economic situations show larger correlations, energy policies (e.g., discounts for renovation, incentives for low-cost electricity self-production) could be preferred: they feature lower effectiveness in the short-run, higher efficiency, impact in the long-run. While these policies are not relevant for the most vulnerable economic situations (e.g., households without sufficient income), they could instead foster interventions with a structural impact for those who can benefit from tax breaks or deductions. Public costs for energy policies are significant, but they are *una tantum*, considering the structural cost reduction.
- Where socioeconomic situation is better, energy efficiency should be fostered with non-costly action: regulatory simplifications can be suitable for peculiar situations (e.g. in historical households, in areas of natural interest); obligations have generally higher effectiveness. While these policies are not of interest for energy poverty, the environmental benefit is substantial.

CRediT authorship contribution statement

Giuliano Rancilio: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Conceptualization. **Laura Campagna:** Writing – review & editing, Writing – original draft, Software, Methodology, Data curation, Conceptualization. **Mattia Ricci:** Writing – review & editing, Supervision, Investigation, Data curation. **Paolo Sdringola:** Supervision, Formal analysis. **Marco Merlo:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2025.115047.

Data availability

Data will be made available on request.

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