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Prejudices May Be Wrong: Exploring Spatial Patterns of Vulnerability to Energy Poverty in Italian Metropolitan Areas

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Abstract: Energy poverty has impressive negative effects on people's health. Alleviating energy poverty is crucial for a just and equitable transition. However, policies and attempts to reduce energy poverty present a challenge to researchers and policymakers due to its complexity. The lack of a clear definition, of a common set of metrics to assess its multiple dimensions, and of spatially explicit assessments represent serious shortcomings that hinder effective policy design. This paper aims to explore the relevance and spatial distribution of the determinants of vulnerability to energy poverty to support the design of effective responses at different scales. To this end, a principal component (PCA) and a geographically weighted principal component analysis (GWPCA) are conducted on more than 1300 municipalities in 15 Italian metropolitan areas, to identify the spatial patterns of vulnerability to energy poverty and its causes. The PCA highlights three main components of vulnerability to energy poverty in the study areas, respectively, related to the job condition and to individual and households' socioeconomic factors, which provide relevant insights for policies at the national level, The GWPCA provides more detailed information to effectively support policies at the local level. The novelty of this work is the comparison of results from a PCA and a GWPCA of their different contributions to policy design at different scales.

Keywords: vulnerability to energy poverty; spatial analysis; decision-support tool; policy design; sustainable energy transition

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1. Introduction

Energy poverty is generally understood as the inability of a person or household to keep the dwelling adequately warm during the winter or cool during the summer, and to access lighting and electricity to fulfil residential needs [1]. The European Commission has emphasized the need for alleviating energy poverty as a key pillar in the context of a just and fair transition with the Green Deal, and the rise of energy poverty as a policy priority is included within the Clean Energy for all Europeans Package (CEP) [2]. Energy poverty leads to increased risk of electricity shutoffs, a high percentage of income spent in energy bills, and a citizens' inability to maintain comfortable indoor temperatures or use energy-dependent desired services (e.g., air conditioning, heat, computers) [3–5]. Energy poverty has striking negative effects on the health and wellbeing of people [6,7], on top of the relevance of tackling energy poverty in reducing carbon emissions [7,8]. On the health and wellbeing side, it is estimated that, annually, thousands of people die in Europe because of exposure to extreme heat. During 2003 alone, heat stoke caused approximately 30,000–70,000 fatalities in Europe [9], with vulnerable people such as low-income, minority, and elderly populations being disproportionally affected [5,10]. Many of these deaths may have been prevented if people could cool their homes properly and if they could afford air conditioning. Climate change triggers and exacerbates heatwaves [11] and deep freezes, and communities need to adapt to prevent or mitigate their risk of illness and death. Adapting also relies on access to energy, and households' resources for adopting energy-efficient heating and cooling systems, and energy-poor households may need to limit their energy consumption, placing themselves at risk of heatstroke or hypothermia.

For these reasons, policies and programs at national, supranational, and local level are making important attempts to reduce energy poverty. However, despite a wide and shared consensus about the urgency and need to address energy poverty, the design of measures to assess and tackle energy poverty represents a challenge for researchers and policymakers because of its interlinks and potential trade-offs with present decarbonization efforts, as well as Sustainable Development Goals (SDG 7), and health and territorial management. In addition to its complexity, outstanding major gaps are being identified at the EU level when addressing energy poverty reduction. A first gap regards the lack of one single and common definition at EU level about what energy poverty is. For Bouzarowki et al. [12] "Energy poverty can be defined as a condition wherein a household is unable to access energy services at the home up to a socially- and materially necessitated level. As such, it is often considered synonymous with some definitions of 'fuel poverty' although this concept is often used in reference to issues of low energy affordability, rather than the broader problems that predicate inadequate energy access". Filippidou et al. [1] added that "energy poverty is commonly understood as the inability of a person or family to keep their dwelling adequately powered and warm during the winter or cool during the summer". Empirical understanding, thus, considers energy-poor households those that cannot afford to fulfil their residential needs for heating, cooling, lighting, and other energy services. Recent studies analyzing and comparing different definitions among EU Member States [2,12] highlight that "energy poverty is a complex socio-economic problem and designing a concept definition, which represents adequately all its symptoms within the EU territory and accommodates all existing national understandings and interventions has proven particularly challenging" [1].

The lack of a clear definition results in the lack of a common index or set of indicators to successfully identify and assess energy poverty within a territory, which represents a second major gap. Many programs and initiatives identify energy-poor households by measuring complete lack of energy services and/or energy expenditure over total income. These programs make an implicit assumption that people meet or try to meet their energy needs first compared to other necessities like food or healthcare, and they do not consider people who forgo energy consumption to pay for other necessities (i.e., energy-limiting behavior). In this way, they overlook households that limit financial strain by reducing their energy consumption [5]. Implicitly, these programs and policies do not offer a clear definition of energy poverty, and they overlook the multidimensional nature of poverty, ultimately reducing the options for policy intervention [13,14]. Cong et al. [5] highlighted the lack of proper metrics, both in policy applications and in the scientific literature, to identify the multidimensional nature of energy poverty. A potential response to such gap was provided by Robinson et al. [7], who proposed a more holistic approach based on the concepts of equity, justice, and vulnerability: vulnerability to energy poverty. Vulnerability to energy poverty encompasses a wide set of drivers determining energy poverty, covering social and economic aspects. Among the pros of applying the concept of vulnerability to energy poverty, instead of pure "energy poverty", to define indicators is that it allows profiling different groups that are vulnerable to energy poverty due to different sets of drivers. Hence, it enables decisionmakers to design dedicated policies to tackle the diverse nature of vulnerability to energy poverty (for example, job uncertainty, health aspects requiring a high usage of energy compared to the average usage, income, types of house and related energy efficiency, etc.).

A third gap affecting the effectiveness of policy design to address energy poverty relates to the level of disaggregation and spatialization of data. In the last decade, the sociospatial dimension of vulnerability that underpins energy poverty has become a focus in the scientific literature [15–17]. Attention is growing to how vulnerability to energy poverty is "highly geographically variable and locally contingent" [18]. Therefore, and in combination with concepts of spatial justice [19], energy vulnerability framings have opened debates on the extent to which spatial distribution of energy poverty or vulnerability to energy poverty should affect policymaking [20]. Based on different approaches to disaggregation and spatialization of vulnerability to energy poverty data, it is possible to see different household types and geographies, within which energy poverty is likely to manifest, appearing [21,22]. Methodologically, vulnerability indexes have often used principal component analysis (PCA), which enables to identify major drivers of vulnerability among extensive sets of indicators [23]. PCA results can then be transferred to a map to show the variability of vulnerability factors across space, for example, within a country or a region. This responds effectively to a widely recognized gap of existing vulnerability indexes [24,25]. It allows for recognition of how the relative importance of vulnerability factors varies geographically.

