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ENERGY POVERTY RISK:
A SPATIAL INDEX BASED ON ENERGY EFFICIENCY

by Luciano Lavecchia*, Raffaele Miniaci*, Paola Valbonesi*
and Gowthami Venkateswaran*

Abstract

We propose an Energy Poverty Risk Index (EPRI) and assess it at the local (municipal) level on Italian regional data. The EPRI includes four components: modelled expenditure required to satisfy household energy needs, severity of climate conditions, quality of the building stock and local 'wealth' (proxied by education and taxable income). The EPRI accounts for local differences in the many factors affecting energy poverty. Specifically, it is based on the idea that the higher the expenditure required to meet the energy needs and/or the severity of climate conditions, the higher the risk of energy poverty; on the contrary, wealthier areas and/or those with higher-quality buildings face a lower energy poverty risk. Our empirical analysis of the Lombardy region confirms these points and highlights a lower energy poverty risk in urban areas and higher energy poverty in rural and mountain municipalities. These results, with a municipal-level granularity, could be a first step towards a national energy poverty dashboard that can help design local actions to reduce the impacts of energy and climate factors on the most vulnerable.

JEL Classification: I32, Q48, Q54.

Keywords: energy poverty, fuel poverty, energy efficiency, residential sector, Energy Performance Certificate (EPC), Italy, Composite Index.

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1. Introduction and motivation

Recently, the public and policymakers have been increasingly concerned about the social and economic impact of the energy and ecological transition. The European Union (EU) produced the most advanced legislation[3], setting ambitious goals and limits to reduce the greenhouse gases (GHGs) emissions. The EU is one of the few jurisdictions putting the concept of sustainable development into action and explicitly considering solutions to strengthen society's resilience in the face of energy and ecological crises, climate change, and the depletion of natural resources.

The energy and ecological transition process and its costs became increasingly under scrutiny in the EU also because of the impact of the Ukraine war on energy inflation. Large countries such as Italy, Germany and also Poland changed their energy sources to reduce Russian dependency, but that came at a cost (i.e., the cost of increasing the share of LNG as a gas source). Lifestyle adjustments enforced by an increase in energy costs could be extremely harmful, particularly for vulnerable households that are particularly prone to fuel poverty (Watson & Maitre, 2015; Pérez-Fargallo et al., 2017; Petrova, 2018).

The implementation of energy and ecological transition looms together with an evident fragility of the EU energy system, and underlines the need to strengthen assessment and monitoring of energy poverty. Energy and fuel poverty (in the rest of the paper we use the two terms interchangeably) is a multi-dimensional issue (Faiella et al. 2022). Family's wealth, composition and related energy consumption choices are not solely responsible for fuel poverty; a home's energy efficiency, location and other spatial elements matter as well, as remarked by Robinson et al. (2018a). Socio-spatial elements such as the physical and constructed environment, infrastructure, demographics, local services, political traits and related actions, and social networks are all integrated within a geographic space. Fuel poverty is therefore a result of the family's socio-spatial economic context embedded in the sense of Granovetter (1985). Bouzarovski et al. (2021) underline that social embeddedness must be considered to explain the complex phenomena of energy poverty and show how the socio-spatial and institutional systems deeply affect energy poverty using Hungarian data.

An energy poverty index should take into account these different dimensions, as well as the right level of granularity and scope for this purpose. Following the literature, in particular Gouveia et al. (2019), we design and test a risk index to account for the spatial distribution of energy poverty. Our energy poverty risk index is based on four components (energy expenditure, climate, the quality of the building, income and education), and is applied to Lombardy, the largest and wealthiest Italian region for population and GDP (see Figure 1).

[3] The European Climate Law (Regulation 2021/1119) establishes an overall target of net zero GHG emissions by 2050 and a reduction of at least 55% by 2030, compared to 1990 levels.

Figure 1: Map of Lombardy

With 9.9 million inhabitants spread across more than 1,500 municipalities, it is more populous than 33 European countries. About half of the population lives in the west of Lombardy, which includes the metropolitan area of Milan and its surrounding areas; the remaining inhabitants are spread over a vast territory, going from the Alps to the plains near and beyond the river Po (*Pianura Padana*) and from the Como to the Garda lakesides. A large part of this remaining territory is sparsely populated, except for the areas around major towns.

Lombardy is also the wealthiest region in Italy. Its 2020 GDP was 367 billion euros, equivalent to Austria or Ireland's GDP and larger than those of countries such as Denmark or Portugal. Within Lombardy, urban areas and lakesides are the richest. On the opposite, Alpine and Pre-Alpine areas experienced the dispossession of human resources in the 80s, when young people started to migrate to cities (Emanuel, 2019). About 11.6 percent of the population immigrated from abroad, 3.1 percentage points higher than the Italian average; immigrants mainly live in the urban areas or the plains. At the end of 2022, 5.1% of the households living in Lombardy were energy-poor, compared to a national average of 7.7% (OIPE, 2024).

Lombardy is rather heterogeneous in terms of climatic conditions (Fratianni & Acquaotta, 2017), from Alpine to the sub-continental temperate climate of the five Italian major lakes and cool temperatures of the Po Valley. Given its dimension and spatial heterogeneity, Lombardy can be considered an emblematic case and provides useful insights also for other territories. Taking advantage of extended databases referring to Lombardy, we run estimations of three versions of a new energy poverty risk index (EPRI), a composite indicator of energy poverty at the local level which ranges between -9 (areas with minimum risk of energy poverty) and +9 (areas with maximum risk)[4]. The results do not seem to be particularly affected by the different weights we adopted in our empirical analysis, suggesting the robustness of our approach. Indeed, all

[4] The rationale of EPRI is that the higher the expenditure required to meet energy needs and/or the severity of the climate (the first two components), the higher the risk of energy poverty. Conversely, wealthier (or more educated) areas and/or those with higher quality buildings face a lower energy poverty risk. In the (extreme) case whether an area belongs to the top deciles of the distribution of the first two components and the bottom of the other two, using the same weights, it should achieve a value of +9 (5+5-0,5-0,5)

indicators consistently reveal that the mountainous regions in the north and southwest of Lombardy (*Oltrepò Pavese*), along with some eastern areas of the Po Valley, face a higher risk of energy poverty compared to the rest of the region; differently, the metropolitan area of Milan and the municipalities within a radius of approximately thirty kilometres are those with the lowest energy poverty risk. This methodology, based on rank statistics, is transferable and can be readily applied to other Italian regions, offering valuable insights to both national and local policymakers for targeted resource allocation in the battle against energy poverty.

In the remaining part of the paper we present the Literature review in Section 2; we illustrate our Data and methodology in Section 3; we discuss in detail our Results in Section 4, and we wrap up our main Conclusions in Section 5.

2. Literature review

Several energy poverty indicators have been developed and discussed in the economic literature. The theoretical (or actual) cost of energy as a share of income (or expenditure) is the most basic metric: if the ratio exceeds a specified level, the household is considered energy poor. Traditionally, this threshold has been around 10%, as stated by Boardman (1991).

