RESEARCH PAPER

Are they Twins or Only Friends? The Redundancy and Complementarity of Energy Poverty Indicators in Italy

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Abstract

A large body of literature has developed numerous unidimensional and multidimensional indicators to identify energy-poor households, also with the aim of targeting public policies. They all have pros and cons and may identify different populations. How do they relate to each other? How should they be used in a country such as Italy where energy poverty has not yet been officially defined? We frame these research questions in a context of general social vulnerability in which several dimensions of poverty intersect. Using SILC data (EU and IT modules) for the period 2004–2015 we compare four widely used unidimensional indicators and provide evidence—for the Italian case—that complementarity among the indicators prevails since the complexity of energy poverty requires a combination of metrics to capture various vulnerabilities. Our results confirm the set of relevant factors affecting the probability of being energy poor which are indicated in the related economics literature, regardless of which indicator is used. They may help tailor policies to tackle the phenomenon. Based on these findings, we strongly support the idea of using a dashboard of different metrics to measure energy poverty to design effective policies.

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1 Introduction

In advanced economies such as in Europe, awareness of energy poverty (EP)[1] as a major problem requiring attention at the institutional level is recent. In general, EP can be defined as a situation in which households are unable to access the energy services that are essential to guarantee a satisfactory standard of living and health, including adequate thermal heat and cooling, lighting and electricity for appliances (EC 2020). The centrality that this phenomenon has acquired in European policy action stems from a realisation that the share of residential energy expenditure in total household expenditure has increased since the economic crisis of 2008–2010 and that low-income households are more exposed to energy price fluctuations and so deserve effective protective measures (Halkos and Gkampoura 2021). This situation has been further exacerbated by the COVID-19 crisis and by the geopolitical tensions in eastern Europe due to a combination of income reduction and ample energy price fluctuations (Bouzarovski et al. 2021; Mastropietro et al. 2020). The literature is unanimous in describing EP as a complex and multifaceted phenomenon explained by various factors and therefore difficult to define. It is no coincidence that there is still no detailed common definition nor a common metric agreed on at the EU level and that many member states have not officially defined and measured EP. Regarding the drivers of energy poverty, the literature has largely focussed on the triad of high energy prices, low household incomes and poor housing efficiency. Recently, a much wider set of factors has been introduced in the debate such as socio-cultural norms (Hitchings et al. 2015; McKague et al. 2017) and the multiple vulnerabilities of household members (Bouzarovski and Petrova 2015), also in terms of information and education gaps, which prevent efficient energy-related choices. This leads to the conclusion that a wider analytical and quantitative framework is needed to consider the complexity of energy poverty (Lowans et al. 2021; Sareen et al. 2020; Thomson et al. 2017a, b).

The aim of this paper is to frame the analysis of EP in a context of general social vulnerability in which different levels of deprivation intersect. The first step is recognising that vulnerability is a complex phenomenon to identify and that the metrics commonly used at the international level can only partially identify the energy poor households and those at risk of poverty. In this sense we support the idea that using a dashboard of energy poverty indicators rather than a single metric enables better understanding of the phenomenon. Availability of a broader set of information is a key prerequisite to designing appropriate policies and effective targeting, as has been verified by several policy studies (Miniaci et al. 2014; Alvarez and Tol 2021). Therefore, we investigate two research questions:

- What are the main patterns of overlap between EP indicators and the general dimensions of vulnerability (age, health, other deprivations, economic situation)?
- Are the most commonly used EP indicators more complements or substitutes?

Focusing on the European Union and Italy as case studies, we examine how different measures widely used in the EP literature may offer a non-homogenous picture of

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[1] Although some of the specific literature in this field distinguishes between 'energy poverty' and 'fuel poverty' and uses the latter in analyses of more developed countries, in this paper we prefer to use the more general term 'energy poverty' to indicate a lack of adequate energy services in Europe.

EP. As the European Commission (EC 2020) suggests, we argue that this apparent contradiction is an asset rather than a problem and we may exploit the different types of indicators to identify people suffering from one or more aspects of EP to design more targeted and therefore effective policies. Using microdata from the European and Italian modules of the Statistics on Income and Living Conditions (SILC), which are widely exploited in the EP literature, we compute a set of consensual and expenditure-based indicators, which show large differences in levels of EP as measured by different unidimensional indicators. Focussing on Italy in the period 2004–2015, we obtain some significant results. First, we confirm that there are large differences and relatively small overlaps between different EP metrics by using tables of joint distributions and Venn diagrams. These methods also allow to show how the selected EP indicators are interrelated with each other and how they are associated with other dimensions of vulnerability, such as aging and health status. Finally, using regression analysis on the pooled dataset, we compare how the key factors identified in the literature impact the four metrics. We thus highlight a set of core factors—such as living in southern Italian regions and in urban areas, being a single-parent family, having a non-EU nationality, suffering from multiple deprivations and having bad health—as characteristics associated with a higher likelihood of being energy poor according to all the indicators. Conversely, some additional factors, for instance old age and the presence of children in large households, have a non-homogeneous influence on the metrics and contribute to identifying different groups within the population. In our view, these findings highlight a need to use different indicators acting as complements to explain the multiple facets of EP.

The paper is organised as follows. In Sect. 2, after a general discussion on the literature on defining and measuring EP, we briefly show how different metrics lead to different rankings among European countries and within Italian macro areas. In a closer analysis of Italian data (Sect. 3) we consider the degree of redundancy of different metrics using contingency tables and Venn diagrams. Finally, we run regressions to separately identify the roles of different socioeconomic factors for each index. Policy implications and future research directions are discussed in the concluding section.

2 Energy Poverty Indicators in the Literature

2.1 Energy Poverty and Vulnerability

The scientific literature on EP has aimed to distinguish its specificities from poverty in general. Although there are significant areas of overlap between income poverty and EP, it is widely recognised that in addition to budget constraints EP is also a result of a lack of energy efficiency in housing—which poses different problems depending on the occupancy status of the property—and high energy prices that create budget problems for the most vulnerable households. From this distinction between the two phenomena emerges the traditional triad of factors that generate EP: low incomes, high prices of residential energy services and poor housing efficiency. The latter is also linked to different abilities to benefit from energy efficiency subsidies because of barriers mainly linked to a lack of access to capital and of adequate information.

Recently, several contributions in the literature have defined so-called 'energy vulnerability thinking': an approach that distinguishes EP from broader vulnerability as a set of conditions that characterise the emergence of a state of deprivation (Simcock et al. 2017). These conditions of vulnerability may be specific to an individual or to a social group and result in less ability to access an adequate level of energy services. In addition to the factors traditionally identified as drivers of EP, Bouzarovski and Petrova (2015) identify a number of dimensions. Vulnerability may result, for example, from a lack of flexibility or inadequacy of the household's energy system to meet the household's consumption habits and practices, presence in the household of people with specific needs related to illness and disability (Snell et al. 2015), the demographic characteristics of the household (e.g. elderly people, single-parent families, immigrants with little familiarity with the language and practices of the country) (Grossmann and Kahlheber 2017). According to this approach, EP is a fluid state which households can enter or exit as a result of changing conditions related to housing status and social and economic dynamics. Consequently, the phenomenon of EP is part of a broader framework of processes and inequalities specific to each country that interact with traditional factors and bring about a condition of energy vulnerability. Along these lines, Middlemiss (2020) proposes a "socially systemic" conceptualisation of EP. This phenomenon must be studied in the context of the social, physical and technological situations that influence personal experiences of EP so that potential solutions are not confined to the sphere of energy policy alone.

The concept of energy vulnerability identified in the literature (Middlemiss and Gillard 2015) is broader than the idea of the 'vulnerable consumer' that has long been the focus of attention in the European internal market. In general terms, the latter refers to a limited ability of the consumer to have full access to the benefits of the internal market[2] and therefore highlights a need to protect these consumers. It is evident that the two phenomena of EP and energy vulnerability intersect, but identifying vulnerable consumers is very difficult because it is a condition linked to the specific definition adopted to measure EP. EU policy documents[3] refer to a need for member states to establish a definition of both vulnerable consumers and EP. It is therefore confirmed, even in the most recent guidelines,[4] that the two concepts are to be understood as distinct and important[5] and that it is desirable to identify both the determinants of them and criteria for monitoring them at the national level, since essential energy services for living with dignity may vary over space and time. For

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[2] In relation to the energy market in particular, vulnerable consumers are individuals who may be dependent on electrical appliances for health reasons or who have difficulties in understanding complex supply contracts. This concept is contained in the European electricity (2019/944/EU) and gas (2009/73/EC) directives.

[3] Reference is made for example to a 2016 Commission Communication (COM(2016) 860 final) followed by the Clean Energy for all Europeans package. More recently the Green New Deal strategy, the Next Generation EU and the aforementioned European Commission recommendation on EP have completed the framework.

[4] Commission Staff Working Document—EU guidance on energy poverty (SWD(2020) 960 final).

[5] The interpretation by Sareen et al. (2020) is different because energy poor and vulnerable consumers are considered the same and therefore to be substitutes: "From a legislative perspective, 'energy poor' equals 'vulnerable consumers' as established in EU Directives on common rules for the internal market in electricity and natural gas" (p.32).

instance, Hargreaves and Middlemiss (2020) argue that energy demand is influenced by a complex web of social relations with family, friends, agencies and communities which shapes energy practices, and shares energy services, advice and support.

This perspective implies a need to measure the areas of overlap between economic poverty indicators, EP measures and, more generally, deprivation in several dimensions, in order to create an outline of the broader condition of energy vulnerability.

2.2 Measurement Issues

Over the last 50 years, Europe has faced tremendous fluctuations in fuel prices, which have impacted households and firms. Moreover, public policies to combat climate change and to stimulate the energy transition have added a significant tax wedge to energy prices, with important distributional and competitiveness effects.[6] EP has become an issue of wide concern and identifying households vulnerable to this type of deprivation has come to be fundamental for environmental policymaking. The empirical literature has produced a large number of EP indices, and identifying the pros and cons of each metric and complementarities and redundancies among them has become very important.[7]

The first EP metric emerged after the oil shock in the 1970s, when rocketing oil prices forced vulnerable families to spend an important proportion of their budgets on energy bills. Therefore, a high budget share of energy expenditure—identified as above 10% of income—became the first indicator (known as the Ten per Cent Rule) used to identify how many households were suffering from reduced purchasing power (Isherwood and Hancock 1979; Boardman 1991). Among unidimensional metrics, the current thriving literature[8] on EP measurement identifies three main families of indicators: the first is the income-expenditure-based approach (also known as an objective metric) using energy expenditure combined with total expenditure or income[9]; the second, known as the consensual (or subjective) approach, is based on personal perceptions, and uses direct questionnaires.[10] The third family adopts a direct approach and measures the standard amount of energy needed to ensure adequate energy services. It is the most promising but also the one on which reliable data are most lacking (Thomson et al. 2017a, b; Tirado Herrero 2017).[11]

The energy-expenditure approach, which is mostly used in a one-dimensional perspective, is often preferred because of the lower influence of self-perceptions and

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[6] For a recent map of the distributional effects of environmental policies, see Lamb et al. (2020).

[7] As Alkire and Foster (2011) stress, "The way we measure poverty can have an important influence on how we understand it, how we analyse it and how we create policies to combat it. For this reason, measurement methodologies can be of enormous practical relevance.".

[8] A number of studies have recently discussed all the important aspects (Tirado Herrero 2017; Castaño-Rosa et al., 2019; Sareen et al. 2020; Heindl and Schüssler, 2015; Faiella and Lavecchia 2021).

[9] Income can be considered as the total or the residual, i.e. after deducting energy expenditure.

[10] In this group we find self-reported assessments of inability to heat the house adequately and more neutral measures such as damp walls or problems with the roof or inability to pay bills on time. We prefer to use 'consensual' instead of 'subjective,' also to be consistent with Sareen et al. (2020), because in our view it is a more neutral compared to the subjective–objective dichotomy.