Regarding the mapping of vulnerability to energy poverty, recent advancements in spatial statistics methodologies such as geographically weighted PCA (GWPCA) are particularly interesting [26,27] as GWPCA provides an opportunity for PCA-based vulnerability assessments to explicitly account for the spatial relationship among the units of analysis. Robinson et al. [7] demonstrated the potentialities of the method through a neighborhood-level analysis in England that revealed diverse sets of relevant vulnerability factors at the local level. Locally relevant factors do not always correspond to the factors that drive the main differences in vulnerability at the country level; hence, they might be overlooked by policies focused on the latter. Despite relevant implications for energy policy design, combined applications of PCA and GWPCA with the explicit aim of supporting multilevel policy design are still lacking.

The ensemble of these three gaps leads to the consequence that, in the current practice, many people suffering access to proper energy provisioning may not qualify for energy poverty alleviation programs [5].

Hence, looking at the panorama energy policy-related present policies and knowledge, many questions still arise. What are the key factors determining vulnerability to energy poverty? Can we read general trends? And what is the spatial distribution of such factors? Do clusters of vulnerability profiles correspond to specific spatial patterns? Do existing policies capture such complexity and effectively address different forms of vulnerability to energy poverty? An effort in supporting policies with scientifically based methods, which can shed a light on the locally specific factors that determine vulnerability in different areas, is mandatory.

This work aims at exploring the relevance and spatial distribution of factors determining vulnerability to energy poverty at different scales to support the design of effective responses. To do so, we start from the definition of vulnerability to energy poverty by [21,22], which define vulnerability to energy poverty as "the degree of susceptibility to a stress, in this case a lack of socially necessitated energy services, which varies socially and spatially". Such a definition draws on the definition of vulnerability as the "degree of susceptibility to . . . stresses, which is not sufficiently counterbalanced by capacities to resist negative impacts in the medium to long term, and to maintain levels of overall wellbeing" [7]. This study mainly addresses two research questions:

- (RQ1) What key components of vulnerability to energy poverty in Italian metropolitan areas should be considered in national-level policy design? And how does their spatial distribution vary across the country?
- (RQ2) What factors play a role in determining vulnerability to energy poverty the local level, and hence should be considered to design local responses to vulnerability to energy poverty?

We adopted the methodology proposed by Robinson et al. [7] to assess and map the main drivers of vulnerability to energy poverty in 15 Italian metropolitan areas. Section 2 presents the policy context, Section 3 the methods, and Section 4 the results. Finally, "Discussion and conclusions" (Section 5) presents limitations, highlights the policy implications of the findings, and draws some conclusions and the way forward.

2. Case Study: Policy Context and Relevance

Vulnerability to energy poverty can be particularly challenging where climate change and weather extremes hit the most, as it hampers climate resilience and human health. In Europe, the increase in the frequency and intensity of extreme cold, as well as of summer heat waves, is expected, especially in southern countries. Cities present a priority target for action [28], as the fraction of vulnerable subgroups living in urban areas is expected to increase, further increasing the health impact of extreme temperatures [29]. Assessments and decision-support tools focusing on the urban scale to tackle vulnerability to energy poverty can provide a sound basis for reducing the future impacts of climate change in Europe. Overall, while the cold and heat extremes are impacting all over Europe and its cities, a greater heat impact was observed in the Mediterranean cities, suggesting that even in cities where hot temperatures occur frequently and where populations and healthcare providers are more capable of adapting to these conditions, heat can cause a considerable burden in terms of hospital admissions or deaths in the elderly population [1]. Metropolitan areas in Italy, therefore, represent an interesting case study for Mediterranean contexts. Moreover, there is wide variation between and within Italian metropolitan areas in the healthcare system, as well as in the spatial distribution of different vulnerable population groups, and in the capacity of public administration to respond to vulnerability to energy poverty and collated policy needs [28,29].

There is an open debate on how to interpret metropolitan areas, and definitions differ from subject to subject and from context to context. The concept of metropolitan area implies a certain notion of spatial development and hinterland–core relationship, where different territorial development patterns have begun to interact with one another, contributing to the aggregate performance of "polycentric urban regions" [30]. Based on this, in this article, we consider metropolitan areas as a mix of urban and peri-urban areas.

As briefly mentioned above, while the research community is taking steps in addressing the fragility of present energy poverty assessments, advances to enhance the design of effective policies to fight the energy poverty phenomena are not included in the policy design practice yet.

In fact, since 2009, EU energy poverty policies have been officially established by the Third Energy Package with the directives 2009/72/EC [31,32] and 2009/73/EC [33]. Then, with the 2030 Agenda for Sustainable Development and its Sustainable Development Goals (SDGs), which include a dedicated goal on energy, SDG 7—"ensure access to affordable, reliable, sustainable and modern energy for all" [34], the concept became one of the main EU issues. In the last years, the discussion has intensified with the creation in 2019 of a new European observatory on energy poverty (EPOV), but only with the Energy Union and the Winter Package has there been an explicit reference to energy poverty, with a comprehensive strategy developed with three directives ("Electricity", "Energy performance in buildings" and "Energy efficiency"), one regulation ("Governance of the energy union"), and some indications of defining and monitoring energy poverty [35]. Under this framework, Member States have developed integrated national energy and climate plans [36] for the period 2021–2030, thus introducing several energy poverty reduction measures.

The main policies available to contrast energy poverty are (i) economic subsidies, (ii) discount schemes or social tariffs, (iii) social bonuses that limit the impact of the price on bills, and (iv) houses' energy efficiency improvement subsidies, the only measure that fights the problem at the bottom, which represents the main investment promoted by the European Union [37]. In Italy, the "Bonus elettrico" and "Bonus gas" are two schemes introduced in 2009, which provide a discount to the energy bill (due to COVID-19 and the Ukraine war in 2021, the Legislator has intervened several times to reduce the final prices of electricity and gas). Furthermore, the "ecobonus" introduced in 2006 is a tax credit on energy retrofitting that allows the recovery of up to 65% of the investment in

10 years. Recently, the program has been extended ("bonus 110"), allowing the tax credit to be transferred to third parties. Finally, with the PNRR plan, EUR 13.81 billion is dedicated for energetic requalification and seismic adaptation.

However, despite these high-level declarations and policies, there is a stalemate in the fight against energy poverty. In Italy, only in the National Energy Strategy (SEN) of 2017 [32] did the government feel the need to establish an official indicator of energy poverty for measuring how many households are eligible for economic support. This indicates that energy poverty identification and poverty reduction measures are disconnected, hence the difficulty in directing policy efforts where they are more needed, and in monitoring their impacts.

3. Materials and Methods

3.1. Vulnerability Factors and Dataset

Based on the literature [7], we selected fifteen variables linked to vulnerability to energy poverty (Table 1). The variables cover both internal (age, income, heating system) and external factors (climate, housing rights) that contribute to the vulnerability to energy poverty of individuals and households. They are recorded at the municipal level for each of the 1346 municipalities included in the 15 metropolitan areas analyzed. Variables are expressed in relative terms with reference to the total population or the total number of households in each municipality, to allow comparison between spatial units of different sizes.