The Low Income-High Cost (LIHC) measure is a more recently designed indicator (Hills, 2012): it offers various improvements over previous indicators, including the ability to discriminate between energy poverty and income poverty due to the use of a dual threshold. The first threshold considers modelled energy costs, while the second considers median household expenditure. Since 2019, England adopted a Low Income Low Energy Efficiency (LILEE) indicator, where a household is considered to be fuel poor if it meets two key criteria: i) Low energy efficiency (Fuel Poverty Energy Efficiency Rating of band D or below); and ii) Low income (households whose residual household income would be below the official poverty line if they were to spend their modelled energy costs - DESNZ, 2024).

Despite the declared attention by policy makers to the problem of energy poverty, few jurisdictions collect systematic data on household energy demand (Belaïd, 2018a; Robinson et al., 2018a; Burlinson et al., 2021): these data are key to estimating energy poverty, along with information on households' characteristics and income (for a survey, see Faiella et al., 2022).

The problem with income (or expenditure)-based methods is that they identify people who are already impoverished as energy-poor. They also disregard households who are on the verge of becoming fuel-poor; and they miss households in the so-called "hidden energy poverty", i.e. households who are so poor that cannot afford to buy energy and they do not record any energy expenditure and, as a consequence, they are not "captured" by any energy poverty indicator. According to Legendre & Ricci (2015), those experiencing energy poverty are not only monetarily poor. Non-monetary factors contribute to energy poverty in several, interrelated, ways. The use of energy poverty indicators that account also for non-monetary factors - i.e. gender, age, and nationality of the head of the household; tenure status, dwelling type, and the degree of urbanisation of the location where the household lives, etc. - is now widespread. In Europe, for example, there are micro-based multidimensional international comparative analyses, such as Bollino & Botti (2017) and Halkos & Gkampoura (2021).

The literature on the spatial distribution of energy poverty shows conflicting results. Liddell et al. (2012) was an early contributor who developed a map of energy poverty for the UK based on an indicator *a la* Boardman (1991). Similarly, Roberts et al. (2015) found that energy poverty is an urban issue, a result that Robinson et al. (2018b) and Burlinson et al. (2021) validated using a LIHC approach, showing that energy poverty disproportionately affects areas with low real estate prices, especially metropolitan areas. Differently from them, Thomson & Snell (2013) found that families that lived in bad-quality houses and inhabitants of rural areas are more prone to energy poverty, a result confirmed in Italy by the Italian Observatory on Energy Poverty, OIPE (2024). The latter evidence is consistent with the results of Chaton & Lacroix (2018) in

France, and Aristondo & Onaindia (2018) in Spain. Bouzarovski & Simcock (2017) assert that the higher incidence of energy poverty in rural areas in developed countries is related to the lack of infrastructure such as the natural gas grid or an efficient fuel distribution network.

A vast literature on low-income countries (e.g. Pachauri et al., 2004 and Sadath & Acharya, 2017) investigates the spatial distribution of energy poverty mainly as a matter of access to adequate energy sources also using multidimensional indices. Although access to energy is almost universal in advanced economies, the use of a multidimensional approach can be appropriate to analyse the so-called "hidden energy poverty". Meyer et al. (2018) take into account both manifest and hidden energy poverty in Belgium by mixing objective indicators and respondents' perceptions. Their measure combines three sub-indices: a LIHC index, an indicator of constrained energy consumption below what is considered the basic level, and an indicator of self-reported difficulties in adequately heating the house. Betto et al. (2020) propose an index of hidden energy poverty that accounts for the climatic heterogeneity across the Italian regions, combining the approaches suggested by Faiella & Lavecchia (2014), Miniaci et al. (2014) and Rademaekers et al. (2016).

Other recent contributions show the link between housing conditions and the spatial distribution of energy poverty. Kelly et al. (2020) developed a composite index utilising 10 indicators refined at the small area level to study home-heating energy-poverty risk in Ireland; Sánchez-Guevara et al. (2019) investigated energy poverty in the 21 districts of the city of Madrid, proposing a High Energy Requirements (HER) index which highlights different patterns of deprivation faced by energy-poor households. Gouveia et al. (2019) propose for Portugal an index of energy poverty risk by combining two sub-indices that do not require micro (household level) data and can be calculated on small area data: the first one called 'energy gap' is the difference between modelled energy demand and actual consumption; the second one, a 'poverty alleviation index', encompasses numerous dimensions such as unemployment, homeownership, education, income, age of the population, and building conservation. The resulting energy poverty risk index of the area is the difference between the rankings based on the energy gap and the poverty alleviation measures.

The alternative methodological approaches discussed above largely differ in terms of data requirements. In most cases, the calculation of the indices requires the availability of household surveys collecting information on housing conditions, energy expenditure and total expenses or income. These surveys are typically run at the national level and rarely can provide robust statistics at the sub-regional level, their inference on smaller samples (e.g. analysis at the municipality level) inadvisable. Consequently, to account for the territorial heterogeneity in the many factors that affect energy poverty it is often necessary to resort to alternative sources and to combine administrative data and small area estimates based on sample surveys. Thus, whenever the focus is on the spatial distribution of energy poverty, the only approach that can be sensibly implemented is to build risk indices similar to those proposed (among others) by Gouveia et al. (2019).

3. Data and methodology

Consistently with the existing literature, in what follows we propose an energy poverty risk index that accounts for four components: the expenditure required to satisfy domestic energy needs (*EE*), the severity of climate conditions (*DD*), the quality of the building stock (*BQI*) and the income and education of the area (*IE*). The underlying rationale of this index is that the higher the expenditure required to meet the energy needs and/or the severity of the climate, the higher the risk of energy poverty; on the contrary, wealthier areas and/or those with higher-quality buildings face a lower energy poverty risk.

In order to linearly capture the four components (i.e. the sub-indices *EE*; *DD*; *BQI*; *IE*) and to operationalize the related rationale, we propose to adopt, for each municipality *m,* an Energy Poverty Risk index ($EPRI_m$), as follows:

$$EPRI_m = \left(w_{EE} \times \rho\left(EE_m\right) + w_{DD} \times \rho\left(DD_m\right)\right) - \left(w_{BQI} \times \rho\left(BQI_m\right) + w_{IE} \times \rho\left(IE_m\right)\right), \quad (1)$$

where the function $\rho\left(X_m\right)$ returns the decile of the municipality m with respect to the distribution of the variable *X*, and the weights w_k have to be determined.

To determine the weights in multidimensional indicators, literature records (at least) two competing approaches. The first can be seen as a data-driven approach, which sets the weights according to some algorithm that reduces the dimensionality of the information space according to some optimality criterion. For example, the weights can coincide with the coefficients resulting from a Principal Component Analysis (PCA). The second is a consensual approach, that is, the weights are set according to rules that require the disclosure of value judgments, opinions, or expectations about which component of the index is considered to be relatively more relevant. Both approaches have *pros* and *cons*, but the consensus approach has the advantage of including more transparent mechanisms that make it easier to subject the conclusions reached to robustness analysis.

The four sub-indices can also be operationalized in many ways, which may differ in logic and data requirements. In what follows we propose a possible definition of the sub-indices for the sake of limited data and flexibility.