[11] For an analysis of smart meter data from a Portuguese case study, see Gouveia et al. (2018).

consumer expectations, which are emblematic of consensual measurements. However, it is worth noting that expectations and perceptions clearly influence expenditure too. Within expenditure-based indicators we can further distinguish between indicators recording too high/too low energy expenditure and those considering residual income after energy expenditure. The abovementioned Ten per Cent Rule belongs in the first group[12] (Boardman 1991). Currently, the most commonly used metric to identify a threshold of expenditure considered too high is twice the median value of the ratio of energy expenditure to income, known as the '2M' indicator. Both the Ten per Cent Rule and 2M have pros and cons, which have been widely debated in the literature. The former has the merit of ease of communication and at the same time the disadvantage of having a fixed threshold that does not necessarily match changes in the context or the actual situation in different countries.[13] As for the latter, the reference to the median value ensures a dynamic threshold that relates to the evolution of actual expenditure in the reference community but also risks bringing vulnerable households out of the EP area due only to changes in total expenditure.[14] As for too low expenditure indicators, the most common indicator—known as 'M/2'—sets the threshold at half the median expenditure of the reference population. This is a mirror-image of the 2M indicator and similar considerations on relative indicators also apply to it. Although M/2 is used by the EU Energy Poverty Advisory Hub (EPAH) to help detecting households that self-impose restrictions on consumption, it is not without criticism.[15] Among indicators looking at residual income after energy expenditure, Low Income High Cost (LIHC) has important positive features.[16] It is a composite measure which identifies EP when high energy costs and a below the official poverty line residual disposable income (net of energy expenditure) occur at the same time. The idea is to detect households that are in the area of vulnerability and may fall into poverty due to their energy expenditure. A variation of the LIHC indicator proposed for the Italian case by Faiella and Lavecchia (2015, 2021) combines the two abovementioned components with so-called hidden EP, which considers both poor households with a too high share of expenditure on energy and those under-consuming, i.e. with low total energy expenditure and no expenditure on heating.[17] This modified-LIHC (henceforth M-LIHC) aims to also identify subjects presumably bound in an 'eat or heat' dilemma, who are difficult to detect with the other expenditure-based indicators. Although there are particular aspects of

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[12] Although this threshold does not show universal empirical evidence (it corresponded to empirical values in the UK in the 1980s), it has been adopted—albeit uncritically—in several countries and is often part of the EP indicator package due to its simplicity and international comparability.

[13] Indeed, 10% was twice the median energy spending as a share of income and at the same time the average share of households belonging to the first three income deciles in the UK during the eighties.

[14] This is an example of a relative indicator because the whole expenditure income distribution is considered. In other words, it represents inequality in energy consumption more than an absolute lack of energy services (Romero et al. 2018).

[15] Indeed, it has been underlined that a low consumption level can be a result of high energy efficient dwellings, specific rent contracts including utility bills or even policy interventions (utility-related subsidies and special tariffs for low income households) (Thema and Vondung 2020).

[16] The LIHC was proposed by Hills (2012) with the aim of looking at household budget vulnerability and was the official reference indicator for the UK up to 2018, when it was replaced by the Low Income Low Energy Efficiency (LILEE) indicator.

[17] For a discussion on the measurement of hidden EP, see Betto and Garengo (2020).

this indicator which may distance it from others generally used in the literature,[18] it is nevertheless the only indicator adopted in Italy in the Integrated National Energy and Climate Plan and therefore it is a relevant measure for national policies aimed at fighting EP. In studying the link between energy poverty and economic inequality in Italy, Bardazzi et al. (2021) stress the importance of a joint analysis of both consensual and expenditure-based indicators—like M-LIHC—because an income threshold alone does not seem to be an adequate way to identify families in need of help.

Although the M-LIHC indicator aims to identify under-consumption, the zero-heating expenditure condition may be too restrictive. As is highlighted in the literature (Meyer et al. 2018; Barrella et al. 2022; Cong et al. 2022), hidden energy poverty (HEP), i.e. the situation in which households self-impose restraint in their energy consumption and use energy services below a certain level deemed necessary, may be tricky to discover and generally requires a relative measure.[19] Following this approach, Meyer et al. (2018) include an HEP pillar in a three-dimensional EP composite indicator. They consider a threshold computed as a simple average of two combinations of median values of energy expenditure according to the size of the family and that of the dwelling. If a certain household consumes less than its specific threshold it can be suspected of being in HEP. Moreover, to reduce the incidence of false positives, only households belonging to the first five income quintiles and with poorly insulated dwellings are considered. Using Italian data, Betto et al. (2020) modify this approach by considering the average value of energy consumption according to climatic zone, family size and general efficiency of the dwelling as proxied by the year of construction. The problem of false positives is addressed by considering both relative and absolute income poverty indicators instead of the decile distribution.

The consensual approach produces metrics that are not threshold-based and provides direct information on the perceived state of household deprivation. It comes closer to the idea that inadequate energy use leads to additional disadvantages such as health fragility and social exclusion. This approach allows various aspects of EP to be captured while avoiding over-focusing on the monetary dimension (Healy 2004; Yip et al. 2020; Delugas and Brau 2021). The two most commonly used consensual

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[18] As is shown in Appendix A, Faiella and Lavecchia (2015, 2021) use the mean instead of the median and a zero-heating expenditure instead of a positive minimum expenditure threshold. The use of the mean clearly raises the benchmark for determining EP status compared with the use of the median. As for the zero-heating condition, it is worth noting that traditionally in southern Italy many households have refrained from installing a heating system in order to save money, despite the fact that there are several weeks when the temperature would require heating indoor spaces.

[19] When considering HEP measures, we can find the usual contrast between relative and absolute measures, which is also highlighted by Barrella et al. (2022). The first approach is based on relative energy expenditure thresholds—and so is more similar to an energy inequality perspective—whereas the second considers absolute energy expenditure thresholds, 'modelled' on a minimum level of energy requirements, and thus is like an absolute poverty perspective. This latter approach more straightforwardly looks for people consuming too little energy, with interesting contributions to the literature like Antepara et al. (2020) on Greece, Portugal and Spain, Barrella et al. (2022) on Spain and Faiella et al. (2017) on Italy. However, in order to be meaningful, this approach requires very detailed data on the energy efficiency of the household—such as heating equipment and thermal characteristics of the dwelling—together with granular data on the climatic zone where buildings are located. In the absence of these specific data, the relative thresholds—and therefore the energy inequality perspective—represent the only viable alternative.

indicators use perceived ability to adequately heat the house in winter[20] and financial difficulties of households in relation to energy costs, which is self-reported as late payment of utility bills.[21] The fact that respondents' demographic and cultural characteristics influence their perceptions of an 'adequate' temperature—like lower expectations on the part of the poor or denial of reality—is considered in some studies to be a relevant limitation (Teschl and Comim 2005) that may hinder its use in public policies. On the other hand, Tirado Herrero (2017) considers the fact that perceptions adapt over time to incorporate changes in socially perceived needs a desirable feature of EP measures. Indeed, this approach puts emphasis on the point that a state of deprivation prevents people from taking an active role in social relations and collective institutions.

To overcome the limits of specific indicators and to go beyond the simple dialectic between consensual and expenditure-based approaches, several interesting multidimensional energy poverty indicators have been designed (Meyer et al. 2018; Berry 2018; Drago and Gatto 2023). However, even this composite approach is not without criticism, since a specific parameterisation system must be chosen to combine the various elements of the index, so that transparency and international comparability can be much more difficult to attain. This is why all reports comparing EP between countries and policy targets set to decrease energy poverty generally refer to unidimensional indicators.

In sum, in the field of EP, as with income poverty, there are no measures free from value judgements or suitable for capturing all factors. In other words, identifying those in need depends on the definition adopted, which in turn depends on the socio-economic characteristics deemed worth protecting. Indeed, after several decades of research on the topic, it is clear that a unique and universal set of metrics is not available and each specific indicator has its strengths and shortcomings (Deller et al. 2021).

2.3 Data and Energy Poverty Analysis: An Uneasy Relationship

Two main data sources are internationally used to construct country-specific EP indicators at the European level. The Statistics on Income and Living Conditions (EU-SILC) provide a set of micro-data on household living conditions, i.e. income and other variables that determine material wellbeing and, more generally, the quality of life. EU-SILC is the main reference for cross-country comparisons of consensual data on EP, i.e. ability to pay bills and to properly heat the house as declared directly by

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[20] It should be noted that the difficulty of cooling, i.e. keeping an adequate temperature in excessively hot environments, a need that has been increasing with climate change and rising temperatures, is generally not considered because of a lack of regular data.

[21] This indicator, although more limited, is nevertheless considered more 'objective' and in principle is easier to compare internationally. However, differences in contracted rental arrangements among countries (with bills included or not in the monthly rent) can hamper comparability at international level.

respondents.[22] Some important features of this reliable and valuable dataset are harmonisation of the questionnaire across member states and availability of data in time series. The main limitation is that EU-SILC does not contain information on household energy expenditure for all countries.

In addition to these data, the Household Budget Survey (HBS) is carried out at the national level to measure household expenditure on goods and services by category, and variables related to demographic and socio-economic characteristics of households.[23] Unlike EU-SILC, the HBS is not governed by a European regulation and therefore harmonised datasets for European countries are released by EUROSTAT only at five-year intervals, making any temporal analysis difficult. Following the growing interest in EP, in 2016 the European Commission launched the Energy Poverty Observatory (EPOV), which developed a collection of national energy poverty indicators and other resources to monitor EP in the European Union. This legacy has been taken up by the Energy Poverty Advisory Hub (EPAH) in recent years to maintain the database and to extend it with a set of local energy poverty indicators. Among many resources, EPAH has published several reports to validate EU-SILC and HBS data and EP metrics (Gouveia et al. 2022).

Although the information landscape is far from satisfactory to analyse the phenomenon of EP at the international level, it is possible to make a cross-country comparison of all the most widely used indicators.[24] This descriptive analysis clearly shows that identifying those in energy poverty strongly depends on the definition adopted and the rankings of European countries differ accordingly, with different metrics apparently giving contradictory signals.[25] In the following bar charts the shares of households in EP in EU members states are presented according to consensual metrics (Fig. 1) and some expenditure-based indicators (Fig. 2). For this analysis Italy is also divided in three geographical macro-areas (North, Centre and South)[26] in order to consider their different characteristics in terms of climate. As for the consensual indicators (Fig. 1), in 2018 the proportion of the Italian population declaring an inability to adequately heat their homes ranked sixth in Europe but the incidence of EP in southern Italy—one of the hottest areas in the continent—ranked third, worse than countries with an unquestionably harsher climate (such as Bulgaria and Latvia). However, when considering the second most commonly used consensual indicator the picture is totally reversed: in Italy, far fewer people than the European average declare that they are in arrears in paying their utility bills and Italy ranks in 21st place in Europe.

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[22] The two questions are:

– In the past twelve months, has the household been in arrears, i.e. has been unable to pay utility bills (heating, electricity, gas, water, etc.) for the main dwelling on time due to financial difficulties? (HS021).

– Can your household afford to keep its home adequately warm? (HH050).

[23] It is important to note that both these data sources were designed for purposes other than study of EP and therefore the variables identified in them may not be the most appropriate for measuring the phenomenon.

[24] See also Gouveia et al. (2022).

[25] See Appendix A for detailed definitions of the indicators.