Table 1. List of variables considered in the analysis, adapted by Robinson et al. [7] All variables are at the municipal level and for the year 2011 (the last available census at the time of analysis).

Indicator	Description	Rationale
Children	Percentage of children (younger than 4 years old)	Dependents and provision of unpaid care; high energy use per capita; lack of financial support for energy bills; under or misrepresented in policymaking; physiological need for energy services; spend large proportion of time at home; large household size; lack of control and choice over daily lives; lack of social relations in/outside home.
Older adults	Percentage of older adults (above 75 years old)	Inability to access appropriate fuel types; less able to benefit from new technologies; dependents and provision of care; high energy use per capita; physiological need for energy services; spend large proportion of time at home; unhealthy warmth-related practices; lack of awareness of support; lack of control and choice over daily lives; reduced autonomy over energy services; lack of social relations in/outside home; living alone.
Un-employed	Percentage of unemployed jobseekers	Reliant on low income; unemployment; inability to invest in energy efficiency.
Home-makers	Percentage of homemakers	Precarious or part-time employment; unemployment; dependents and provision of unpaid care; spend large proportion of time at home; lack of control and choice over daily lives.
Retired	Percentage of retired people	Reliant on state pension; spend large proportion of time at home.
Foreigners	Percentage of foreigners	Reliant on low income; precarious living arrangements; under- or misrepresented in policymaking.
Students	Percentage of students (above 15 years old)	Reliant on low income; inability to switch to cheaper tariff; inability to invest in energy efficiency measures.
Lone-parents	Percentage of single-parent households	Precarious or part-time employment; reliant on a low income; reliant on a single income; dependents and provision of unpaid care; under- or misrepresentation in policy; spend large proportion of time at home; lack of control and choice over daily lives.

Table 1. *Cont.*

Indicator	Description	Rationale
Large households	Percentage of households with 6 or more components	Large household size.
Renting	Percentage of households living in a rented accommodation	Inability to switch to cheaper tariff; limited availability of efficiency measures; inability to invest in energy efficiency; lack of housing rights; precarious living arrangements; unaffordability of owner occupancy; under- or misrepresentation in policy; reduced autonomy over energy services.
Living space	Surface of living space per inhabitant	Potential unaffordability of owner occupancy.
Autonomous	Percentage of accommodations with autonomous heating	Inability to access appropriate fuel types; inefficient energy conversion by appliances.
No heating	Percentage of accommodations with no heating system	Inability to access appropriate fuel types; inability to switch to cheaper tariff.
DD	Degree day	Low outdoor temperature.
Low income	Percentage of taxpayers with income lower than EUR 10,000	Inability to pay/afford energy in needed quantities.

We provide an illustrative application using data for the year 2011, corresponding to the last available census in Italy at the time of the analysis. The census was based on a complete survey of the population, with under-representation rates lower than 2% in all regions. All indicators were collected and made available by the Italian Statistical Office (ISTAT) and were retrieved from the Statistical Atlas of Municipalities (https://asc.istat.it/ASC/) accessed on 23 August 2024, except for the degree days, which are defined by a national decree (DPR412/93).

3.2. Identification of Key Factors Determining Vulnerability to Energy Poverty at the National Level

We investigated the spatial distribution of vulnerability to energy poverty and the most influential factors that affect it at two different scales: the global scale of the whole sample of municipalities included in Italian metropolitan areas (Torino, Genova, Milano, Venezia, Bologna, Firenze, Roma, Napoli, Bari, Reggio Calabria, Palermo, Messina, Catania, Sassari, and Cagliari), and the local scale of each metropolitan area.

At the global scale, we used principal component analysis (PCA) as a dimension-reduction technique [38] to identify the most relevant factors influencing the variability of vulnerability to energy poverty in the analyzed sample. PCA does not account for the spatial relationship between the municipalities, but it provides an overview of the most influential factors, considering the whole sample. Prior to the analysis, we standardized the input data using the mean and standard deviation and we investigated the correlation between the variables.

In the global PCA, we retained components with an eigenvalue larger than 1. Each component is a linear combination of the original variables, as summarized by the loadings of the factors. In principle, loadings range from −1 to +1. A high absolute value of the loading means that the variable contributes greatly to that component. A positive loading means that the component and the variable have the same signs, i.e., positive values of the variable correspond to positive values of the component. A negative loading means that the component and the variable have different signs. By mapping the retained components, we obtain a picture of the spatial patterns of the vulnerability factors that each component represents. Additionally, we calculated the percentage of total variance

(PTV), which describes how much of the total variance in the input data is explained by the retained components.

3.3. Factors Affecting the Variability of Vulnerability to Energy Poverty at the Local Level

Given the overall results of the global PCA, we wanted to explore how the most relevant factors that define the vulnerability to energy poverty vary at the local scale. To this purpose, we conducted a geographically weighted principal components analysis (GWPCA) [39]. GWPCA adopts a moving window weighting approach to run a localized PCA focused on each unit of analysis and its surroundings. The size of the surrounding area to consider (called bandwidth) can be automatically calibrated through a cross-validation approach [39]. We chose a method that selects adaptive bandwidths based on the number of neighbors to include in the analysis. Adaptive bandwidths ensure that enough data are included in each local calibration, and are especially useful when the spatial configuration of the sample is irregular. In the analyzed sample, the distance between neighboring municipalities is highly variable; hence, a fixed distance radius would not have been appropriate. We run the GWPCA separately for each metropolitan area, using the coordinates of the town hall (usually located in the main urban center) to represent the location of each municipality.

GWPCA generates a set of components and loadings for each municipality. Following the approach by Robinson et al. [7], we selected the leading factors of the first components, i.e., the variable that has a greater loading, to reveal what factors have the greatest influence at the local level.

Statistical analysis was carried out in R using the packages factoextra [40] for PCA and GWmodel [41,42] for GWPCA. The maps' final layout was prepared in QGIS.

4. Results

4.1. The Key Components of Vulnerability to Energy Poverty at the National Scale

Figure 1 presents the correlation graph of the 15 factors analyzed considering the entire sample (1346 municipalities included in the Italian metropolitan areas). Blue dots indicate direct correlation, and red dots indicate inverse correlation. The darker the dot, the stronger the correlation. Strong positive correlations emerge, as could be expected, between the share of older adults and the percentage of retired people, as well as between share of housing units with no heating system, share of people with low income, and unemployment rates. Percentage of retired people and living surface per inhabitant are also positively correlated, as are unemployment rate and the share of homemakers.