3.1 Energy expenditure component

To assess the affordability of households' energy expenditure, the energy poverty literature considers two different measures of household energy expenditure: actual *vs* modelled expenditure. As surveys on household expenditure are very common, the approaches based on actual expenditure are widespread. However, the main drawback of referring to the actual expenditure is that families with limited resources can reduce their fuel consumption below the level considered socially acceptable and, in doing so, give the illusion that there is no fuel affordability problem. Therefore, although more data demanding, looking at the expenditure required to achieve standardised energy use is preferable (e.g., the LIHC or the LILEE index for England).

The Energy Performance Certificates (EPCs - *Attestato di prestazione energetica, APE,* in Italian) provide the information necessary to calculate how much households living in certified homes should spend to maintain an adequate winter indoor temperature for a given number of hours per day, how much for space cooling, lighting and water heating. For every certified home *i* in the municipality *m* the required energy expenditure can be computed as

$$EE_{im} = \sum_{v=1}^{V} p_{vm} \bullet C_{imv}, \quad (2)$$

where C_{imv} is the required consumption per square metre of the energy vector *v*[5], $v = 1, \ldots, V$, and p_{vm} is its (local) unitary cost. Prices for each energy vectors are from several data sources: as for electricity and natural gas we use the average unit costs from Eurostat[6]; for district heating, we took the average price for 2020

[5] We used all the energy sources reported in the database, such as electricity, natural gas, LPG, coal, gasoil, liquid, gaseous and solid biomasses, and district heating.

[6] We download the 2019 average unit costs from table NRG_PC_202 (natural gas) and NRG_PC_204 (electricity) which are available for bands of consumption. We built a weighted average unit cost by using household consumption

from ARERA[7]; for heating oil, we used the 2019 average provided from the Ministry of Environment and Energy Security[8]; for LPG, we used the information from the Varese's Chamber of Commerce[9]. Finally, for solid biomass, the pellet price was taken from the Italian Association of Agroforestry Energies.[10]

At the local level, when data on individual EPCs is available, it is possible to calculate the average required expenditure:

$$EE_m = \frac{1}{N_m} \sum_{i=1}^{N_m} EE_{im}, \tag{3}$$

where N_m is the number of certified homes in the municipality m[11].

The European Union Energy Performance of Buildings Directive (EPBD, 2002/91/EC) introduced European standards for the Energy Performance Certificates (EPCs), which were updated in 2018 (Directive 2018/844/EU). An EPC is required for every new, renovated, purchased, or rented building or dwelling. In Italy, regional authorities are in charge of the administration of the EPC registers and - at the time of writing - in Lombardy, Piedmont and Trento, the archives of the certificates are open-access and regularly updated.[12] In this paper, we use the archive from Lombardy (CENED+2). After some data cleaning of duplicated EPCs (we kept the most updated), the regional archive includes 737,000 certificates between October 2015 and January 2021, which is equivalent to about 13% of the housing stock recorded by the 2021 general population and housing census.

Each EPC provides an estimate of the energy required to maintain the house at 20° C (±2°C), for 14 hours during the heating season, which goes from mid-October to mid-April where the number of degree-days is lower than 3.000 and covers the entire year for the coldest municipalities. Instead, for refrigerating it is determined solely to maintain the dwelling at 26 °C (±2°C), for 3 summer months, regardless of degree-days of the municipality[13]. That is, for each certified house i in municipality m, the consumption C_{imv} in equation (2) is known and used (together with price information) to estimate the average cost of fuel to have an adequately heated, cooled and lit home in the m municipality (EE_m).

3.2 Climate conditions component

Heating Degree Days (*HDD*) is a simple, readily available index that measures the number of days for which heating is necessary in the considered municipality, thus capturing the severity of the climatic conditions faced by the households living there. This measure not only adequately depicts the different needs of the

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volumes of electricity and natural gas by consumption bands (tables NRG_PC_202_V and NRG_PC_204_V, respectively). All prices are in euros per kWh.

[7] "Esiti dell'indagine conoscitiva sull'evoluzione dei prezzi e dei costi del servizio di teleriscaldamento", Allegato A, fig. 1, ARERA, 22 november 2022 (https://www.arera.it/allegati/docs/22/547-22alla.pdf). The price used is 0.1 euros per kWh.

[8] https://dgsaie.mise.gov.it/prezzi-mensili-carburanti?pid=3. The price used is 1.307 € per liter.

[9] We used the price for delivery of 1,000 litres in a tank owned by the user which in 2019 was equal to 0.890 euro per litre, to which we added the VAT (22%). https://www.prezzivarese.it/retail/prodotti-petroliferi/.

[10] Available at https://www.aielenergia.it/pubblicazioni-agriforenergy, 0.256666 per kg, to which we added the VAT (22%).

[11] At the end of May 2024, there were over 5 million EPCs for Italian homes in the national archive, the Sistema Informativo sugli Attestati di Prestazione Energetica (SIAPE), maintained by ENEA.

[12] In the case of Lombardy, the archive is available at https://www.dati.lombardia.it/Energia/Database-CENED-2-Certificazione-ENergetica-degli-E/bbky-sde5. All the certificates are based on CENED+2.0 software, see https://www.cened.it/software-cened2. For Piedmont: https://www.dati.piemonte.it/#/catalogodetail/regpie_ckan_ckan2_yucca_sdp_smartdatanet.it_Sicee_v_datigen_energetici_v2_8407; For Trento: https://dati.trentino.it/dataset/attestati-di-prestazione-energetica-trentino.

[13] It is not possible to disentangle consumption for electric heating and electric cooling.

different areas, but also takes into consideration the (national and local) social norms on the reference temperatures and heating seasons.

Italy has an official climatic classification of all its municipalities (Presidential Decree 412/1993 and following updates); this classification is based on the number of heating degree days defined as[14]:

$$HDD_m = \sum_{t=1}^{HS_m} max\left(20 - T_{mt}, 0\right) \tag{4}$$

where T_{mt} is the average temperature in the municipality m at day t, and HS_m is the length of the monitored season, which starts with the first three consecutive days with the average temperature below 12°C and ends with the first three consecutive days with the average temperature above 12°C (or from December 1st to February 28th for warmer areas). Thus, HDD_m describes the typical temperatures of the municipality. The presence of seasons with particularly adverse or mild meteorological conditions is captured by another set of variables such as the deviation of the average monthly temperature in 2019 of the autumn and winter months from the ten-year average of temperatures in the same months:

$$DT_{mj} = T_{mj,2019} - T_{mj} \qquad j = 1,..., 6 \tag{5}$$

where $T_{mj,2019}$ is the average temperature in the municipality m in the month j of the year 2019 and T_{mj} is a long run mean (between 1980 and 2014)[15].

Finally, we build our climate condition component, DD_m , as a linear combination of the tenths to which the municipalities belong with respect to the distribution of the variables HDD_m and DT_{mj}:

$$DD_m = \omega_{HDD} \times \rho\left(HDD_m\right) + \sum_{j=1...6} \omega_{DTmj} \times \rho\left(DT_{mj}\right), \tag{6}$$

where ω_{HDD} and $\omega_{DTm,j}$ are the weights of the first component of a PCA for the aforementioned variables.