[26] The geographical macro-areas are defined as follows. North: Valley of Aosta, Piedmont, Lombardy, Veneto, Trentino Alto Adige, Friuli Venezia Giulia, Liguria, Emilia Romagna. Centre: Tuscany, Umbria, Marche, Lazio. South: Abruzzo, Molise, Campania, Apulia, Basilicata, Calabria, Sicily, Sardinia.
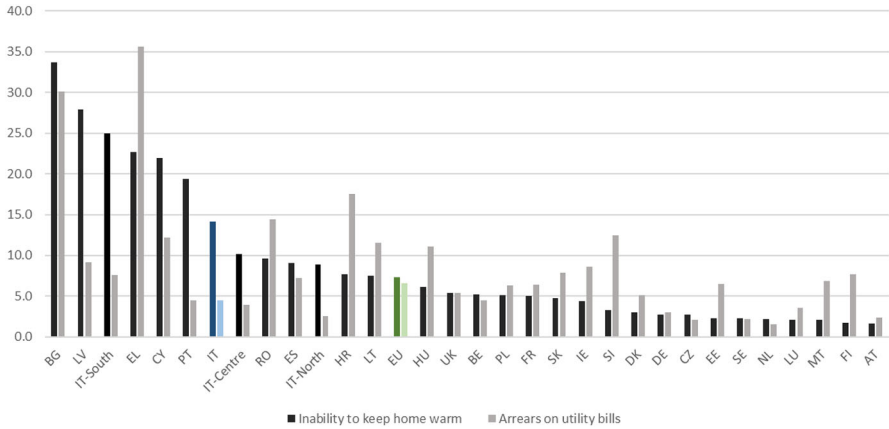
Fig. 1 Share of the population in energy poverty according to consensual indicators (2018) (Country abbreviations: *AT* Austria, *BE* Belgium, *BG* Bulgaria, *CY* Cyprus, *CZ* Czech Republic, *DE* Germany, *DK* Denmark, *EE* Estonia, *EL* Greece, *ES* Spain, *FI* Finland, *FR* France, *HR* Croatia, *HU* Hungary, *IE* Ireland, *IT* Italy, *LT* Latvia, *LU* Luxembourg, LV Lithuania, *MT* Malta, *NL* Netherlands, *PL* Poland, *PT* Portugal, *RO* Romania, *SE* Sweden, *SI* Slovenia, *SK* Slovakia, *UK* United Kingdom). Source: Authors using EU-SILC data
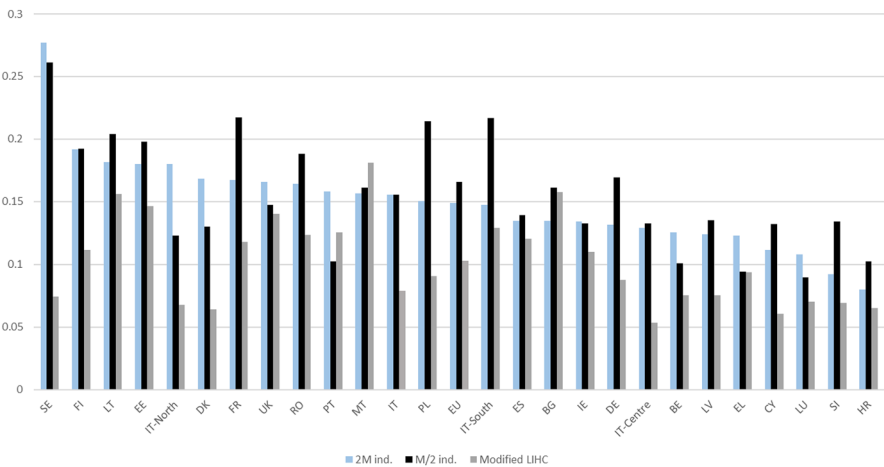

Fig. 2 Households in energy poverty according to three expenditure-based indicators (2010) (Ranked according to the 2M indicator). Source: Authors using EU-HBS data

Similarly, expenditure-based rankings are strongly differentiated according to the specific selected metric, although the cross-country comparison is limited to the year 2010.

More specifically, Fig. 2 compares the incidence of households with too high energy expenditure (2M), too low expenditure (M/2) and with low residual income and consumption constraints (M-LIHC). Overall, the three indicators put Italy in a position not far from the European average, but the macro-areas show strong differences. In

particular, in northern Italy there is a share of households with too high energy expenditure close to that of cooler countries (such as the Baltic republics and Finland), while in southern Italy there is a high share of households with too little energy expenditure and a substantial share of hardship in terms of residual disposable income and under-consumption (M-LIHC).

These two approaches—consensual and expenditure based—in some cases give diametrically opposed results. For example, Bulgaria and Greece show a very worrying situation when looking at consensual indicators and a less extreme one when looking at expenditure-based ones. For Sweden and Finland exactly the opposite is true: they show a high incidence of EP according to expenditure-based indicators and extremely comfortable circumstances when looking at consensual indicators. Besides showing different aspects of EP, these polarisations reflect cultural and institutional characteristics at the national level, and differences in climate, sociodemographic features and welfare.[27] In Appendix B additional scatter plots are presented to better show the relative positions of countries. However, these results from international comparisons, which are seemingly inconsistent when looking at different indices, simply validate the idea that energy poverty is an extremely difficult phenomenon to measure and that even within individual countries the situation can be highly heterogeneous among geographical areas.[28]

3 Overlaps and Redundancies of Energy Poverty Indicators in Italy: A Closer Look

3.1 Data and Methods

To explore the extent to which different unidimensional energy poverty indicators capture different aspects of EP status, we conduct an analysis of socio-demographic characteristics and of other deprivations and vulnerabilities beyond income poverty, with a specific focus on the Italian case. We exploit the fact that for the period 2004–2015 the Italian SILC survey (IT-SILC) includes additional data on energy expenditure and ad hoc modules on deprivations and wellbeing. Therefore, we use these microdata for this timespan as it is possible to compute consensual and expenditure-based indicators. As was mentioned in the previous section, this dataset is very reliable (Wirth and Pforr 2022) and extensively used in social studies. Indeed, both the standard and ad-hoc modules are subjected to quality analysis by Eurostat and national statistical offices.[29]

Regarding our methodology, we focus on four unidimensional indicators which are widely used for policy purposes. We first compute a consensual indicator—the ability

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[27] As is pointed out by Bouzarovski et al. (2020), comparing countries where payment of utility bills is generally included in the rent with countries where it is generally left to be paid by tenant households may result in biased indicators.

[28] For an analysis of energy poverty in selected EU countries see Bardazzi and Pazienza (2023).

[29] This is specified in EU regulation 2019/1700 on European statistics relating to persons and households. Quality reports are freely available at https://ec.europa.eu/eurostat/web/income-and-living-conditions/quality.

to keep the home adequately warm (henceforth Warm)—and two of the expenditure-based indicators shown in the cross-country comparison in the previous section (2M and M-LIHC).[30] Furthermore, following Betto et al. (2020), we calculate a specific indicator of hidden energy poverty (HEP) to identify households limiting their energy consumption behaviour because of vulnerability. In particular, we compute an HEP indicator with a threshold based on family size, the climatic condition of each Italian region (looking at the Heating and Cooling Degree Days), the presence of a leaking roof/damp walls as a proxy for efficiency of the building and relative income poverty status to deal with the false positive issue.[31] The formula is shown in Appendix A.

These four unidimensional indicators are all zero–one dummies with a positive value when the household is classified as energy poor and zero otherwise. For all the households we also select other socio-demographic characteristics to be associated with energy poverty to characterise the phenomenon according to each EP metric. First, we perform a descriptive analysis using contingency tables and Venn diagrams to show how the four indicators are interrelated with each other and how they are associated with other dimensions of vulnerability. These methods are commonly used in the empirical literature to assess poverty with a dashboard of indicators. According to Alkire et al. (2015a, b), these approaches belong to a broad category of techniques that reflect the joint distribution of individuals' deprivations in multiple dimensions. Alternatively, other statistical approaches, including principal component analysis and multiple correspondence analysis, are used to reduce the number of dimensions associated with poverty and finally construct a composite indicator. In this paper we prefer to use tables of joint distributions and Venn diagrams because our aim is to compare different EP unidimensional indicators, not to compute a composite synthetic indicator of energy poverty since EU countries design their policies based on one or more unidimensional metrics. Indeed, we want to highlight the extent that the energy-poor populations identified by each indicator overlap with each other and the type of vulnerability captured by each metric. This exploratory analysis is followed by a regression analysis to assess how and the extent to which some household characteristics suggested in the related EP literature are associated with a probability of being energy poor according to each selected indicator (see Deller et al. (2021) for a similar analysis on the UK).[32] This evidence has important policy implications as it can help policymakers tailor their energy poverty reduction policies.

3.2 Redundancies and Complementarities of EP Indicators in Italy: A Descriptive Analysis

In the last decade, and particularly during the worst phase of the economic crisis in 2012–2013, Italy recorded a progressive increase in the number of households in

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[30] The detailed formulas for these indicators are presented in Appendix A.

[31] We have slightly modified the original indicator because of data availability. We do not use the absolute poverty line for each household because it is not available in the EU-SILC dataset. Indeed, consistent time series on absolute poverty by family size and geographical location are not provided by the Italian National Institute for the whole period of analysis.

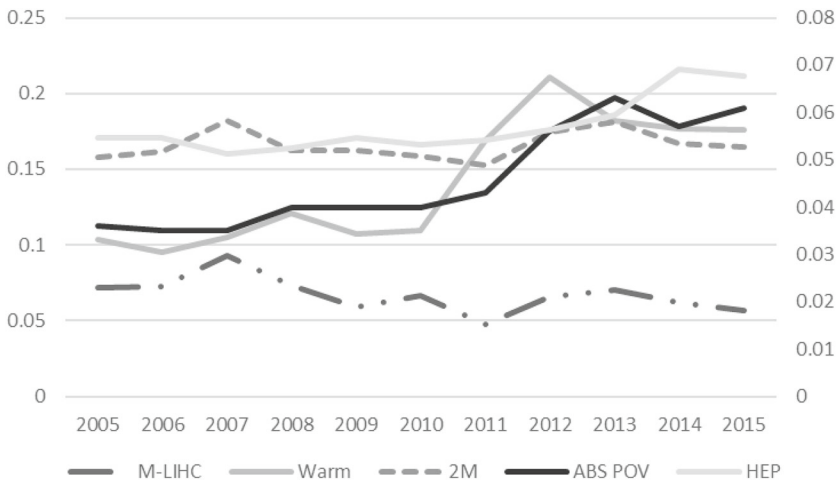[32] All the analyses are performed using Stata software.

Fig. 3 Absolute income poverty and EP indicators in Italy (2005–2015). Source: Authors using IT-SILC and ISTAT data

income poverty (absolute and relative). Figure 3 shows a peak of absolute poverty in the decade 2005–2015 in 2013. As for EP, the Warm and HEP indicators respectively peaked in 2012 and 2014 whereas the expenditure-based indices (2M and M-LIHC) are almost constant. These contradictory trends do not allow a clear-cut judgement on the dynamics in the decade. This may be due to the fact the EP indicators tend to capture partly different phenomena and so identify structurally different portions of the population.

To describe the different perspectives captured by EP indicators in Italy, we compute contingency tables of weighted data for the pooled dataset. Table 1 shows a non-homogeneous overlap between different EP indicators.[33] 2.1% of the households can be considered energy poor according to both Warm and M-LIHC,[34] whereas the incidence of EP according to the consensual indicator is on average 14.3% and that of M-LIHC is 6.9%.[35]

As expected, the two expenditure-based indicators (M-LIHC and 2M) show a much stronger correlation: 4.85% of the population can be considered energy poor according to both indicators, and this means that about 70% of the energy poor according to the M-LIHC indicator are also poor according to the 2M metric. On the other hand, only a few households showing difficulty in keeping the home adequately warm (3.9% out of 14.3%, less than a third) are detected as energy poor by the 2M index. To summarise, we can say that over the whole period, the Warm indicator has a low degree of substitution for both 2M and M-LIHC. On the contrary, M-LIHC and 2M

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[33] See also Villalobos et al. (2021) for an analysis of overlapping EP indicators in Chile.