Three components were retained from the PCA analysis (Figure 2), which together explain 60.1% of the variance observed in the dataset. The first component, explaining 29.7% of the variance, highlights the relevance of factors related to employment, such as the percentage of the unemployed jobseekers, the percentage of homemakers, and the percentage of the student population (>15 years old), all with a positive loading on the component (blue dots). On the other hand, the percentage of retired population and correlated factors such as the surface of living space per inhabitant all have a negative loading on the component (red dots). Component one also highlights the relevance of factors such as climate (degree days, with a strong negative loading) and the percentage of households with six or more members (positive loading).

The second component, explaining an additional 15.9% of the variance, marks the relevance of demographic and economic factors at the individual level. The factors with the greatest positive loading on the second component are the percentage of population under 4 years old, the percentage of foreign population, and the percentage of dwellings with autonomous heating. The percentage of the elderly population, the percentage of dwellings without heating, and the percentage of taxpayers with an income up to EUR 10,000 have a negative loading on the component.

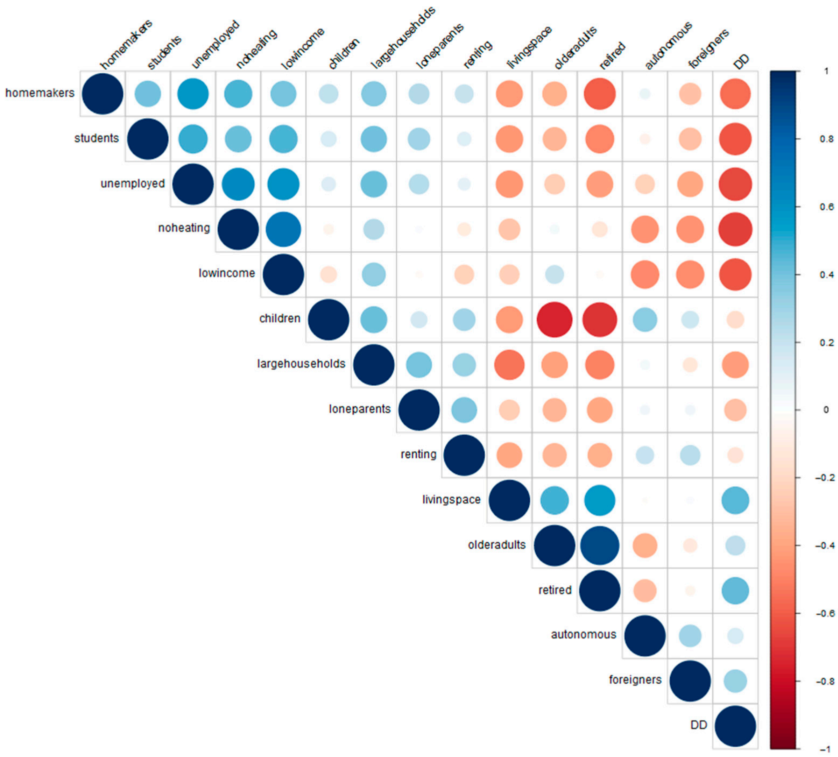

Figure 1. Correlation plot of the analyzed factors considering the whole sample (1346 municipalities included in Italian metropolitan areas).

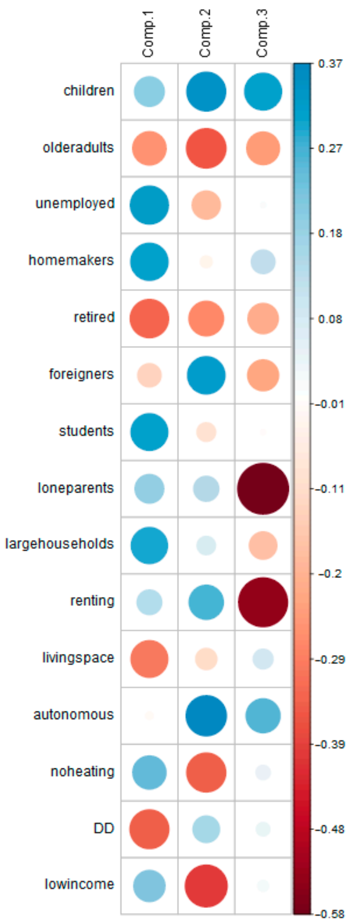

Figure 2. Loading of the analyzed factors on the three components retained in the global PCA.

The third component represents two main characteristics of the households that have a strong negative loading on the component: the percentage of single-parent households and the percentage of households living in rented accommodations. It explains 14.5% of the total variance within the dataset.

In short, we can summarize the relevant factors for component one as "job", for component two as "individual socioeconomic factors", and for component three as "household socioeconomic factors".

4.2. Spatial Analysis of Key Components Determining Vulnerability to Energy Poverty through PCA

Figures 3–5 show the spatial distribution of component 1, component 2, and component 3, respectively. As in Figures 1 and 2, blue indicates direct correlation: the darker the blue, the stronger the significance. Likewise, red indicates an inverse correlation: the darker the red, the stronger the relevance. Light colors indicate the lack of relevance of the component in the areas.

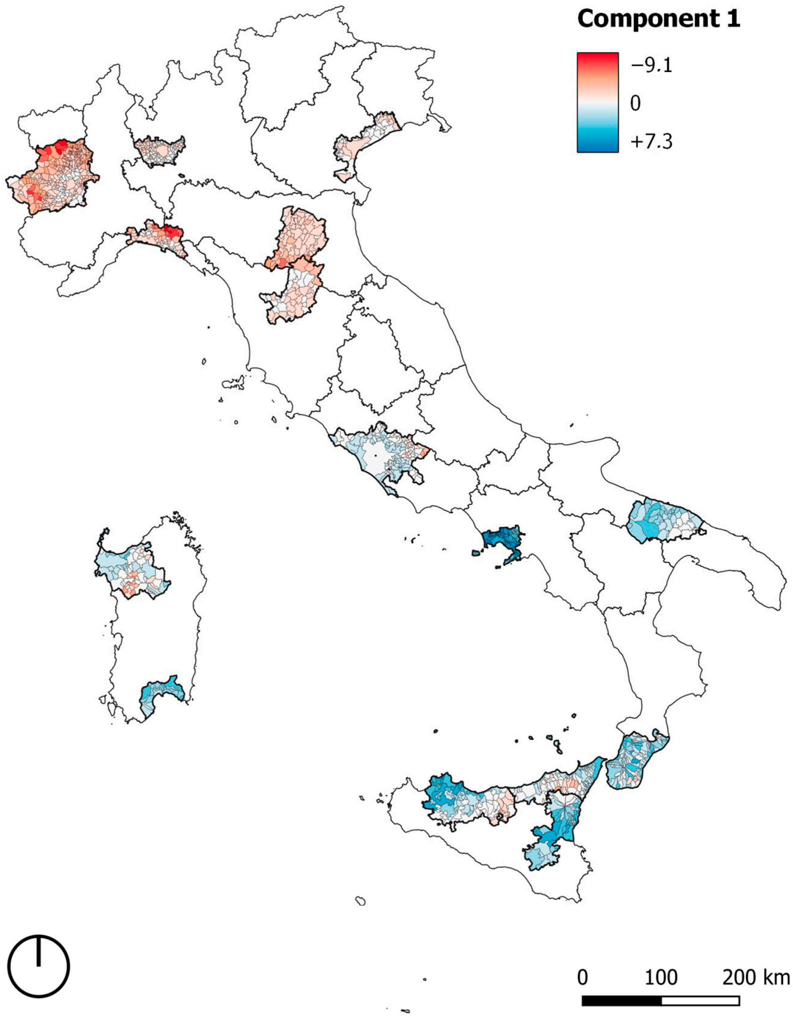

Figure 3. Component 1: Unemployed, homemakers, students, and large families (+) and degree day and surface per inhabitants (–). Blue indicates areas of relatively strong vulnerability using positive loadings of indicators, and red indicates areas of strong vulnerability according to negative loadings of indicators.