3.3 Building quality component

The overall quality of the building stock in a local area is associated with three correlated characteristics: weighted average age of buildings (*BA*), market values (*HP*) and energy performance (*EP*) of the houses. Given a measure of these three constituents, an index of the quality of the buildings for the local area *m* can be defined as a linear combination of the tenths to which the municipalities belong with respect to the distribution of the aforementioned characteristics:

$$BQI_m = \omega_{BS}\rho\left(BA_m\right) + \omega_{HP}\rho\left(HP_m\right) + \omega_{EP}\rho\left(EP_m\right) \tag{7}$$

with weights ω_k as the first component of a PCA of BA_m, HP_m and EP_m.

[14] The Presidential Decree 412/1993 classifies the Italian cities in 6 climate zone, from the warmer to the coldest zone: A (with HDD < 600); B (600<HDD<900); C (900<HDD<1,400); D (1,400<HDD<2,100); E (2,100<HDD<3,000); F (HDD>3,000).

[15] The source for climate data comes from *Terra Climate* (https://www.climatologylab.org/terraclimate.html) where data has been available since 1958.

The three characteristics capture different aspects of the quality of housing conditions which contribute to the risk of energy poverty. Camboni et al. (2021) show that the building age is a key determinant of energy poverty in Italy, where older homes are typically larger and more energy-demanding than recent ones.

As for the average building age (BA_m), the Italian National Statistical Office (ISTAT) makes data from the general census of population and housing at the municipality level available to the public: we run our analysis on population statistics from the 2019 continuous census. It contains critical information on the socio-demographic characteristics of households (including educational attainments). The census is also the basis for building construction dates but, unfortunately, the most recent data for this information dates back to 2011[16]: thus, we set BA_m as the average age of construction of the residential buildings in the m-th area.

Residential real estate prices (HP_m) increase with the quality of the buildings, but houses are heterogeneous goods, and their price depends on a multiplicity of both micro and meso factors. Using average area prices eliminates some hedonic factors due to the within-area location; however, some of the spatial price heterogeneity is due to the specificities of supply and demand interplay in local real estate markets rather than to the intrinsic quality of housing. Again, we consider the tenth of the distribution of the average housing prices for the municipality, with pieces of information provided by a branch of the Italian Revenue Agency (Osservatorio Immobiliare, OMI[17]). Thus, for each municipality, in our analysis, we adopt the average price of the residential real estate transactions registered in the first semester of 2019.[18]

Finally, the energy efficiency of a house (EP_m) - a crucial feature for our aim - is associated with the construction period but it also depends on features such as size, building insulation, windows, type of heating and cooling systems. It contributes to the market value of the house. The EPCs provide pieces of information on the energy requirement of renewable (*ep_gl, ren*) and non-renewable (*ep_gl,nren*) energy (in kWh per square metre per year) of the house. EP_m is built to provide the decile of the average energy requirement distribution.

3.4 Income and education components

A suitable synthetic indicator of the economic wealth of a territorial area needs to account for both current and prospective households' ability to pay for their energy needs. Whereas the current spending ability can be approximated by the average personal taxable income (*TI*), the prospective one is associated with the educational attainment of the population (*EDU*) which we disentangle into three groups: the share of individuals with low education (up to lower secondary school, *EDU1*), the share with medium education (with upper secondary or vocational school degree, *EDU2*) and the share with high education (with bachelor or upper degree, *EDU3*), even though for our analysis we will use only EDU1 and EDU2. The three components can be combined in a wealth index, IE_m (which, as before, is the tenth of the distribution of the linear combination of the three components):

$$IE_m = \omega_{TI}\rho\left(TI_m\right) + \omega_{EDU1}\rho\left(EDU1_m\right) + \omega_{EDU2}\rho\left(EDU2_m\right) \quad (8)$$

As for the building quality component, BQI_m, the set of weights can be obtained via a Principal Component Analysis (PCA): we define weights in equation (8) by using local statistics for disposable income and educational attainments which are often available either from administrative records or from surveys and censuses.The Italian Ministry of Economy and Finance publishes statistics from the personal income tax files

[16] Available at http://dati-censimentopopolazione.istat.it/Index.aspx?lang=it#
[17] https://www.agenziaentrate.gov.it/portale/schede/fabbricatiterreni/omi/banche-dati/quotazioni-immobiliari
[18] Data is available for all but two municipalities, for which the price has been imputed.

at the municipality level. We chose to use data for the year 2019, as the latest available year (2020) is the first year of the COVID-19 Pandemic, which severely affected (and with significant heterogeneity) incomes.[19] These data provide the overall taxable personal income of the residents in the municipality. Based on this, per-capita taxable income can be calculated using population data from the census.

Information on the education of the population in 2019 is provided by the general census of population and housing at the municipality level[20].

4. Results

The following subsections present the spatial distribution of both the energy poverty risk drivers and the composite Energy Poverty Risk Indices.

4.1 Energy expenditure component

Figure 2: Energy expenditure spatial distribution

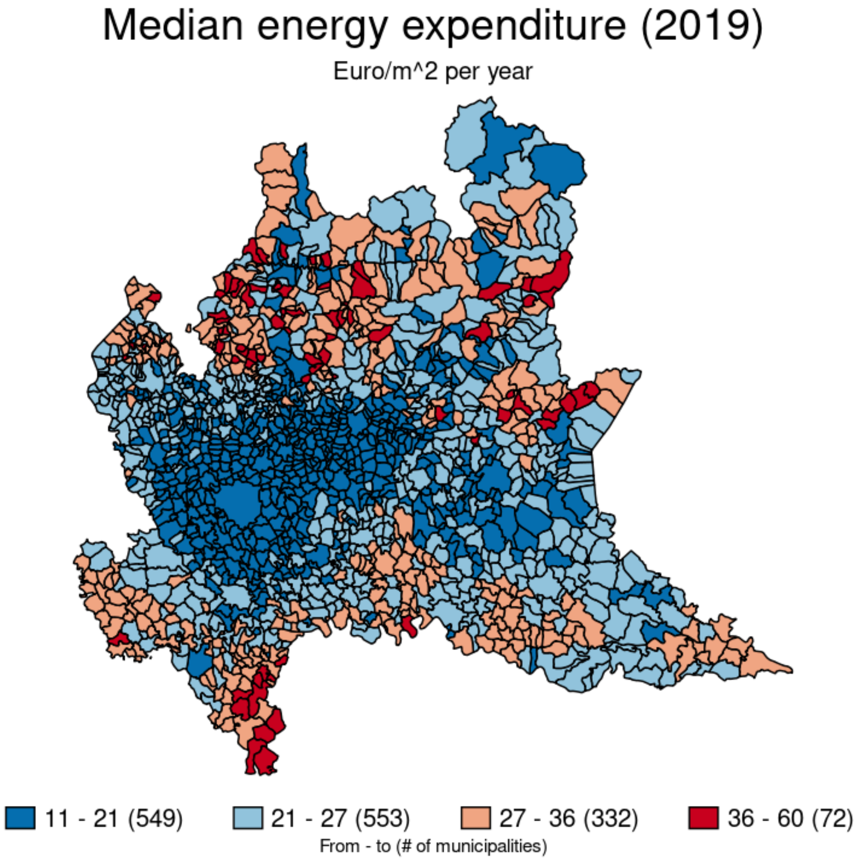


Figure 2 illustrates the distribution of the modelled energy expenditure per square metre (euro per sqm). In this map, and the following ones, the municipalities are partitioned into four clusters using a *k*-means procedure. For each cluster, the legend shows the lower and upper limits of the values included in the cluster and, in brackets, the number of municipalities that belong to the cluster. Strong heterogeneity emerges in the modelled energy expenditure recorded for the different local areas (EE_m). The Milan conurbation is the area where energy expenditure is lower (between 11 and 21 euros per m^2 per year) as compared to the other local