[34] These results are confirmed both when considering the pooled dataset—that is the average situation over the whole timespan shown in the table—and each year separately.

[35] In other words, according to the M-LIHC indicator only one in three energy poor households declared an inability to keep the house adequately warm. On the contrary, according to the Warm indicator only 15% of energy poor households are detected by the M-LIHC metric.

Table 1 Contingency tables for consensual, expenditure-based and hidden poverty indicators in Italy (pooled and weighted data 2004–2015) Source: Authors using IT-SILC data

Warm	M-LIHC			Warm	HEP		
	No EP	EP	Total		No EP	EP	Total
No EP	80.97%	4.78%		No EP	82.29%	3.45%	
EP	12.14%	**2.11%**	14.26%	EP	11.75%	**2.51%**	14.26%
Total		6.89%		Total		5.96%	

2M	M-LIHC			2M	HEP		
	No EP	EP	Total		No EP	EP	Total
No EP	80.47%	2.04%		No EP	77.70%	4.80%	
EP	12.64%	**4.85%**	17.49%	EP	16.33%	**1.16%**	17.49%
Total		6.89%		Total		5.96%	

Warm	2M			M-LIHC	HEP		
	No EP	EP	Total		No EP	EP	Total
No EP	72.11%	13.63%		No EP	87.96%	5.14%	
EP	10.40%	**3.86%**	14.26%	EP	6.07%	**0.82%**	6.89%
Total		17.49%		Total		5.96%	

Overlapping between EP indicators are in bold

show a remarkable degree of redundancy (Alkire et al. 2015a, b).[36] Considering the hidden energy poverty measured by HEP, we find a high level of complementarity with the two expenditure-based indicators and a non-negligible level of overlapping with the Warm indicator. More specifically, approximately 1% of the population are simultaneously in energy poverty according to expenditure-based indicators and HEP. This means that for only 7% of those considered 2M-poor, self-restraint in consumption can be presumed (the figure is 12% with respect to the M-LIHC). However, there is a stronger correlation with the consensual approach: 2.5% of the total population are jointly identified by Warm and HEP as struggling to use energy services. This means that 42% of those identified as being in hidden energy poverty are also identified by the consensual approach.[37]

As for the link between EP indicators and the life cycle, Table 2 shows that only the Warm indicator moderately increases with householder age, while all the other metrics, including HEP, show a spike for the youngest householders and a feeble U-shape profile. The trend by age is consistent with an intergenerational distribution with

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[36] The levels of redundancy—computed according to Alkire et al. (2015a, b)—are respectively 31% (M-LIHC and Warm), 70% (M-LIHC and 2M) and 27% (Warm and 2M).

[37] The redundancy ratios are respectively 42.1% (Warm and HEP), 13.8% (M-LIHC and HEP) and 19.4% (2M and HEP).

Table 2 Energy poverty incidence in Italy by age class according to different indicators (Pooled and weighted data 2004–2015). Source: Authors using IT-SILC data

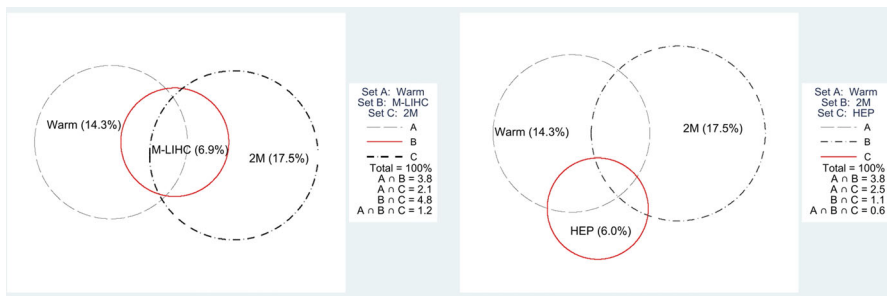|	18–39	40–64	65–75	75 +	Total
2M	16.7%	15.0%	20.3%	24.5%	17.5%
Warm	13.7%	14.1%	15.0%	14.8%	14.3%
M-LIHC	8.0%	6.0%	7.0%	8.7%	6.9%
HEP	6.9%	5.6%	5.3%	6.8%	6.0%

Fig. 4 Energy poverty in Italy according to different metrics (2004–2015). Within each panel the different sets are proportional but proportionality is not maintained between different panels. Source: Authors using IT-SILC data

younger householders particularly hit by the 2008 financial crisis, an element we will return to in the next section.

Focusing on the four EP indicators—2M, M-LIHC, Warm and HEP—we use Venn diagrams to visualise joint overlaps. Adopting a broader definition of energy poverty (a person is defined as energy poor if this is identified by at least one indicator in each dyad of metrics), the incidence of EP in the Italian population can reach 30% (Fig. 4, left-hand panel), given the union of the circles referring to the Warm and the 2M indicators that identify the highest level of EP and considering the low level of redundancy (only 3.9% of cases are jointly detected by the two indicators). Indeed, this limited intersection is also found for Belgium by Meyer et al. (2018), who relate it to the possibility of self-rationing of consumption. The first graph also shows that the M-LIHC index, although it detects a smaller percentage of EP cases, is almost entirely superimposed on the intersection area of the other two indicators. This means that the M-LIHC index detects the very core[38] of the 'certainly energy poor' population (the intersection of all the circles) and the side areas belonging only to Warm and 2M identify a 'quasi energy poor' population. The M-LIHC metric is crucial for the

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[38] As previously discussed, the use of the mean instead of the median tends to narrow the identification of those in EP.
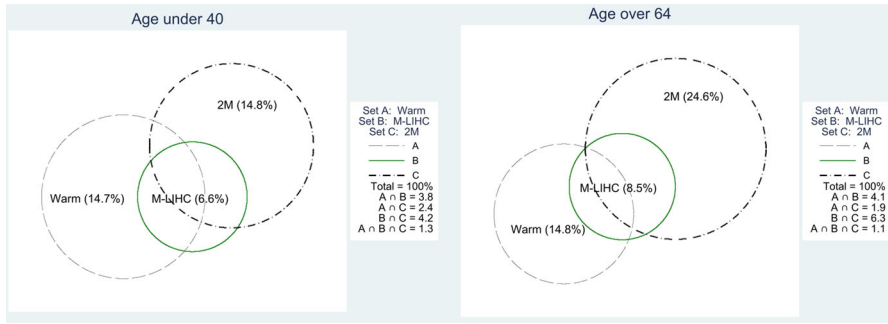
Fig. 5 Energy poverty in Italy according to three metrics: the effect of age (2004–2015). Within each panel the different sets are proportional but proportionality is not maintained between different panels. Source: Authors using IT-SILC data

Italian case because it is the only indicator used to measure energy poverty in the Italian National Energy and Climate Plan submitted to the European Commission.[39]

The right-hand diagram in Fig. 4 shows that the additional indicator of hidden energy poverty (HEP) identifies some energy poor subjects who are not captured by either the consensual or the 2M metrics, with a limited overlap with both indicators. This finding confirms that there are people identified by the consensual indicator who are not captured by the other two expenditure-based metrics, even considering under-consumption (Meyer et al. 2018). It can also be seen that HEP has a rather limited intersection with the M-LIHC indicator (0.8% out of 6%, shown in Table 1), and this finding stresses the importance of adding a specific hidden energy poverty metric to a hypothetical dashboard of indicators. Indeed, this result is also found by Meyer et al. (2018).

As for the life-cycle effect, Fig. 5 highlights different overlapping patterns for younger and older householders. Older household heads are slightly less energy poor according to the Warm and M-LIHC indicators but they devote a higher share of their income to electricity (not shown in the figure). As a result, among older householders, M-LIHC poor fully overlap with other definitions of EP. Indeed, in the left-hand panel, 1.3% of individuals living with a younger household head are jointly considered energy poor by the three indicators and there is a specific poverty area identified only by the M-LIHC metric. On the right-hand side, on the contrary, it is evident that nearly all the energy poor according to the M-LIHC metric are also detected by one of the other two indexes.

As was previously discussed, EP can be associated—in some cases as a specific cause or even effect—with many aspects of vulnerability, and obviously the strongest relationship is with income poverty. However, EP and various deprivations can also be identified in the wealthiest strata of the population, precisely because it is a multifaceted

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[39] See https://energy.ec.europa.eu/topics/energy-strategy/national-energy-and-climate-plans-necps_en#final-necps
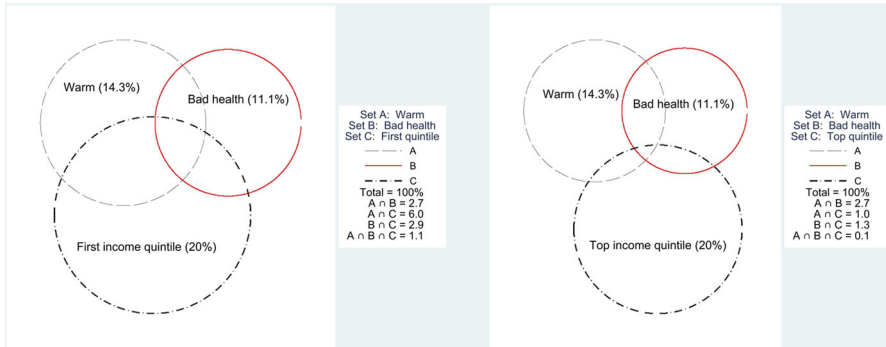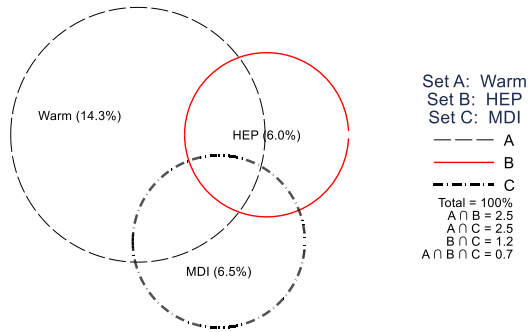
Fig. 6 Difficulty in keeping the home adequately warm and poor health in Italy by income quintile (2004–2015). Within each panel the different sets are proportional but proportionality is not maintained between different panels. Source: Authors using IT-SILC data

Fig. 7 Energy poverty and other deprivations (2004–2015). Source: Authors using IT-SILC data

phenomenon. As for health vulnerability[40]—which is widely linked to energy poverty in the related literature (Churchill and Smyth 2021; Oliveras et al. 2021; Thomson et al. 2017a, b)—Fig. 6 shows that self-assessment of bad health is present among both the poorest strata of the population (intersection of poor health and the first quintile) and among the richest (intersection with the top quintile). On the other hand, energy poverty measured with the Warm indicator overlaps more with income poverty, but also exists in the context of the richest 20% of the population.

Finally, to check correlations with other forms of deprivation besides poor health status, Fig. 7 includes a multidimensional deprivation index (MDI) built according to Alkire and Foster (2011) on eight types of deprivation.[41] These deprivations are relevant to the definition of multidimensional wellbeing but also, more specifically, in

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[40] We use information provided in the IT-SILC dataset on responses to the question 'How is your health in general?' which identifies as individuals with fragile health those who choose the options 'bad' or 'very bad'.

[41] We combine eight different dimensions: 1) Education (Did not get primary education); 2) Employment (Unemployed); 3) Safety (The area you live in has problems with crime, violence or vandalism); 4) Environment (The area where you live has problems with pollution, dirt or other environmental problems); 5) Housing (The home has problems with insufficient space); 6) Assets (The household cannot afford more than two of the following durable goods: computer; washing machine; car; dishwasher; refrigerator); 7)

relation to consensual definitions of EP and to the constrained energy-related behaviour captured by the HEP indicator. Indeed, the diagram shows that there is a significant overlap between the EP population identified by the consensual approach and subjects suffering multiple deprivations that are only partially identified by the HEP metric.