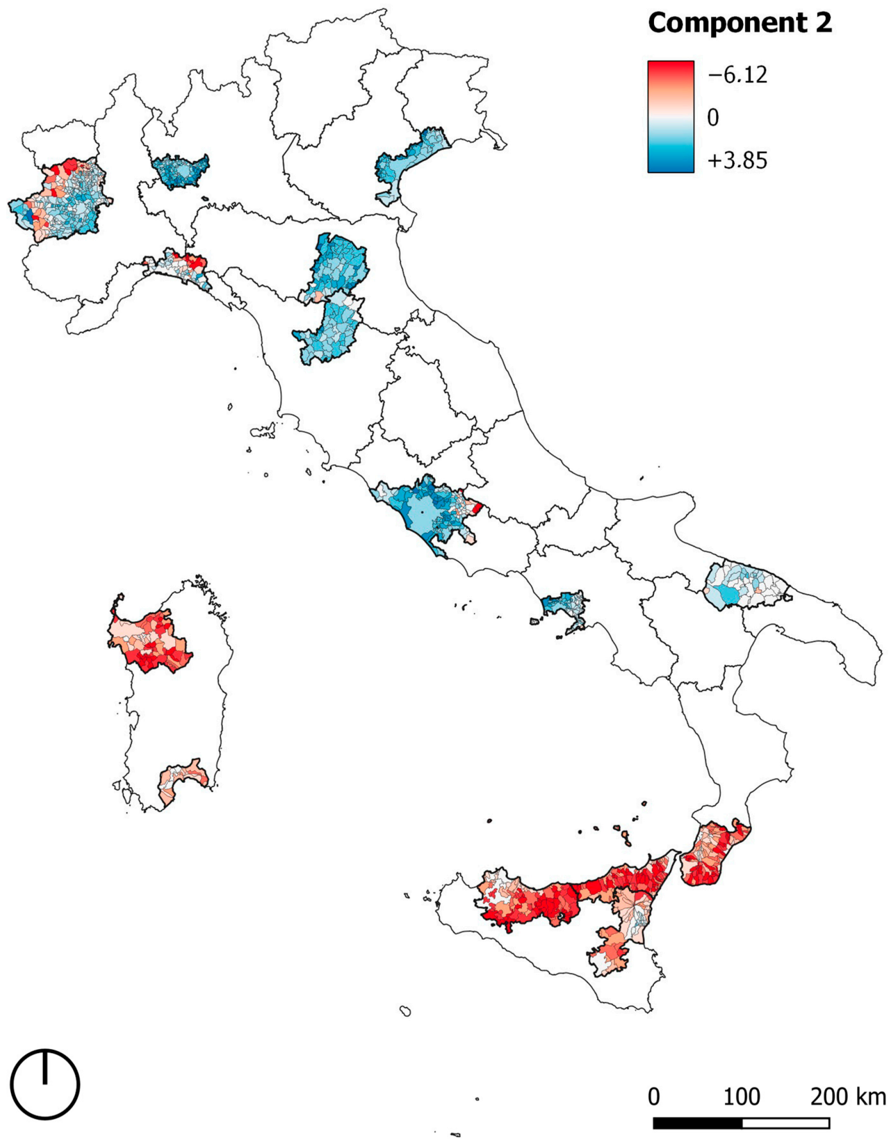

Figure 4. Component 2: Small children, foreigner, and autonomous heating (+) and elderly, no heating, and low income (–). Blue indicates areas of relatively strong vulnerability using positive loadings of indicators, and red indicates areas of strong vulnerability according to negative loadings of indicator.

Reading the three maps (Figures 3–5) with this lens, we can deduce from Figure 3 that component 1 divides the map into two main areas: north and south. Metropolitan areas of central–northern Italy are characterized by the relevance of factors with a negative loading on component 1, among which are the presence of retired people, the surface area of dwellings, and the degree days. In Southern Italy, the most relevant factors (positive loading) are unemployment (percentage of population looking for job), percentage of homemaker's population, and household size (percentage of households with six or more members).

Component 2 (Figure 4), similarly to component 1 (Figure 3), has a behavior that divides the map into two major areas. However, while for component 1 it a matter of north/south divide, for component 2 we can see a "continent/islands" divide. In the peninsular part of Italy, factors with a positive loading on component 2 are the most relevant, including children (percentage of population under 4 years old), foreigners (percentage of foreign population), and the type of heating system (percentage of homes with independent heating). In the islands and in the metropolitan area of Reggio Calabria, in the extreme south of the peninsula close to Sicily, the relevant factors (with a negative loading on the component) are the elderly (percentage of population over 75 years), the lack of heating systems (percentage of dwellings without heating), and income (percentage of taxpayers with an income up to EUR 10,000).