[19] Available at https://www1.finanze.gov.it/finanze3/analisi_stat/v_4_0_0/contenuti/Redditi_e_principali_variabili_IRPEF_su_base_comunale_CSV_2019.zip?d=1595352600

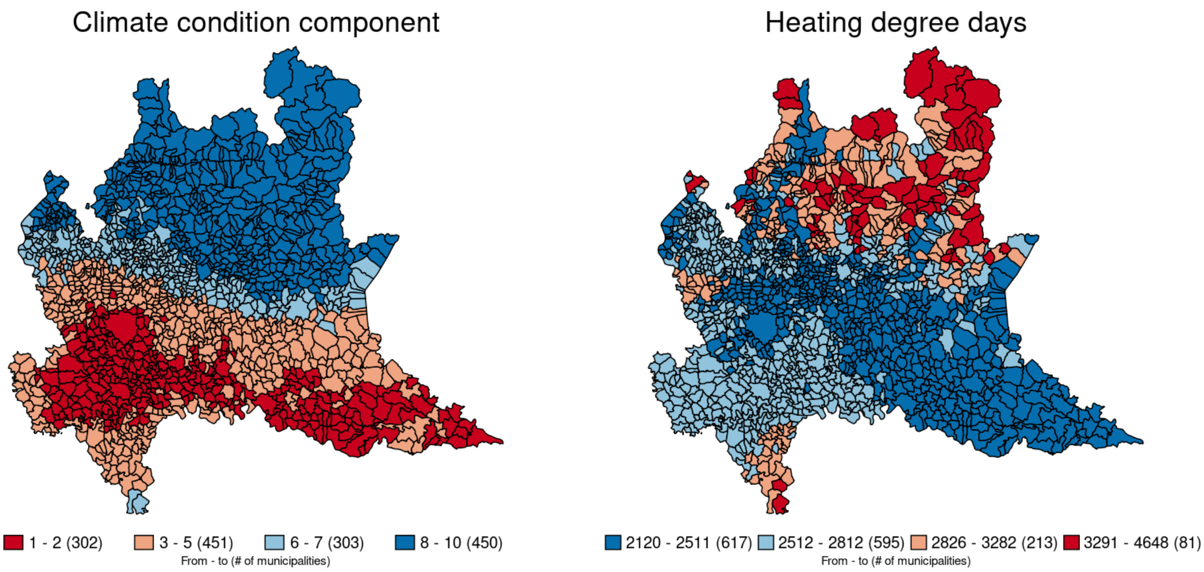
[20] Available at http://dati-censimentipermanenti.istat.it/

areas in the region. In 2019 the median energy annual expenditure for an apartment of 100 m^2 was, *ceteris paribus*, € 1,600 in Milan and € 6,000 in Magasa, a small village in a mountainous area in the north-east. The lower expenses can be recorded in the areas north of Milan and close to Brescia, while the highest-spending areas are the Alpine and Pre-Alpine areas in the north, and in the southern areas of the Oltrepò Pavese and the Po River basin.

4.2 Climate conditions component

Figure 3 illustrates the regional heterogeneity of climate conditions, by plotting the clusters of municipalities based on the distribution of the climate condition component (DD_m, left panel) and of the heating degree days (HDD_m, right panel), one of its subcomponents. Focusing on HDD_m, the municipalities of the shores of Maggiore, Como, Iseo and Garda lakes, and those in eastern part of *Pianura Padana* have the mildest climates, with less than 2,500 heating degree days. Instead, the extensive northern Orobic and Rhaetian Alps and Prealps together with the southern hilly *Oltrepò Pavese* are the coldest areas, with peaks above 3,000 degree days.

Figure 3: Climate conditions component



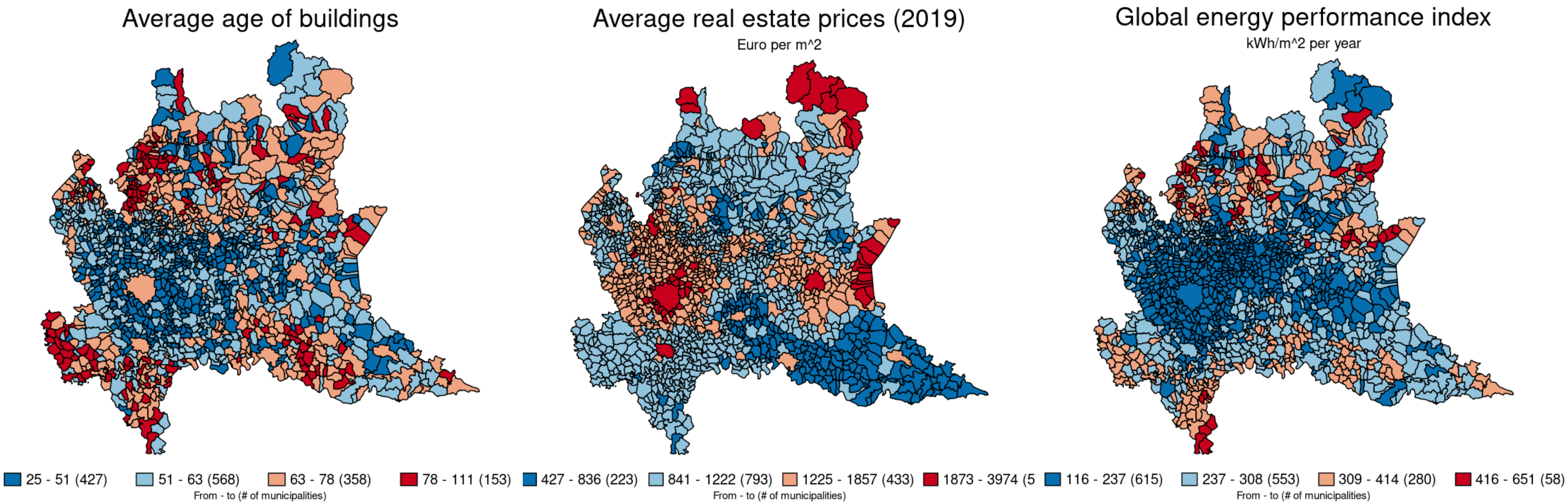
Combining the climate conditions (HDD_m) and the 2019 meteorological conditions (DT_{mj}) into the climate condition component (DD_m), the left panel of Figure 3 shows that the northern (and mountainous) areas are the most demanding ones, whereas the municipalities south of Milan in the Po Valley are those with the most favourable climatic conditions.