3.3 Which Kinds of Energy Poverty are Detected by Different Metrics? A Regression Analysis

To further investigate the extent to which different EP indicators are complements or substitutes in identifying the energy poor share of the population, we run logistic regressions on pooled Italian data for the whole period of the IT-SILC dataset covering the years 2004–2015. We estimate the likelihood of being energy poor at the household level by applying the following general equation:

$$Pr(Energy\ poverty = 1|Z_i) = f(\beta_0 + \beta_1 Z_i + u_i) \tag{1}$$

The dependent variable is measured by the energy poverty indicators already used in the previous sections: inability to keep the home adequately warm (*Warm*), modified LIHC (*M-LIHC*), 2M and Hidden Energy Poverty (HEP). In selecting the covariates Z_i we focus on the main socioeconomic characteristics highlighted as important in the empirical literature and, as in Deller et al. (2021), we estimate the same model for each of these metrics. Table 3 presents the average values of the dependent and independent variables for the whole timespan. Besides the main socio-demographic characteristics such as age of the householder and household size, the presence of children and being a single-parent family are included as proxies for unfavourable demographic situations, as has already been tested in previous work (Bardazzi et al. 2021). These characteristics are widely used in the literature as relevant factors influencing the probability of being in EP in southern Europe (Scarpellini et al. 2015). Moreover, we add a dummy indicating whether the household head is a migrant from a country outside the EU to capture a further situation of vulnerability (Grossmann and Kahlheber 2017; Middlemiss et al. 2019). Following our analysis in the previous sections, we also consider the deprivation status of the household as summarised by the state of health and the multidimensional deprivation index (MDI) previously defined.[42] Additionally, we control for the location of the household and the climate, as the heterogeneity across the peninsula suggests considering geographical data (Bardazzi et al. 2021). Population density is used to consider the availability of different types of energy infrastructure while the average temperature in the regions is accounted for with the heating and cooling degree days (HDD and CDD) shown in the map in Appendix C from the EUROSTAT

Footnote 41 continued

Mobility (The household has no private transport and does not use public transport because it is far away, expensive or inaccessible); 8) Connectivity (The household owns no more than one of the following goods: telephone; television; internet access). An individual is deprived if he/she scores 1 in at least 3 dimensions. We do not include energy poverty-related questions or income poverty ones because we already consider these items in our EP indexes. The source of these data is Istat—Questionnaire IT SILC 2015.

[42] As previously discussed, the Multidimensional Index also includes a dummy for educational deprivation. Therefore, the education level is not considered among the covariates. Moreover, we do not include income in our model since expenditure-based EP indicators are based on household income.

Table 3 Descriptive statistics (pooled data 2004–2015). Source: Authors using IT-SILC data

	Observations	Mean	Std. Dev	Min	Max
Inability to keep home adequately warm	517,143	0.1426	0.3496	0	1
M-LIHC	517,143	0.0689	0.2534	0	1
2M	517,143	0.1749	0.3799	0	1
HEP	517,143	0.0523	0.2226	0	1
Age of household head					
18–39	517,143	0.1730	0.3782	0	1
40–64	517,143	0.5262	0.4993	0	1
65–75	517,143	0.1596	0.3663	0	1
75+	517,143	0.1412	0.3482	0	1
Family size					
1 person	517,143	0.1460	0.3531	0	1
2 persons	517,143	0.2574	0.4372	0	1
3 persons	517,143	0.2520	0.4342	0	1
4 persons	517,143	0.2475	0.4315	0	1
5 or more persons	517,143	0.0971	0.2961	0	1
Population density					
Densely-populated area	517,143	0.4249	0.4943	0	1
Intermediate area	517,143	0.4066	0.4912	0	1
Sparsely-populated area	517,143	0.1685	0.3744	0	1
Non-EU head of household	517,143	0.0410	0.1984	0	1
Single parent	517,143	0.0224	0.1479	0	1
Children	517,143	0.4034	0.4906	0	1
Bad health	517,143	0.1116	0.3148	0	1
Other deprivations (MDI)	517,143	0.0646	0.2458	0	1
Heating degree days	517,143	2016.92	716.34	916.74	4902.01
Cooling degree days	517,143	205.03	102.31	0.32	512.95

database.[43] Finally, since we use a pooled dataset over a long timespan, we also control for the year and month of the survey (the estimated coefficients of which are reported in the supplementary material for reasons of space).

We observe from the statistics in Table 3 that in this period about 50 per cent of the householders are in the age group 40–64 years, which will be our reference category in the model. Household size in Italy has been steadily decreasing in recent decades

[43] Heating and cooling degree days (HDD and CDD) are weather-based technical indexes designed to estimate the heating or cooling energy requirements of buildings. They are measures of how much the outside air temperature is lower or higher than a specific 'base temperature' (15° for heating and 24° for cooling). Data are presented as C° temperature sums at the regional level (https://ec.europa.eu/eurostat/cache/metadata/en/nrg_chdd_esms.htm#unit_measure1599744381054).

(Bardazzi and Pazienza 2017) and it is quite evenly distributed across the classes of 2, 3 and 4 family members. Only a small share of householders are from non-EU countries (4 per cent) and single-parent families represent on average 2 per cent of the total. Most of the population lives in areas with large and medium density (42 and 40 per cent respectively).

The analyses we show in this section are based on pooling of yearly data, and sample weights are used to generalise the results to the population.

Since the overall aim of the paper is to better understand how indicators can be said to complement or substitute each other, what we are interested in is a horizontal comparison across the models estimated for each EP indicator, looking for the importance of different characteristics in the probability of being energy poor. In this analysis we do not claim any causal effect between the regressors and energy poverty status, as our aim is to assess whether it is appropriate to use more than one metric to identify the energy poor population.

Table 4 shows the average marginal effects of the logistic regressions to provide easier interpretation of the model estimates for the pooled sample under analysis.[44] We observe that, other things being equal, households with certain socio-demographic characteristics have a higher probability of being energy poor regardless of the metric adopted: location of the family in a southern region and in an urban area, small family size, nationality (non-EU) and marital status (single-parent family) of the householder. All these characteristics increase the probability of being in energy poverty as measured by all the indexes, although they show different magnitudes of the marginal effects. Similar results are found in the related literature (among others, Drescher and Janzen (2021) and Deller et al. (2021) are recent examples for Germany and the UK respectively). Similarly, the disadvantage of households is higher when multiple deprivations and poor health status are experienced. Marginal effects associated with other variables, such as climatic conditions (HDD and CDD),[45] age, family size and the presence of children in the household, exhibit different signs and significance in the four models, signalling less clear-cut links.

To better explain the results, in the following we focus on the deprivation index (MDI) by family size. Figure 8 shows the marginal effects of the multiple deprivation situation while holding family size at different values and keeping all the other covariates constant. We observe that the effect of MDI on the predicted probabilities differs across family size and the indicators: having multiple deprivations increases the probability of being energy poor particularly for large households according to the Warm and HEP measures, while the opposite is true for the expenditure-based indicators (2M and M-LIHC).

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[44] Tables with the coefficients and robust standard errors of the estimates are available on request as supplementary materials. Goodness-of-fit measure and chi-square tests are reported.

[45] See Appendix C for a map of HDD.

Table 4 Marginal effects (2004–2015) Source: Authors using IT-SILC data

	Warm		M-LIHC		2M		HEP	
	dy/dx	P > z	dy/dx	P > z	dy/dx	P > z	dy/dx	P > z
Age of household head (ref: 40–64)								
18–39	− 0.002	0.363	0.007	0.000	− 0.005	0.009	0.006	0.000
65–75	0.002	0.286	0.005	0.000	0.035	0.000	0.002	0.149
75+	− 0.016	0.000	− 0.001	0.314	0.033	0.000	0.004	0.008
Family size (ref: 1 person)								
2 persons	− 0.024	0.000	− 0.099	0.000	− 0.144	0.000	− 0.003	0.027
3 persons	− 0.010	0.000	− 0.130	0.000	− 0.234	0.000	− 0.012	0.000
4 persons	− 0.008	0.001	− 0.132	0.000	− 0.253	0.000	− 0.007	0.000
5 or more persons	0.033	0.000	− 0.127	0.000	− 0.252	0.000	0.007	0.001
Non-EU head of household	0.116	0.000	0.048	0.000	0.042	0.000	0.075	0.000
Single parent	0.075	0.000	0.054	0.000	0.106	0.000	0.023	0.000
Children	− 0.023	0.000	0.029	0.000	0.074	0.000	0.021	0.000
Bad health	0.063	0.000	0.012	0.000	0.035	0.000	0.028	0.000
Other deprivations	0.122	0.000	0.029	0.000	0.033	0.000	0.074	0.000
Region (ref: Piedmont, N)[a]								
Valley of Aosta (N)	− 0.031	0.000	− 0.034	0.000	− 0.058	0.000	− 0.005	0.288
Lombardy (N)	0.009	0.000	− 0.009	0.000	− 0.012	0.000	− 0.002	0.145
Bozen-Bolzano (N)	− 0.036	0.000	− 0.034	0.000	− 0.124	0.000	− 0.005	0.238
Trento (N)	− 0.028	0.000	− 0.028	0.000	− 0.071	0.000	− 0.002	0.444

Table 4 (continued)

	Warm		M-LIHC		2M		HEP	
	dy/dx	P > z	dy/dx	P > z	dy/dx	P > z	dy/dx	P > z
Veneto (N)	0.025	0.000	0.006	0.001	0.016	0.000	0.010	0.000
Friuli-Venezia Giulia (N)	0.023	0.000	− 0.012	0.000	− 0.036	0.000	0.009	0.000
Liguria (N)	0.038	0.000	− 0.003	0.351	− 0.055	0.000	0.000	0.984
Emilia-Romagna (N)	0.012	0.000	− 0.000	0.887	− 0.028	0.000	− 0.002	0.448
Tuscany (C)	0.040	0.000	0.000	0.902	− 0.059	0.000	0.008	0.008
Umbria (C)	0.048	0.000	− 0.006	0.027	− 0.059	0.000	0.004	0.072
Marche (C)	0.053	0.000	− 0.002	0.472	− 0.049	0.000	0.022	0.000
Lazio (C)	0.061	0.000	0.016	0.000	− 0.029	0.000	0.015	0.000
Abruzzo (S)	0.071	0.000	0.015	0.000	0.027	0.000	0.040	0.000
Molise (S)	0.101	0.000	0.024	0.000	0.011	0.135	0.030	0.000
Campania (S)	0.220	0.000	0.061	0.000	0.042	0.000	0.055	0.000
Apulia (S)	0.238	0.000	0.037	0.000	− 0.013	0.108	0.051	0.000
Basilicata (S)	0.140	0.000	0.034	0.000	0.019	0.011	0.032	0.000
Calabria (S)	0.178	0.000	0.078	0.000	0.034	0.000	0.057	0.000
Sicily (S)	0.344	0.000	0.140	0.000	0.013	0.194	0.091	0.000
Sardinia (S)	0.233	0.000	0.027	0.000	− 0.004	0.716	0.021	0.000
Population density (ref: Densely pop.)								
Intermediate area	0.029	0.000	0.019	0.000	0.078	0.000	0.009	0.000
Sparsely-populated area	0.019	0.000	0.043	0.000	0.142	0.000	0.009	0.000
Heating degree days	0.000	0.000	0.000	0.000	0.000	0.644	− 0.000	0.299
Cooling degree days	0.000	0.917	0.000	0.088	0.000	0.871	− 0.000	0.000

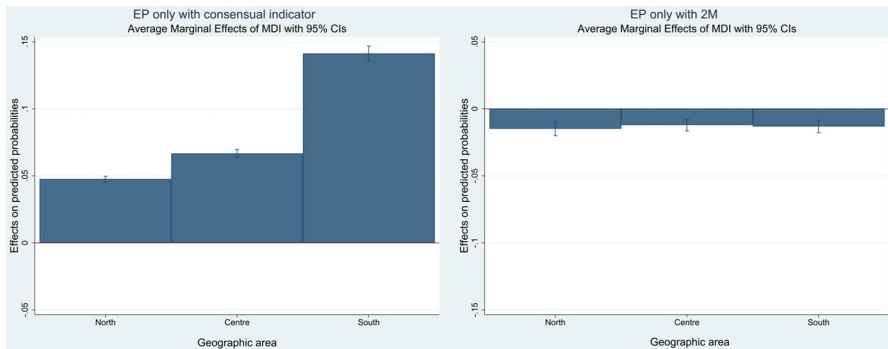[a]Regions are labelled according to their location: (N) North, (C) Centre, (S) South

Fig. 8 Marginal effects of MDI on the energy poor by family size (95% CI). Source: Authors using IT-SILC data

3.4 Further Empirical Insights

We gain some additional insights to answer our research questions by running our models on different sub-samples of the IT-SILC microdata. These estimations also serve as robustness checks of our main findings and to provide support for our conclusions.