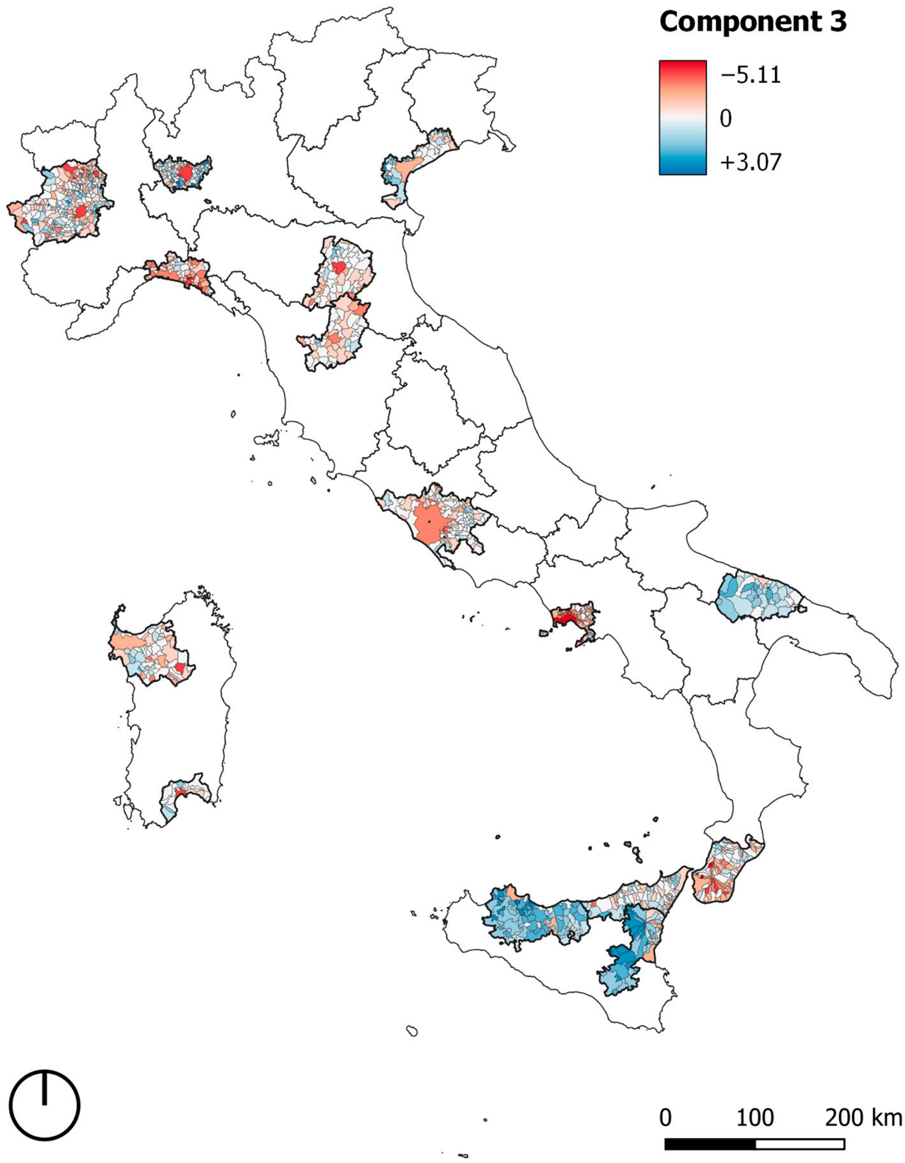

Figure 5. Component 3: Lone-parent household and rented property (–). Blue indicates areas of relatively strong vulnerability using positive loadings of indicators, and red indicates areas of strong vulnerability according to negative loadings of indicators.

Component 3 (Figure 5) shows variations at a finer scale within each metropolitan area. Although it is difficult to identify common patterns, metropolitan centers stand out in many cases for being characterized by more negative values of component 3 compared to their surroundings (e.g., Naples, Milan, Bologna). This indicates that the vulnerability to energy poverty in the main cities tends to be related to those factors that have a negative loading on component 3, i.e., percentage of single-parent households and percentage of households living in rented accommodations. Overall, these have a much stronger influence than the factors characterized by a direct correlation (percentage of population under 4 and percentage of homes with independent heating).

Table 2 synthetizes the average relevance of the three components in each of the metropolitan areas analyzed.

Table 2. Average score (and standard deviation) of the municipalities included in each metropolitan area with respect to the three components identified in the PCA.

Metropolitan Area	Component 1	Component 2	Component 3
Torino	−2.14 (±1.10)	0.46 (±1.19)	0.01 (±0.91)
Genova	−2.05 (±1.93)	−0.33 (±1.75)	−1.03 (±1.01)
Milano	−0.96 (±0.48)	1.86 (±0.64)	0.46 (±1.12)
Venezia	−0.71 (±0.43)	1.72 (±0.64)	0.56 (±0.76)
Bologna	−1.88 (±0.64)	1.67 (±0.78)	−0.30 (±0.71)
Firenze	−1.07 (±0.66)	1.36 (±0.58)	−0.39 (±0.64)
Roma	0.42 (±1.15)	1.19 (±1.29)	−0.18 (±0.67)
Napoli	4.61 (±1.40)	0.93 (±0.80)	−0.99 (±0.95)
Bari	1.82 (±0.93)	0.45 (±0.59)	0.81 (±0.58)
Reggio Calabria	1.64 (±1.36)	−2.16 (±1.23)	−0.56 (±0.97)
Palermo	1.67 (±1.87)	−2.22 (±1.15)	1.29 (±0.73)
Messina	0.73 (±1.37)	−2.38 (±1.14)	0.00 (±0.73)
Catania	2.62 (±1.17)	−0.79 (±1.09)	1.01 (±1.30)
Sassari	0.20 (±1.47)	−2.23 (±1.18)	−0.25 (±0.78)
Cagliari	2.40 (±0.63)	−0.91 (±0.59)	0.04 (±0.78)

Table 2 can be read in both directions. Vertically, it is possible to understand the relative importance of the components in the different metropolitan areas, while horizontally, it is possible to compare the importance of the three components for each metropolitan area.

For example, the metropolitan area of Napoli has the highest average score of component 1, and the latter has more importance than components 2 and 3. This means that for Napoli the share of unemployed, homemakers, students, and large families (i.e., the factors that have a positive loading on Cmponent 1) have the greatest impacts on vulnerability, impacts that are also greater than in the other metropolitan areas. Milano and Messina are both characterized by a great importance of component 2, having, respectively, the highest and lowest average values of the component. In Milano, vulnerability is related to small children, foreigners, and autonomous heating, while in Messina it is related to the elderly, no heating, and low income. Finally, some metropolitan areas show average values close to zero with respect to component 3 (e.g., Torino and Cagliari). However, it should be highlighted that the average values have a high standard deviation, pointing to quite strong differences among the municipalities within these metropolitan areas.

4.3. Local GWPCA

Figure 6 presents the application of the GWPCA to the 15 Italian metropolitan areas. The GWPCA shows the most relevant factors influencing vulnerability to energy poverty at the local level. Following the approach proposed by Robinson et al. [7], we selected the factors that, for each municipality, load either most positively or most negatively on the first component, which, therefore, can be expected to play a main role in determining vulnerability. These factors vary by municipality even within the same metropolitan area, where different clusters can often be identified. The diversity of factors that appear to be the most relevant for the municipalities within a metropolitan area vary from a minimum of three in the metropolitan area of Genova to thirteen in the metropolitan area of Napoli.

Taking the metropolitan area of Venezia (Venice) as an illustrative example, it is possible to identify four different factors that play a main role in different municipalities: the presence of older adults (percentage of population above 75 years), of children (percentage of population under 4 years), of foreigners (percentage of foreign population), and the type of heating system (percentage of homes with autonomous heating). These factors determine clusters within the metropolitan area. In particular, the relevance of the share of older adults becomes particularly significant in western/southern municipalities, including the city of Venice, while the presence of foreigners is particularly significant in eastern/northern municipalities. The presence of children is especially significant in the central part of the metropolitan area (in yellow), while the percentage of homes with independent heating is the most relevant factor in only two municipalities.