4.3 Building quality component

The quality of the housing stock is associated with the average age, market value and energy efficiency of the buildings in the municipality. Figure 4 shows the spatial distribution of three constituents of the building quality component (BQI_m). For what concerns the building age (BA_m), according to the 2011 census data, 73% of Lombard houses were built before 1980, that is, before the introduction of the first law that imposed energy efficiency standards for residential buildings (Law 373/76). Although part of this stock might be retrofitted, a large share of the dwellings in Lombardy is old and, in principle, energy inefficient. With the noticeable exception of the largest towns, with their historical centres, the municipalities with the oldest housing stocks (more than 63 years old) are those of the mountainous areas, the rural part of the *Pianura*

Padana and the southeastern area, which are areas that attracted little or even lost population (see left panel of Figure 4).

Figure 4: Average age of buildings, real estate prices and global performance index

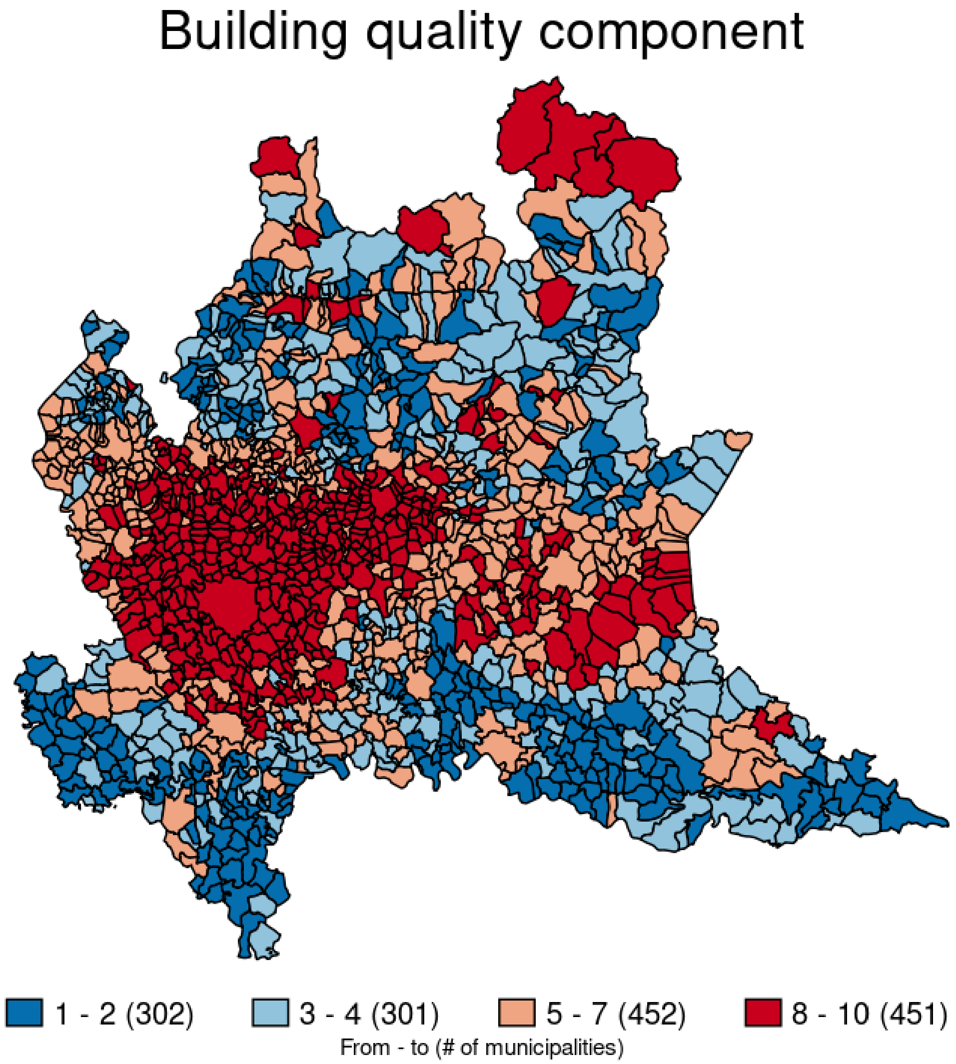


Based on 2019 data, the spatial distribution of the house prices (HP_m, mid panel in Figure 4) is such that it is possible to recognize four groups of municipalities in the highest-price cluster (more than € 1,800 per sqm): the city of Milan and surroundings to the west; the city of Brescia to the east; Pavia to the south of Milan and the tourist areas of lakes and of mountains. This is unsurprising, as house prices are driven not only by construction quality but also by the demand/supply balance of the local real estate markets. On the opposite, there are vast territorial areas with prices below 1,000 euro per sqm, less than one-fourth of the average price in Milan.

The last constituent of BQI_m is associated with the energy performance of the houses (EP_m). The right panel of Figure 4 shows that in the mountainous areas further north (where winters can be very cold), situations in which energy demand is on average very high (more than 400 kWh/sqm) alternate with others in which it is relatively low (less than 300 kWh/sqm). This is consistent with the average age of the buildings (see left panel in Figure 4) and the average energy expenditure (see Figure 2). The southern part of Lombardy is instead characterised by a more homogeneous distribution of energy demand, in almost all municipalities above 300 kWh/sqm.

The map of the building quality component (BQI_m), which is the first principal component of the PCA on the average age of buildings, the market values and energy performance of the houses (see eq. 6) is presented on Figure 5.

Figure 5: Building quality component



The overall building quality is the highest in the metropolitan area of Milan and its surroundings, for a group of municipalities on the south west east of the lake of Garda and for a few touristic municipalities in the northern mountains. Instead, the rest of the mountainous municipalities and almost all of those in the *Pianura Padana* and the *Oltrepò Pavese* in the south score poorly in terms of building quality.

4.4 Income and education component

Figure 6 shows the spatial distribution of three constituents of the income and education component (IE_m).