First, we focus on the sub-samples of energy poor households identified only by the Warm or by the 2M indicator. We defined these subjects as 'quasi-energy poor' and they are represented by the non-overlapping areas in Fig. 4. In other words, they do not belong to the population identified as 'certainly energy poor' by all the indicators (the intersection of all the circles). We investigate whether the likelihood of being 'quasi-energy poor' is associated with the same factors as being 'certainly energy poor.' When we run our model on these two pooled sub-samples of energy poor households we find that the role of the covariates is generally confirmed in both cases with respect to the results for the whole sample, although with some exceptions.[46] Indeed we observe some sign changes, concerning in particular the family size for the Warm indicator and the deprivation index for 2M. Other things being equal, for those belonging to the quasi energy poverty area, the estimated probability of perceiving a difficulty in heating the home monotonically increases with family size and is not only positive for very large households as was estimated for the whole sample. Furthermore, the multidimensional deprivation index (MDI) has a positive marginal effect in the Warm sub-sample estimation and instead a negative sign for 2M. This result could support evidence that the 2M indicator may identify, among overspending people, households not suffering further deprivations, a drawback highlighted by Romero et al. (2018) of all metrics that use a simple expenditure share. Additionally, to help grasp the importance of these results, we focus on the interplay between the MDI and the geographical macro areas of residence. Figure 9 confirms that a context of multiple deprivations is associated with a higher perception of energy deprivation (left-hand panel), while the quasi energy poor identified only by the 2M indicator (right-hand panel) are households without significant vulnerabilities in other domains but with a specific problem of high energy expenditure.

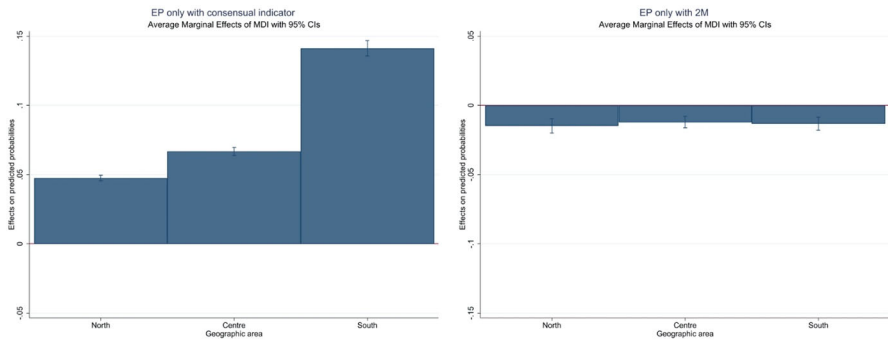[46] The estimated marginal effects are shown in Table 5 in Appendix D.

Fig. 9 Marginal effects of MDI on the quasi-energy poor according to only one metric in different macro areas (pooled sub-samples including energy poor households according to only Warm (left-hand panel) and 2M (right-hand panel). Source: Authors using IT-SILC data

In our opinion, these findings support the conclusion that different EP metrics are complementary in explaining the multifaceted nature of energy poverty. Therefore, rather than looking for the 'best' measure to define policies to combat EP we suggest creating a dashboard of multiple unidimensional indicators, including the consensual and hidden poverty metrics, to identify an elusive condition that in any case would need better and more up-to-date data, such as those in the possible energy efficiency gap and with cooling needs.

These findings are also confirmed by estimating our models for two sub-samples for the years 2004–2009 and 2010–2015. Indeed, several studies in the economics literature (Mussida and Parisi (2020); Halkos and Gkampoura (2021)) describe the financial crisis in Italy as a structural break.[47] Notwithstanding this, our empirical estimates show that most covariates display a similar sign of marginal effects for all EP models also when separately considering the years before and after the peak of the financial crisis (Table 6 in Appendix D). On the contrary, the role of age strongly varies between the two periods. Overall, other things being equal, the likelihood of being energy poor was greater for younger householders whose situation had been worsened by the economic crisis. In our view, these results are in line with evidence on the effect of the crisis on the Italian population, which was more pronounced for those of working age than for retired householders. The welfare and pension systems protected the elderly much more than the young and may have changed the distribution of EP across age groups.[48]

Finally, as a sensitivity analysis we estimated our models using different functional forms such as a probit model fitted by maximum likelihood and a linear probability

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[47] We split the timespan at 2009 because in Italy the effects of the crisis on household income were limited in 2008–2009 but they became particularly severe in 2012. This is why for the Italian case the financial crisis is frequently labelled a double dip recession.

[48] According to Brandolini et al. (2018), during the crisis *"The number of pensioners in the top two fifths increased by 3.3 million persons, while that of labour-income earners by only 300,000; on the contrary, in the two bottom fifths an increase in the number of labour-income earners by 1.5 million persons was accompanied by a decline in the number of pensioners by 350,000 persons"* p.15.

model fitted by OLS. The marginal effects estimated and levels of significance were very similar in all cases.[49]

4 Concluding Remarks and Policy Implications

Energy poverty is a complex phenomenon that includes elements that overlap with economic poverty—a lack of financial resources—and deprivation, i.e. a combination of situations that prevent individuals enjoying adequate energy services and being active members of society. Precisely because of this, there are different definitions of EP and different metrics to evaluate it, which often lead to discordant results at both the international and local levels. In particular, Italy is a country with a considerable incidence of EP according to the main consensual indicator (Warm) and at much lower levels according to expenditure-based indicators. This difference in the results of the two approaches can be partly explained by self-imposed restrictions on heating, so a hidden energy poverty indicator (HEP) appears crucial for the Italian case. Within this general framework, our analysis has focused on the relations between consensual- and expenditure-based indicators in Italy, and has highlighted their complementarities at different levels. In fact, if the results of expenditure-based indicators have a more direct correspondence with income poverty, consensual indicators signal a situation of deprivation that is reflected in other factors in addition to economic ones, and highlight the presence of hardship even in the theoretically more affluent segments of the population. Therefore, we have considered the degrees of complementarity and redundancy of different metrics, including HEP, so as to identify the main aspects of EP which deserve attention and to create a dashboard of essential indicators relevant in the Italian case, with its specific social, energy market and climatic situations. In order to understand this elusive phenomenon, we have considered three different metrics: Warm corresponds to the consensual approach, while M-LIHC (modified Low Income High Cost) and 2M (2 times the median) are expenditure-based approaches which respectively correspond to too low and too high expenditure. We have also complemented these metrics with the Hidden Energy Poverty indicator to better grasp too low energy expenditures since M-LIHC specifically focuses only on zero heating expenditure. A visual analysis makes it evident that the M-LIHC index is almost perfectly superimposed on the intersection of the other two main indicators (Warm and 2M) and so it detects 'certainly poor' households. However, it is also evident that the other three metrics (Warm, 2M and HEP) reveal large proportions of the population with difficulty in getting adequate energy services and so highlight a wide area of vulnerability. Regression analysis has confirmed that there are a set of socio-demographic characteristics related to the probability of being energy poor regardless of which metric is used, such as the economy of scale effect of large families, being a single parent, having non-EU nationality, the degree of urbanisation, health status and other types of deprivation. Since we are also interested in disentangling the factors that characterise energy poverty vulnerability, we have run regressions on the probability of being identified as energy poor exclusively by one indicator, 2M or consensual, these being the two metrics that overlap with each other the least. Our findings confirm

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[49] The results are available from the authors on request.

complementarity between these indicators: large households living in the south and in a context of multiple vulnerabilities are likely to be identified as quasi-energy poor according to the self-reported indicator, while the expenditure-based measure emphasises the burden of energy expenditure on smaller households living in the northern regions without a specific multidimensional deprivation.

To sum up, we can conclude that the consensual and expenditure-based approaches are complementary for the Italian case but they do not seem able to fully detect self-restraint behaviour, so a hidden energy poverty metric should also be considered to complete the picture. The M-LIHC indicator may appear redundant as it produces results at the intersection of the other two metrics but at the same time it also seems able to identify the core of 'certainly energy poor' households. With these results we can confirm the finding in the literature that the complexity of EP requires a combination of metrics to capture the various vulnerabilities—and their multiple intersections—leading to this condition (Meyer et al. 2018; Palma et al. 2022). This also confirms the results of Bardazzi et al. (2021), in which the two approaches—consensual- and expenditure-based—prove useful to test the link between inequalities and energy poverty in Italian regions.

The idea of using a set of indicators rather than trying to find the best approximation—either by choosing the best one or by composing a multidimensional index—has important consequences for policy design. Reliance on just one specific indicator could lead to policies that are hampered by the limitations of the metric and may hide serious drawbacks because they ignore subjects that are not identified by that metric—for instance households with low heating expenditure—but who are nonetheless energy poor according to a different metric.[50] As has been documented in this paper, the state of hardship depends on several factors that interact with income levels and the more information that is available the more effective policies can be. This is the approach implemented in Spain and in Greece, where energy related action plans use more than one indicator with different measurement approaches. Notwithstanding the high level of EP signalled by several metrics, Italy has not officially adopted either a bundle of metrics or a single EP index, although M-LIHC is the only one considered in the latest Integrated Energy and Climate Plan. This partiality of information is not helpful in designing effective policies to address energy poverty. Indeed, all the indicators signal a profound heterogeneity in energy poverty across areas, which partially correlates with the income divide which is generally meant to be tackled with subsidies (against poverty or specifically targeted at energy, such as bonuses for gas and electricity). However, subsidies have several shortcomings. They generally reach the poor but not the vulnerable population, which is by definition situated slightly above the subsidy thresholds, and at the same time they may reduce incentives to become more energy efficient. Generally speaking, those in poverty or quasi-poverty are more likely to face greater difficulties in investing to increase the efficiency of their energy use. In this respect, the recent *Superbonus* policy experiment in Italy, which was designed to increase energy efficiency and to remove financial barriers to low-income families investing in energy efficiency, appears not to have achieved this aim. Although the

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[50] Furthermore, it should be considered that cooling needs are still under-studied in Europe (neither with consensual nor expenditure based indicators), despite the fact that heat waves are a reality that creates peak mortality in many European countries.

economic resources committed to this policy reached a very important level, thanks also to the Recovery and Resilience Facility funds, the overall distributive impact appears characterised by regressivity (UPB 2023). This unsatisfactory result does not come as a surprise, as the literature stresses that energy poverty is greater in areas characterised by higher inequality (Galvin 2019; Bardazzi et al. 2021; Igawa and Managi 2022), where the institutions are also less efficient and it is therefore more difficult to implement public policies to close the various interregional development gaps (Rodríguez-Pose 2020). As was discussed above, the aim of reducing energy poverty requires complex policies (income and investment-related subsidies) to tailor assistance for the poor and quasi-poor, but the strategies planned may be insufficient to effectively eradicate the problem if weak institutions are unable to regulate the market and support household participation, both in terms of the ability to use public support and the ability to express new needs (Certomà et al. 2023). Specific attention to this point is suggested by the European Commission in the framework of the 2023 Council Recommendation (EC 2023), in which tackling energy poverty is identified as a priority for Italy. In particular, it suggests prioritising structural measures such as energy efficiency investments targeted at the energy poor and improving energy savings through one-stop shops that provide personalised energy services. All these measures should help reduce EP and achieve a fairer green transition.