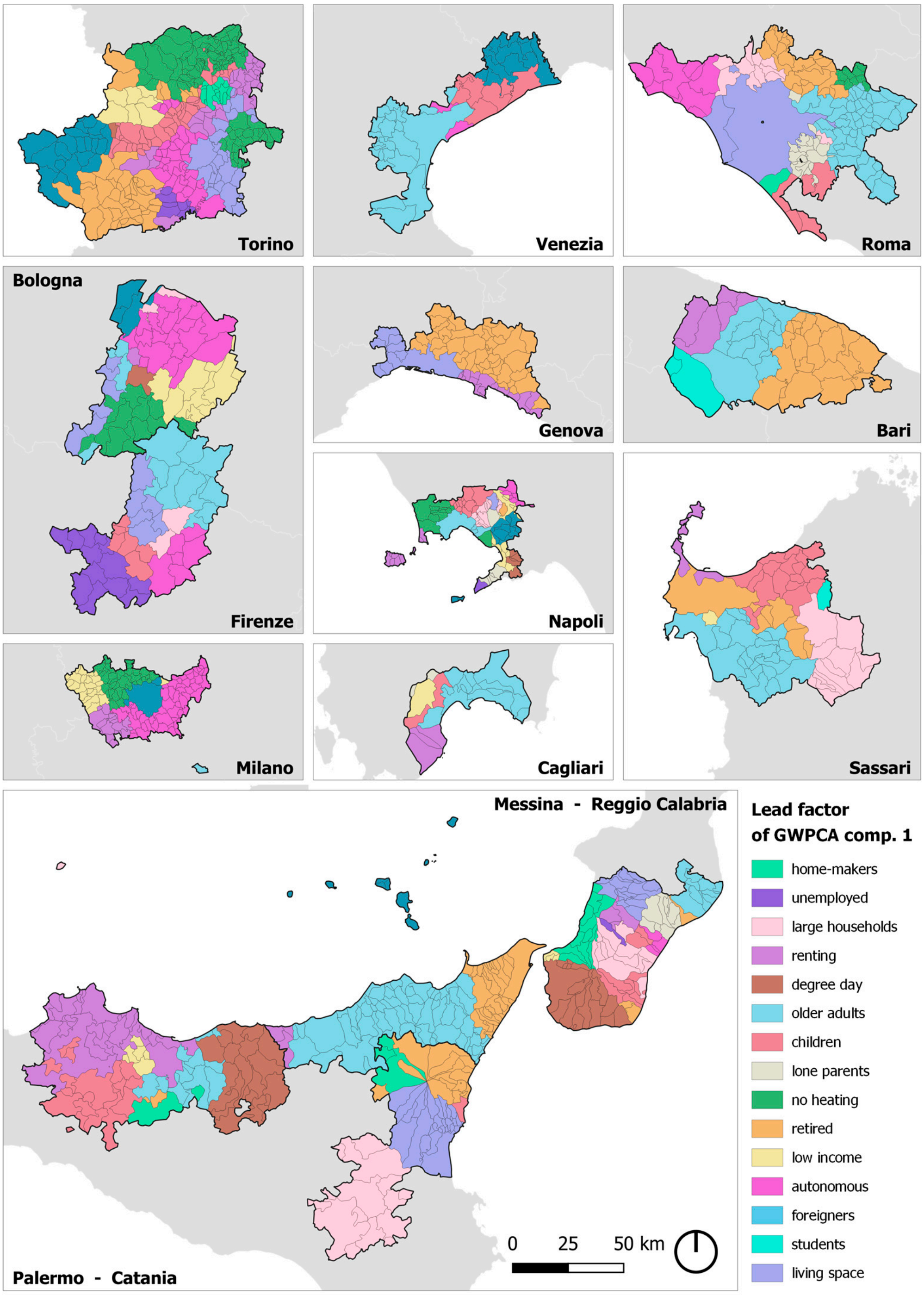

Figure 6. Lead factor of component 1 of the geographically weighted principal component analysis applied to all municipalities within Italian metropolitan areas.

When comparing the results from the two methods, it emerges that while PCA shows that component 2 plays a key role in defining the vulnerability of the metropolitan area of Venice, the GWPCA can illustrate, municipality by municipality, which are the single factors with the greatest importance at the local level. In fact, the four factors highlighted by the GWPCA all belong to component 2 of the global PCA.

5. Discussion and Conclusions

Depending on how we define energy poverty, what metrics we use to measure it, and how we understand it, we tackle it differently and we may reach different levels of success. This work started from the definition of vulnerability to energy poverty by Bouzarovski and Petrova [21] and Middlemiss and Gillard [22], which define vulnerability to energy poverty as "the degree of susceptibility to a stress, in this case a lack of socially necessitated energy services, which varies socially and spatially". The present study aimed at exploring spatial trends of factors determining vulnerability to energy poverty to support the design of effective responses. The research began from two research question: (RQ1) What key components of vulnerability to energy poverty in Italian metropolitan areas should be considered for national level policy design? And how does their spatial distribution vary across the country?; and (RQ2) What factors play a role in determining vulnerability to energy poverty the local level, and hence should be considered to design local responses to vulnerability to energy poverty?

Key insights emerging from the study are presented here below.

5.1. Relevance and Utility of the PCA for National Level Policies

In this study, the application of PCA to 15 metropolitan areas in Italy led to the identification of 3 main components of vulnerability to energy poverty. These are related to three major factors: (i) work, (ii) high sensitivity and poor adaptive capacity, and (iii) wealth, respectively. The identification of three main components, on one hand, enables a priority setting for policy design at the national level, and tells us that to effectively reduce vulnerability to energy poverty, the most relevant factors to tackle are job-related aspects (such as unemployment, unpaid jobs, part time jobs, etc.), followed by sensitivity and adaptive capacity aspects (elderly, kids, foreigners, etc.), and then wealth-related aspects. Of course, the order and, even more important, the weight of these three components vary from one metropolitan area to another (see Table 2). However, from a national-level perspective, this is already a first relevant insight to support policy making.

From the mapping of the three PCA components, it is possible to read the spatial distribution of each of them, which presents specific patterns. For example, from the map of component 1 (Figure 3), it is possible to see that the factors with direct correlation are more present in the north, and factors with indirect correlations are more present in the south. On top of this, the same map shows that the relevant factors in the north are mainly related to peripheral areas; hence, policies addressing phenomena such as unemployment and unpaid work (homemakers) shall focus on peripheral areas. On the contrary, in the south, component 1 highlights as key issues the low income and the presence of a high number of children. In this case, the same component can suggest two different paths: the first one could be related to the creation of community of services to support elderly people in marginal areas; the second one should be related to economic and house efficiency support. Similar interpretations can be replicated for components 2 and 3 (results from Figures 4 and 5).