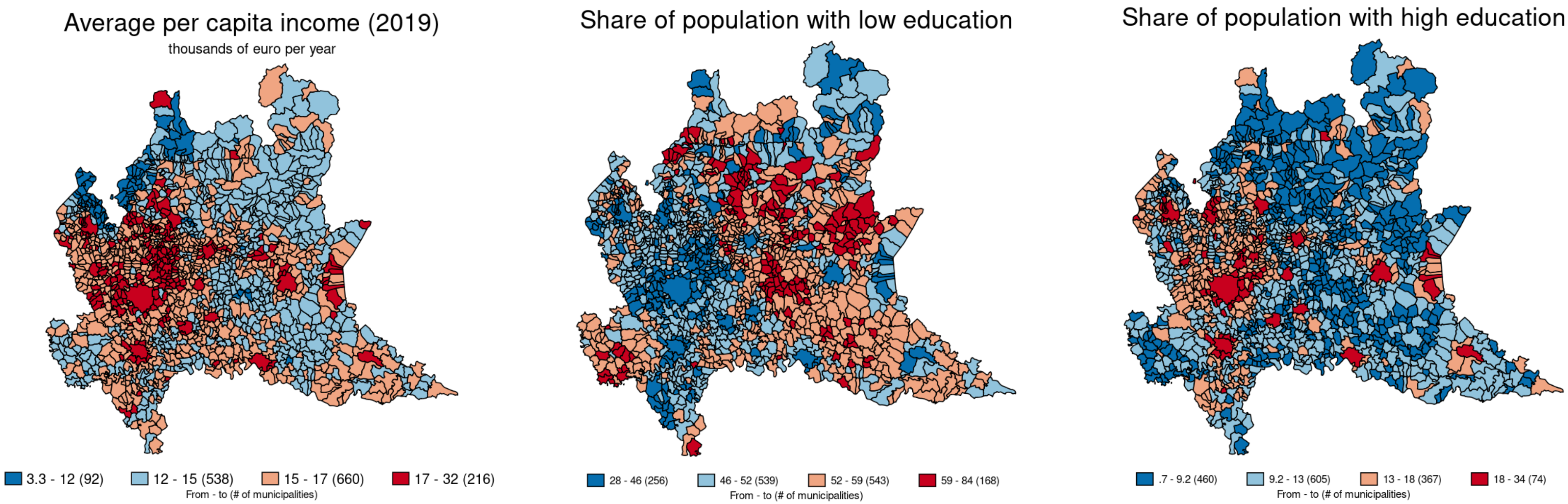
According to data from the national tax revenue agency, in 2019 the average per capita personal taxable income of the Lombard municipalities was 25,780 euro, compared to a national average of 21,800 euro. On the left panel of Figure 6, it can be observed that the richest municipalities (with TI_m higher than € 17,000 average per capita personal taxable income) are concentrated in the urbanised areas of the main cities, their surroundings, and the lakesides of Garda and Como. On the opposite, a cluster of low-income municipalities is recognizable in the most north-western alpine territories, at the Swiss border.

The income spatial distribution is related to that of the educational attainment of the population (low education, $EDU1_m$, and high education[21], $EDU3_m$). The areas with the highest incomes are also those with the

[21] Share of the population with a bachelor, master or PhD.

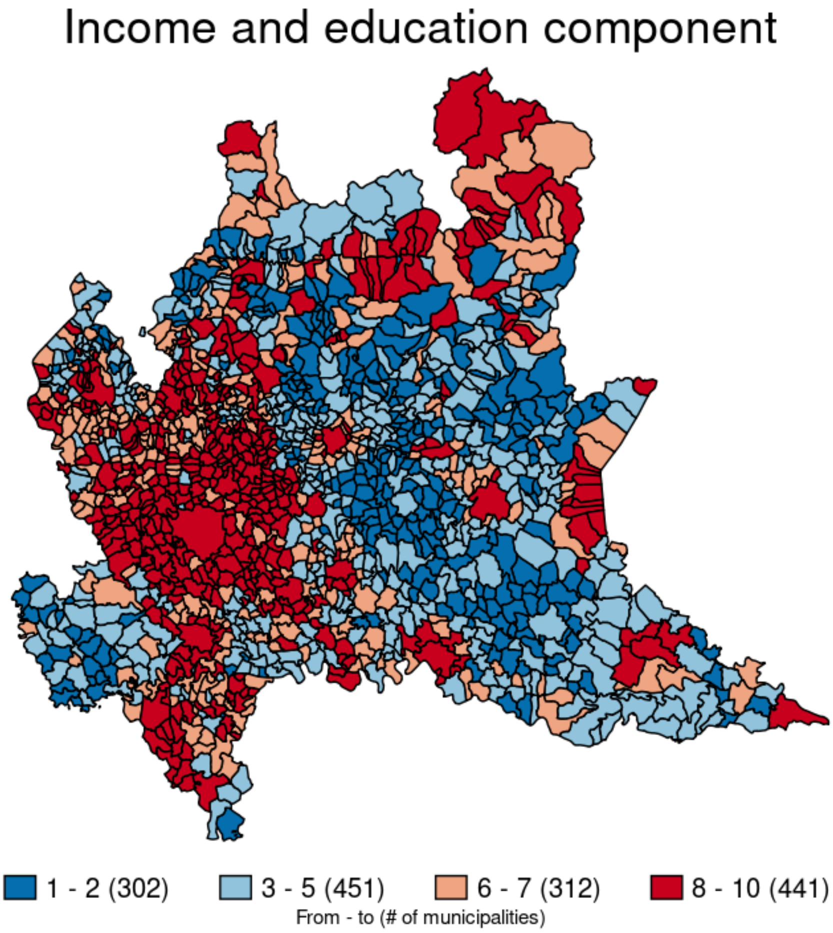
highest percentage of the population with at least a bachelor degree (Figure 6, right panel), whereas the low-income municipalities of the Pre-Alps and the Po Valley are those with the highest share of the population that attained at most a lower secondary school certificate (low education).

Figure 6: Average per capita personal taxable income; percentage of population with at most elementary school (low education) or tertiary education (high education).



The map of the income and education component (IE_m), which is the first principal component of the PCA on TI_m, $EUD1_m$ and $EDU2_m$ (see eq. 6), is presented on Figure 7. On average, the western part of Lombardy, together with the main cities and their surroundings show higher levels of education and income and therefore a higher value of IE_m.

Figure 7: Income and education component



4.3 Energy Poverty Risk Index (EPRI)

The data described in the previous subsection are the ingredients of our energy poverty risk index (*EPRI)*.

As for the subcomponents, the weights result from PCA. We now have to decide the weights of the four components in equation 1. This is a judgement call. In what follows we assess three possibilities. As a benchmark, we consider - $EPRI_1$ - an index of energy poverty risk where equal weights are assigned to each components:

$$EPRI_1 = \left(0.5\times\rho\left(EE_m\right) + 0.5\times\rho\left(HDD_m\right)\right) - \left(0.5\times\rho\left(BQI_m\right) + 0.5\times\rho\left(IE_m\right)\right) \qquad (7)$$

By using equal weights, the implicit assumption is that an improvement in the ranking of the municipality with respect to income and education (IE_m) has the same effect as an improvement in housing quality (BQI_m); or that a worsening in the ranking of energy expenditure, (.e. a higher value of $\rho\left(EE_m\right)$, has the same impact as a similar worsening of the climatic conditions. Given the assigned equal weights, a potential drawback of $EPRI_1$ is that it overweighs the role of the climate, which directly determines HDD_m, and indirectly both the necessary energy expenditure EE_m and the energy performance index EP_{im} that enters the building index. Under the assumption that all that matters in terms of building quality for energy poverty is the energy efficiency of the dwellings, and that this is fully captured by the expense for the modelled demand of energy, then w_{BQI} can be set to zero. To consider the role already played by HDD_m, in the calculation of EE_m, the weight w_{DD} can be reduced to 0.1, which brings us to the definition of $EPRI_2$ as:

$$EPRI_2 = \left(0.9\times\rho\left(EE_m\right) + 0.1\times\rho\left(HDD_m\right)\right) - IE_m \tag{8}$$

Somewhat at the opposite of the previous approach, under the assumption that all that matters in terms of attenuating factors of the energy poverty risk is the quality of the building, we can overweight BQI_m as in $EPRI_3$:

$$EPRI_3 = \left(0.5\times\rho\left(EE_m\right) + 0.5\times\rho\left(HDD_m\right)\right) - \left(0.9\times\rho\left(BQI_m\right) + 0.1\times\rho\left(IE_m\right)\right) \tag{9}$$

Using the tenths of the distributions of the four components, all three indices have support between -9 (for municipalities with minimal risk) and +9 (for those with the highest risk). Their distributions are depicted in Figure 8: they are all nearly symmetrical, but those of $EPRI_2$ and $EPRI_3$ have much fatter tails.