For all these reasons, we strongly support the idea that policymakers need to change their approach to energy poverty. It must start by identifying the poor and the quasi-poor with a dashboard of indicators able to capture different vulnerabilities and even self-restraining behaviours. Indeed, effective policies cannot be based solely on financial assistance in paying energy bills, but must also strengthen institutions, including local ones, to ensure that households can benefit from bill- and investment-related subsidies.

Declarations

Appendix A: Energy Poverty Indicator Definitions

Family	Definition
Consensual approach—Warm	The household cannot afford to keep its home adequately warm
Expenditure-based—modified low income high cost	$I_{MLIHC} = \frac{1}{n}\sum_{i=1}^{n} w_i \left(I\left(\left(\frac{s_{ie}}{Y_i} > 2 \times \frac{1}{n}\sum_{i=1}^{n} \frac{s_{ie}}{Y_i}\right) \times I\left((Y_i^{eq} - s_{ie}^{eq}) < Y^{eq*}\right) \cup \left(I(s_i^r = 0) \times I(s_i^{eq} < P50(s_i^{eq}))\right)\right)\right)$
Expenditure-based—2M	$I_{2M} = \left(\frac{s_{ie}^{eq}}{Y_{ie}^{eq}} > 2 \times P50\left(\frac{s_{ie}^{eq}}{Y_{ie}^{eq}}\right)\right)$
Expenditure-based—M/2	$I_{M/2} = \left(s_{ie}^{eq} < 1/2 \times P50(s_{ie}^{eq})\right)$
Consensual and expenditure based—Hidden energy poverty	$HEP = 1 \forall (H_{I(jk)}) < \left(\left(\frac{1}{n}\right)\sum_{i=1}^{n} H_{I(jk)}\right) \cap (LR_i = 1) \cap (RP_i = 1)$
	i Household index (1...n)
	s_{ie} energy expenditure of the ith household (hh)
	Y_i income of the ith hh
	s_{ie}^{eq} equivalent expenditure of the ith hh
	s_i^r heating expenditure of the ith hh
	Y_i^{eq} equivalent income of the ith hh
	Y^{eq*} relative income poverty threshold, 60% of the median
	w_i sample weights
	$P50()$ median operator
	LR_i indicator for leaking roof of the ith hh
	RP_i relative poverty indicator of the ith hh
	$H_{I(jk)}$ energy expenditure of the ith hh in the jth family size class and in the k_{th} climatic zone

Source: Authors

Appendix B: Scatter Plots of Cross-country Data on Consensual and Expenditure-Based Indicators

Scatter plot by country and Italian macro area: two consensual indicators (2018)
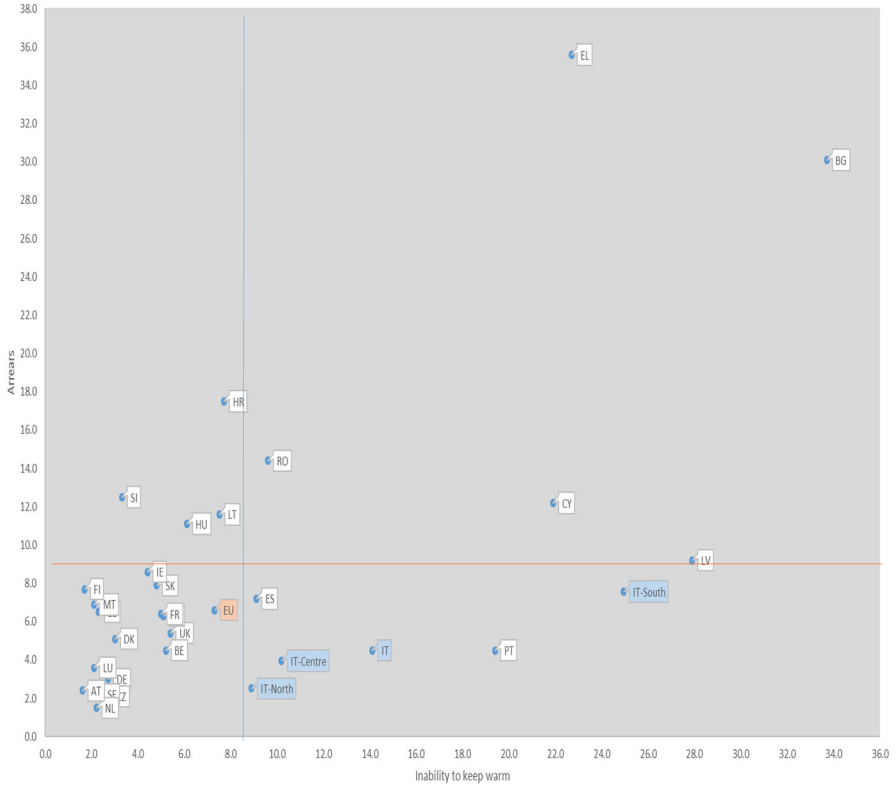
Scatter plot by country and Italian macro area: two expenditure based indicators (2M and M/2) (2010)
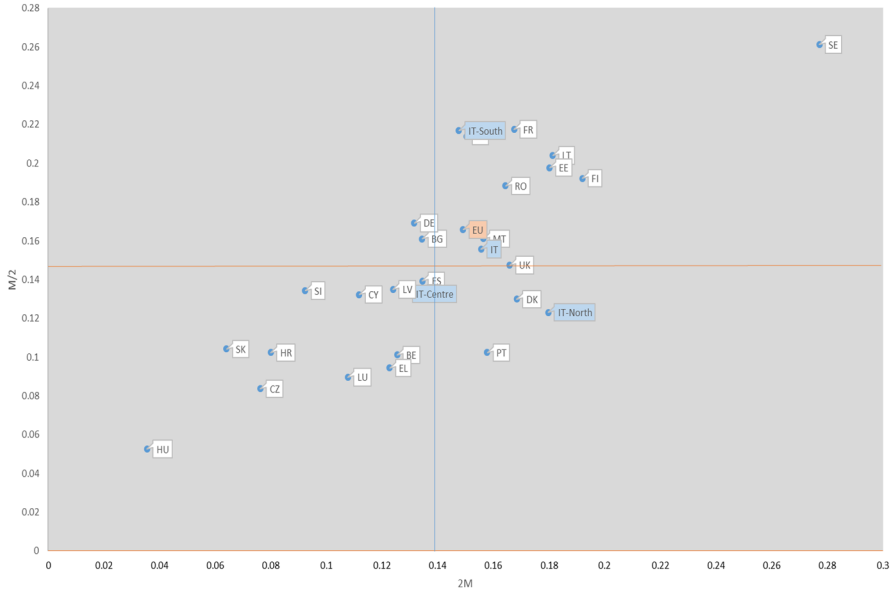
Scatter plot by country and Italian macro area: two expenditure-based indicators (M-LIHC and M/2) (2010)
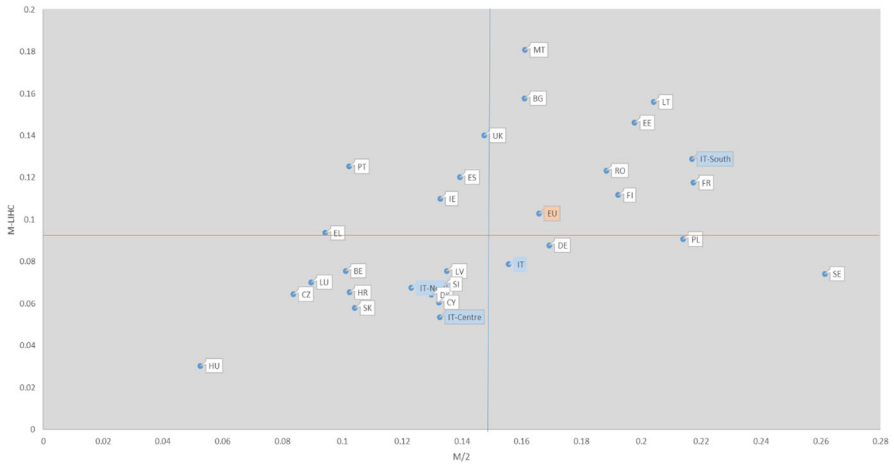
Scatter plot by country and Italian macro area: two expenditure-based indicators (M-LIHC and 2M) (2010)
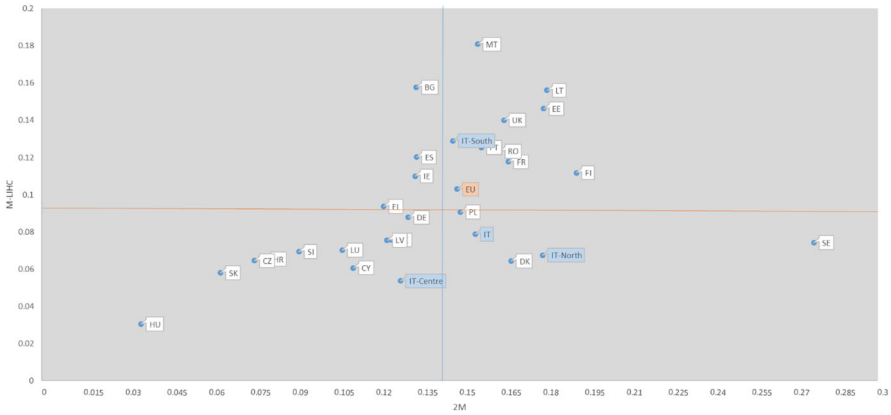
Appendix C: Map of Climatic Zones by Heating Degree Days

ZONE A	HDD ≤ 600
ZONE B	601 ≤ HDD ≤ 900
ZONE C	901 ≤ HDD ≤ 1400
ZONE D	1401 ≤ HDD ≤ 2100
ZONE E	2101 ≤ HDD ≤ 3000
ZONE F	HDD > 3000
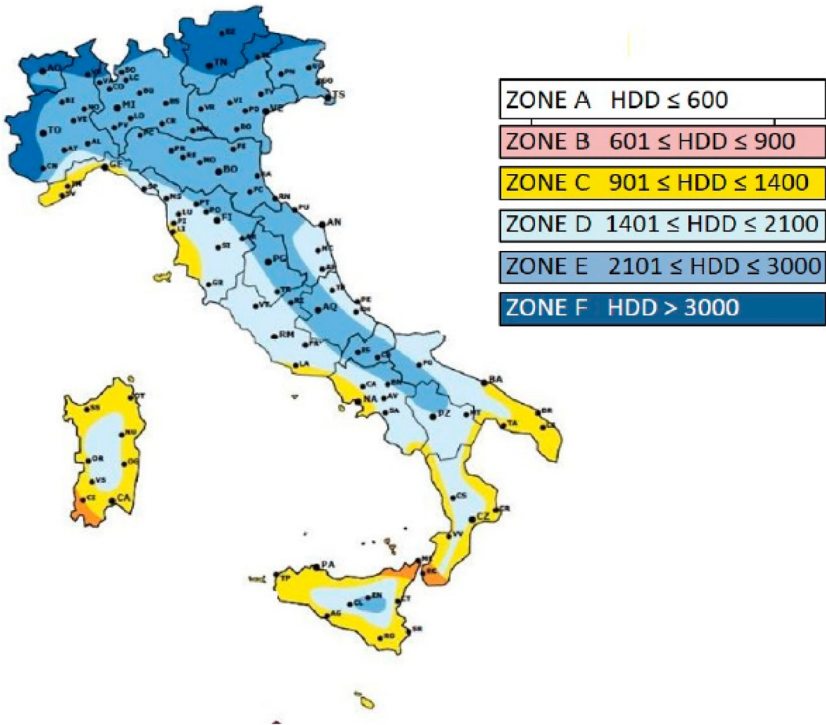
Source: De Angelis et al. (2020), page 11.