The absolute most relevant factors at the national level are those related to working conditions, which alone explain one-third of the variability between municipalities at the national level. Some trends are not surprising. The first one relates to the north–south divide (component 1), given the Italian situation where the north is known for being wealthier than the south. The second "intuitive" trend is represented by the center–periphery difference (component 3), which reflects usual urban dynamics. Other trends, however, are more unexpected, e.g., the strong peninsula–island divide. Usually, in the Italian context, the socioeconomic behavior of the islands tends to follow that of the south, while in this case, the islands have a different behavior from the peninsula, including its southern part.

Considering the main energy poverty policy measures currently in place in Italy, described in Section 2, the country is focusing on rebates on energy bills and a tax credit for energy requalification ("ecobonus"). In particular, the ecobonus itself targets a more long-term issue than measures on energy bills. Indeed, according to Filippidou et al. [1] and

Bouzarovki et al. [2], energy efficiency is fundamental in tackling energy poverty in the long term. However, in the present ecobonus, energy poverty and its multidimensionality issues are not considered in an integrated way: the two policy strands are still disaggregated, and this undermines the effectiveness of the ecobonus to really be an answer to energy poverty.

The comparison between the vulnerability of the energy factors assessed and mapped in this paper and current policies allows us to identify important gaps in existing measures to address components 2 and 3 of energy poverty vulnerability (individual and household socioeconomic factors), as well as long-term responses to component 1 (working conditions). More specifically, by combining the vulnerability of energy poverty factors and the whole study with the types of policies to address energy poverty categorized by the Energy Poverty Observatory for Europe [43], we would recommend for component 1 (work) to develop social support measures. Social support measures provide general income support for households to cover more general expenses, and financial assistance to reduce energy bills or ease the difficulty to pay can be given in two ways: social tariffs and energy bill payment support. Policy recommendations regarding component 2 (high sensitivity and poor adaptive capacity) could focus on energy audits, which visit vulnerable households to provide direct advice on how to improve their specific energy vulnerability situation (on top of disconnection bans providing protection against disconnection for households, often in colder months during the wintertime or summertime). In response to the aspects raised by component 2, it would also be useful to boost information and awareness as measures that indirectly facilitate households to improve their situation by providing advice, information, or education for behavioural changes or best solutions. Recommendations to tackle component 3 (wealth) could be related to financing support for energy-efficiency improvements and facilitating intervention for rented apartments and houses as the most preferred option to solve energy poverty structurally.

5.2. Local Level Policies and GWPCA

Again, Table 2, which shows the average values for each of the three components for each metropolitan area, if read line by line, quite clearly sets out the relevance and contribution of each component, metropolitan area by metropolitan area. For example, in the case of Venice, we see that component 2 has more weight than components 1 and 3 (C1: −0.71; C2: 1.72; C3: 0.56). Consequently, policies at the local level for the metropolitan area of Venice should prioritize the factors included in component 2.

In general, from the GWPCA, we can state that metropolitan areas could use the results of this analysis, for example, by targeting specific funds available to them or by creating synergies with other local policies. For example, we can see cities such as Venice, Rome, and Bari needing to address the older-adults-related dynamics through policies, while Turin and Genoa are characterized by the prevalence of other indicators.

GWPCA results for all metropolitan areas could be used to identify areas with common traits and promote cross-fertilization and mutual learning between metropolitan areas.

5.3. Limitations, Way Forward, and Concluding Remarks

This work has some methodological limitations. First, the data used date back to 2011 due to a limitation of the national database. At the date of processing the methods, these were the only comparable and homogeneous data available for processing at the municipal level, so we gave priority to the comparability of the data with respect to the update date. It would be interesting to replicate the study with more recent data as soon as the national census allows. However, this limitation does not compromise the validity of the proposed method in terms of replicability both to other contexts and with more up-to-date data. The results could also serve as a benchmark to compare with the most recent situation and to link changes in the spatial distribution of vulnerability and in the relative importance of the different underlying factors to their potential drivers, including policies implemented in the past decade.

Another type of limitation is related to the indicators used. Thus, the indicators used are taken from an accurate study which, however, has as its case study the United Kingdom, where the issue of "indoor temperature" links energy poverty and access to a comfortable indoor temperature to the response to winter cold and, thus, the need to heat. This work, on the other hand, focuses on Italian metropolitan areas, where indoor temperature requires not only heating in winter, but also cooling in summer (especially in light of increasing heat waves).

In addition, it would be interesting to overlap results from this study with an energy poverty map to draw some discussion among mismatches between energy poverty, mapped with a standard index, and vulnerability to energy poverty. However, fine-scale data for energy poverty for the Italian context, highlighting difference between metropolitan areas, are not available to the best of our knowledge. This may represent a future piece of research.

A novelty of this work, from a methodological and application point of view, is represented by using PCA and GWPCA and the comparison of their results in terms of major factors determining vulnerability to energy poverty and their spatial distribution at two different scales. Attempts so far have reached the point of comparing the PCA and GWPCA at the same scale. For example, the work of Robinson et al. [7] did so, and highlighted that "The GWPCA recognizes vulnerabilities that the global components (PCA) fail to recognize. A geographically weighted assessment of vulnerability can therefore be useful in drawing attention to vulnerabilities commonly overlooked or hidden from policymakers". In addition to these findings, which we found relevant and inspiring, our work enables us to add that that the two approaches can target different scales (the national scale is well addressed by the PCA, while the local scale reasonings benefit from a GWPCA) and support policy making at different levels.

To conclude, a last aspect that we would like to consider relates the multiple dimensions underpinning the vulnerability to energy poverty. As mentioned in the introduction, current policies do not share a common definition of what energy poverty is, and governments tend to measure it with synthetic indexes or indicators that mainly focus only on the economic dimension of poverty. Consequently, measures and actions mainly focus on subsidies and financial help, which represent short-term solutions and avoid considering "hidden" types of energy poverty caused by weak social networks, lacking capacity and so on. As Filippodu et al. [1] stated, addressing energy poverty with business-as-usual indicators and policy can represent a way of "burning money". In line with Cong et al. [5], we agree with the need to go beyond "standard" energy poverty indicators (such as the percentage of household income spent on utility bills) as a guide for policymakers. In this vein, our analysis identifies three main components of vulnerability to energy poverty and shows, on the one hand, that focusing on economic indicators beyond "spending on utility bills" can help policymakers design long-term economic measures (such as working on energy efficiency with the specific aim of tackling energy poverty, as described among policy recommendations above); on the other hand, relevant noneconomic factors (such as social and capacity aspects) have emerged, and the maps show their presence, relevance, and distribution.

Given the urgency and the magnitude of the phenomena, it becomes mandatory to tackle the root causes of the problem. Our work can represent one of the small but needed steps to design fit-for-purpose policies, aware of the specificities of different geographical areas and of the factors that need to be addressed. Further steps, by the EU, the public bodies, and academia are, of course, needed and, hopefully, they will be taken in a joint, integrated, and collaborative way.

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