Figure 8: Energy poverty risk indices distribution

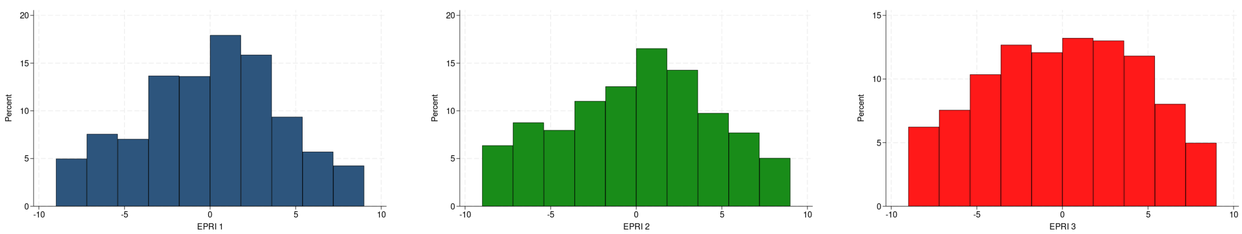
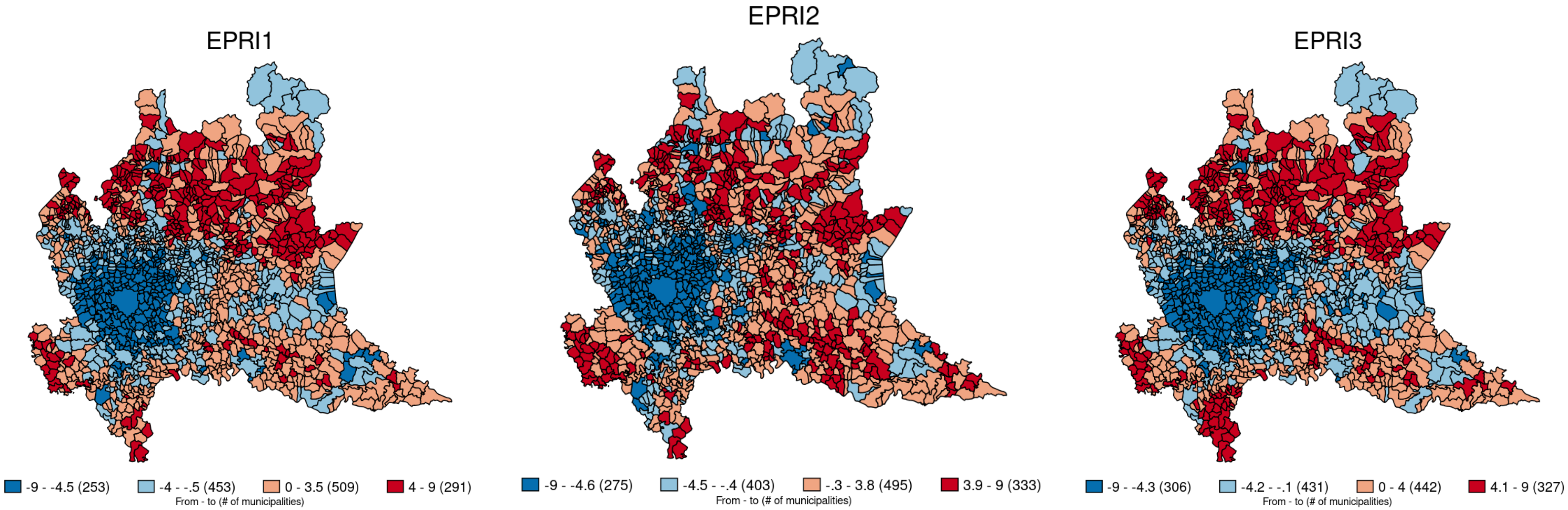


Figure 9 clearly shows that all three indicators identify the mountainous areas of the north and south-west, together with the eastern part of the Po Valley, as areas with a higher risk of energy poverty than the rest of the region. Also mountain areas have a higher risk of energy poverty. This is particularly relevant in mountain areas of the provinces of Bergamo, Brescia, and Sondrio and as well in the province of Pavia. $EPRI_2$ shows instead a poverty risk cluster in lowlands in the area around Cremona and Lodi. $EPRI_1$ and $EPRI_3$ shows instead that in lowlands the risk of energy poverty is mild, especially in the provinces of Mantua, Cremona, and Lodi. Risk remains high in mountain areas. The differences in measurement derive from the fact that the quality of the buildings are taken into account in the $EPRI_1$ and $EPRI_3$, while in $EPRI_2$ it is not.

In the end, as there is no significant differences among the 3 simulations, we suggest to use $EPRI_3$

Figure 9: Energy poverty risk indices spatial distribution: $EPRI_1$, $EPRI_2$ and $EPRI_3$



5. Conclusions

The changes in the energy settings driven by the very ambitious EU energy and climate policies, combined with the fragility of a system still exposed to the volatility of the global commodities markets, underline the need to strengthen the assessment and monitoring of households in energy poverty—those vulnerable individuals who have fewer resources to withstand the costs of the transition.

In this paper, we contribute to the literature on the spatial distribution of energy poverty by proposing a new energy poverty risk index (EPRI) and applying it using information on Lombardy, the largest Italian region by population and GDP. This indicator allows us to identify the areas most exposed to the risk of energy poverty by building rank statistics. The basic underlying rationale of EPRI is that the higher the expenditure required to meet energy needs and/or the severity of the climate, the higher the risk of energy poverty. Conversely, wealthier (or more educated) areas and/or those with higher quality buildings face a lower energy poverty risk.

Our analysis illustrates the main choices made in constructing the EPRI index and presents its estimation using granular databases referring to the Lombardy Region, a large region located in the north of Italy. The results do not seem to be particularly affected by the weighting system, suggesting the robustness of our approach. Specifically, our findings indicate that the risk of being fuel poor is lower in urban areas and higher in rural and mountainous municipalities. The availability of a local area-level indicator can be a first step towards a national energy poverty dashboard that supports the design of targeted policies to combat energy poverty at the local level (especially within large metropolitan areas, by differentiating between neighbourhoods), thereby addressing the various sources of the issue.

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