Appendix D: Regression Results

See Tables 5 and 6.

Table 5 Marginal effects (2004–2015) for EP according to only one metric Source: Authors using IT-SILC data

	Only Warm		Only 2M	
	dy/dx	P > z	dy/dx	P > z
Age of household head (ref: 40–64)				
18–39	− 0.004	0.019	− 0.004	0.004
65–75	0.005	0.002	0.027	0.000
75+	− 0.000	0.875	0.037	0.000
Family size (ref: 1 person)				
2 persons	0.006	0.000	− 0.061	0.000
3 persons	0.030	0.000	− 0.120	0.000
4 persons	0.034	0.000	− 0.131	0.000
5 or more persons	0.070	0.000	− 0.135	0.000
Non-EU head of household	0.077	0.000	0.008	0.021
Single parent	0.025	0.000	0.028	0.000
Children	− 0.029	0.000	0.046	0.000
Bad health	0.038	0.000	0.009	0.000
Other deprivations	0.070	0.000	− 0.012	0.000
Region (ref: Piedmont, N)[a]				
Valley of Aosta (N)	− 0.015	0.000	− 0.018	0.041
Lombardy (N)	0.009	0.000	− 0.006	0.035
Bozen-Bolzano (N)	− 0.016	0.000	− 0.071	0.000
Trento (N)	− 0.015	0.000	− 0.038	0.000
Veneto (N)	0.013	0.000	0.005	0.111
Friuli-Venezia Giulia (N)	0.021	0.000	− 0.027	0.000
Liguria (N)	0.023	0.000	− 0.048	0.000
Emilia-Romagna (N)	0.006	0.008	− 0.020	0.000
Tuscany (C)	0.024	0.000	− 0.047	0.000
Umbria (C)	0.037	0.000	− 0.047	0.000
Marche (C)	0.035	0.000	− 0.041	0.000
Lazio (C)	0.037	0.000	− 0.031	0.000
Abruzzo (S)	0.035	0.000	− 0.001	0.880
Molise (S)	0.060	0.000	− 0.008	0.213
Campania (S)	0.130	0.000	− 0.021	0.002
Apulia (S)	0.155	0.000	− 0.047	0.000

Table 5 (continued)

	Only Warm		Only 2M	
	dy/dx	P > z	dy/dx	P > z
Basilicata (S)	0.086	0.000	− 0.011	0.072
Calabria (S)	0.082	0.000	− 0.019	0.008
Sicily (S)	0.174	0.000	− 0.051	0.000
Sardinia (S)	0.136	0.000	− 0.046	0.000
Population density (ref: Densely pop.)				
Intermediate area	0.014	0.000	0.044	0.000
Thinly-populated area	− 0.002	0.216	0.082	0.000
Heating degree days	0.000	0.179	− 0.000	0.039
Cooling degree days	− 0.000	0.291	− 0.000	0.000

[a]The regions are labelled according to their location: (N) North, (C) Centre, (S) South

Table 6 Marginal effects before and during the financial crisis Source: Authors using IT-SILC data

	Years 2004–2009								Years 2010–2015							
	Warm		M-LIHC		2M		HEP		Warm		M-LIHC		2M		HEP	
	dy/dx	P > z	dy/dx	P > z	dy/dx	P > z	dy/dx	P > z	dy/dx	P > z	dy/dx	P > z	dy/dx	P > z	dy/dx	P > z
Age of household head (ref: 40–64)																
18–39	− 0.007	0.000	− 0.001	0.390	− 0.008	0.000	0.003	0.058	0.004	0.231	0.017	0.000	− 0.001	0.832	0.010	0.000
65–75	0.002	0.299	0.016	0.000	0.048	0.000	0.004	0.014	− 0.001	0.840	− 0.006	0.001	0.024	0.000	− 0.002	0.392
75+	− 0.010	0.000	0.010	0.000	0.030	0.000	0.008	0.000	− 0.027	0.000	− 0.012	0.000	0.040	0.000	− 0.004	0.051
Family size (ref: 1 person)																
2 persons	− 0.019	0.000	− 0.107	0.000	− 0.146	0.000	− 0.007	0.001	− 0.029	0.000	− 0.091	0.000	− 0.141	0.000	− 0.001	0.652
3 persons	− 0.008	0.001	− 0.148	0.000	− 0.248	0.000	− 0.023	0.000	− 0.012	0.000	− 0.114	0.000	− 0.220	0.000	− 0.004	0.078
4 persons	− 0.006	0.030	− 0.150	0.000	− 0.268	0.000	− 0.022	0.000	− 0.011	0.006	− 0.115	0.000	− 0.237	0.000	0.005	0.086
5 or more persons	0.029	0.000	− 0.150	0.000	− 0.269	0.000	− 0.006	0.060	0.034	0.000	− 0.105	0.000	− 0.234	0.000	0.016	0.000
Non-EU head of household	0.095	0.000	0.042	0.000	− 0.000	0.933	0.071	0.000	0.138	0.000	0.048	0.000	0.068	0.000	0.077	0.000
Single parent	0.060	0.000	0.056	0.000	0.095	0.000	0.022	0.000	0.090	0.000	0.051	0.000	0.115	0.000	0.023	0.000
Children	− 0.006	0.001	0.036	0.000	0.084	0.000	0.031	0.000	− 0.040	0.000	0.023	0.000	0.065	0.000	0.010	0.000
Bad health	0.052	0.000	0.016	0.000	0.040	0.000	0.029	0.000	0.074	0.000	0.012	0.000	0.029	0.000	0.028	0.000
Other deprivations	0.100	0.000	0.024	0.000	0.034	0.000	0.066	0.000	0.144	0.000	0.033	0.000	0.031	0.000	0.082	0.000
Region (ref: Piedmont, N)(a)																
Valley of Aosta (N)	− 0.015	0.001	− 0.002	0.919	− 0.029	0.092	− 0.008	0.098	0.157	0.000	− 0.026	0.000	− 0.070	0.000	− 0.015	0.001
Lombardy (N)	− 0.002	0.408	− 0.009	0.015	− 0.004	0.388	0.005	0.012	0.027	0.000	− 0.005	0.001	− 0.016	0.001	− 0.008	0.001
Bozen-Bolzano (N)	− 0.020	0.000	0.014	0.403	− 0.106	0.000	− 0.005	0.325	0.069	0.018	− 0.026	0.000	− 0.127	0.000	− 0.017	0.000
Trento (N)	− 0.008	0.036	− 0.011	0.187	− 0.058	0.000	− 0.008	0.004	− 0.008	0.528	− 0.022	0.000	− 0.075	0.000	− 0.005	0.283
Veneto (N)	0.032	0.000	0.009	0.000	0.021	0.026	0.014	0.000	− 0.007	0.255	0.011	0.000	0.014	0.011	0.008	0.005

Table 6 (continued)

	Years 2004–2009								Years 2010–2015							
	Warm		M-LIHC		2M		HEP		Warm		M-LIHC		2M		HEP	
	dy/dx	P > z	dy/dx	P > z	dy/dx	P > z	dy/dx	P > z	dy/dx	P > z	dy/dx	P > z	dy/dx	P > z	dy/dx	P > z
Friuli-Venezia Giulia (N)	0.027	0.000	− 0.015	0.000	− 0.038	0.000	0.014	0.000	0.029	0.000	− 0.006	0.000	− 0.034	0.000	0.002	0.460
Liguria (N)	0.004	0.286	− 0.045	0.000	− 0.077	0.000	0.002	0.502	− 0.003	0.733	0.027	0.000	− 0.044	0.000	0.005	0.265
Emilia-Romagna (N)	0.009	0.001	− 0.026	0.000	− 0.043	0.000	0.003	0.188	− 0.042	0.000	0.021	0.000	− 0.017	0.015	− 0.001	0.836
Tuscany (C)	0.026	0.000	− 0.040	0.000	− 0.078	0.000	0.004	0.189	− 0.033	0.001	0.037	0.000	− 0.046	0.000	0.019	0.000
Umbria (C)	0.030	0.000	− 0.037	0.000	− 0.081	0.000	0.010	0.000	0.014	0.079	0.018	0.000	− 0.043	0.000	0.003	0.393
Marche (C)	0.035	0.000	− 0.036	0.000	− 0.070	0.000	0.021	0.000	− 0.008	0.380	0.027	0.000	− 0.033	0.000	0.030	0.000
Lazio (C)	0.043	0.000	− 0.031	0.000	− 0.062	0.000	0.022	0.000	− 0.029	0.006	0.071	0.000	− 0.005	0.663	0.020	0.001
Abruzzo (S)	0.037	0.000	− 0.018	0.004	0.011	0.197	0.031	0.000	0.029	0.005	0.051	0.000	0.040	0.000	0.056	0.000
Molise (S)	0.054	0.000	− 0.019	0.014	− 0.030	0.003	0.043	0.000	0.037	0.003	0.080	0.000	0.047	0.000	0.029	0.000
Campania (S)	0.190	0.000	− 0.007	0.464	0.005	0.722	0.064	0.000	0.044	0.004	0.173	0.000	0.074	0.000	0.068	0.000
Apulia (S)	0.163	0.000	− 0.016	0.099	− 0.041	0.001	0.069	0.000	0.091	0.000	0.129	0.000	0.011	0.460	0.056	0.000
Basilicata (S)	0.084	0.000	− 0.014	0.079	− 0.018	0.091	0.044	0.000	0.065	0.000	0.098	0.000	0.050	0.000	0.032	0.000
Calabria (S)	0.139	0.000	0.012	0.269	0.008	0.561	0.058	0.000	0.028	0.057	0.176	0.000	0.050	0.000	0.080	0.001
Sicily (S)	0.237	0.000	− 0.004	0.739	− 0.049	0.001	0.132	0.000	0.145	0.000	0.386	0.000	0.070	0.000	0.088	0.000
Sardinia (S)	0.183	0.000	− 0.040	0.000	− 0.055	0.000	0.033	0.000	0.041	0.019	0.136	0.000	0.041	0.018	0.032	0.003
Population density (ref: Densely pop.)																
Intermediate area	0.020	0.000	0.024	0.000	0.087	0.000	0.006	0.000	0.037	0.000	0.014	0.000	0.069	0.000	0.012	0.000

Table 6 (continued)

| | Years 2004–2009 | | | | | | | | Years 2010–2015 | | | | | | | |
| | Warm | | M-LIHC | | 2M | | HEP | | Warm | | M-LIHC | | 2M | | HEP | |
	dy/dx	P > z	dy/dx	P > z	dy/dx	P > z	dy/dx	P > z	dy/dx	P > z	dy/dx	P > z	dy/dx	P > z	dy/dx	P > z
Scarcely-populated area	0.008	0.000	0.059	0.000	0.169	0.000	0.011	0.000	0.030	0.000	0.027	0.000	0.116	0.000	0.007	0.000
Heating degree days	0.000	0.779	− 0.000	0.001	− 0.000	0.011	− 0.000	0.923	− 0.000	0.000	0.000	0.000	0.000	0.060	0.000	0.239
Cooling degree days	− 0.000	0.012	0.000	0.887	0.000	0.902	− 0.000	0.000	0.000	0.000	− 0.000	0.000	− 0.000	0.101	− 0.000	0.027

[a]The regions are labelled according to their location: (N) North, (C) Centre, (S) South

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