

Energy poverty as capacity deprivation: A study of social housing using the partially ordered set

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ABSTRACT

The energy crisis generated by the Russia-Ukraine war has further highlighted the urgency of addressing energy poverty. A comprehensive understanding of its incidence, severity, and drivers is crucial to contrast its increasing diffusion effectively. This need is even more evident in the Italian social housing sector, characterized by the deep obsolescence of the building stock and the economic precariousness of its users, but still, little examined due to the scarce availability of data. According to the Capability approach, this paper aims to estimate the incidence and severity of multidimensional energy poverty in the social housing building stocks by presenting a pilot survey by administering a questionnaire to 431 households living in public housing stock in the Province of Viterbo (Italy). Although the dual cut-off identification procedure is considered the traditional approach to multidimensional poverty, it is significantly influenced by researchers' choices on weights and trade-offs between dimensions. Conversely, the partially ordered set (poset) does not require any compensation between energy dimensions. To overcome the limits of the counting approach, this paper adopts the poset to estimate the multidimensional headcount ratio and poverty gap indices. The results show a high diffusion of the phenomenon among the interviewed households: 71,23% experienced severe forms of energy deprivation, on which the inability to cool the dwelling in the summer adequately exerts a significant influence. The survey suggests the ineffectiveness of the eligibility criteria of social measures in reducing the incidence of energy poverty in this specific sector, which requires long-term structural solutions such as energy requalification programs.

1. Introduction

In recent years, the essential role of energy in human well-being has drawn the attention of policymakers, institutions, and academia to the issue of energy poverty [1]. Energy poverty refers to a situation in which households are unable to access or afford essential energy services [2]. The energy vulnerability of numerous households has been intensified by the reduction of disposable incomes resulting from the labor market crisis, escalating unemployment triggered by the COVID-19 pandemic, and the increase in domestic energy demand brought about by the extended periods of lockdown [3,4]. Moreover, the escalation of energy prices generated by the Ukraine war has further exacerbated the inability to pay for vulnerable groups. At the European level, energy poverty affects more than 34 million individuals [5]. Remarkably, approximately 85% of those energy-poor are located in just ten eastern, central and southern European countries. According to the 2020 EPOV estimations [6], Bulgaria has the highest incidence at 33.7%, followed

by Lithuania (27.9%), Greece (22.7%), Portugal (19.4%), Italy (14.1%), Romania (9.6%), Spain (9.1%), Croatia (7.7%), Hungary (6.1%) and United Kingdom (5.4%). In Italy, energy poverty has impacted an average of 8% of the population. However, the Italian Energy Poverty Observatory¹ estimates it hit more than 2.2 million households (8.5%) in 2021.

Energy poverty is a central concern within civil society, assuming a prominent role as a foundational component in various initiatives and policy considerations proposed by the European Commission aimed at enhancing building stock energy performance [7]. By combining with the Green Deal and the 2020 Recovery strategies, the primary objective of the Renovation wave strategy is to double the European annual renovation rate, thereby facilitating job creation, carbon emissions reduction, and improved housing conditions [8,9]. Specifically, one of its priorities is to alleviate energy poverty through energy retrofit of buildings inhabited by low-income and energy-poor households. Aligned with the European policy, the 2019 Italian Integrated National

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¹ <https://oipeosservatorio.it/wp-content/uploads/2023/07/rapporto2023.pdf>.

Energy and Climate Plan² (NECP) has defined energy poverty mitigation as a priority action by upgrading building stock and implementing a specific program for the social housing sector.

According to Corsetti [10], the Italian housing stock is significantly outdated, primarily because over half of the buildings were constructed prior to 1976, the year when the first Law (No. 373/76) addressing thermal consumption containment in buildings was introduced. This issue is particularly prevalent in the social housing sector. Its deeper physical and energy deterioration stems from the lack of public structural financial programs and the minimal rent levied by the managing agencies [11,12]: 44% of dwellings suffers from structural damage, while at least 24% are plagued by moisture and mould problems. This necessitates urgent energy redevelopment measures for more than 400,000 social buildings [12]. Furthermore, 58% of users are low-income households, unemployed, elderly and immigrants, categories with unstable socio-economic status [13]. Consequently, the energy obsolescence of building stock, combined with the precarious socio-economic condition of households, makes social housing the second most vulnerable sector to energy poverty in Italy [14]. However, *“it is generally accepted that the accurate identification and evaluation of the causes of energy poverty constitute the first step in solving the problem [...] The specialised literature on energy and building has put forward interesting ideas concerning social housing but an integrated analysis of household energy poverty and the management of social housing is still lacking”* [15].

While a consensus prevails regarding the need for a unified definition and methodology for energy poverty in Europe, an ongoing divergence of opinions persists with respect to the precise delineation and indicators [16]. For a long time, the main conceptual frameworks have been divided between “fuel poverty” and “energy poverty” concepts [17]. The latter often refers to inadequate access to modern energy carriers and infrastructures in developing countries [18]. In English-speaking developed countries where the study of this phenomenon originated [19], fuel poverty term is preferred to describe a situation wherein *“households needing to spend a disproportionately high share of their income on energy services”*, focusing on heating and excluding other essential energy services [20]. This terminological confusion has resulted in a plurality of measurement approaches, with the most commonly used being expenditure and consensual methods. Based on a household's self-assessment of its energy precariousness, the consensual approach provides valuable insights into real experiences of energy deprivation. However, it has a potential limitation in underestimating the phenomenon due to the risk of exclusion errors arising from the subjective nature of survey responses [21]. Conversely, the expenditure approach³ is the most widely employed method for evaluating energy poverty within individual Member States [22]. Based on assessing the incidence of energy expenditure on household disposable income, this method fails to capture the broader elements of deprivation and social exclusion that characterize the experience of the energy poor. Consequently, it reduces a multidimensional issue to a unidimensional perspective, solely focusing on energy affordability [22,23].

Overcoming the dichotomy between energy availability and affordability, Bouzarovski and Petrova [24] argue that all forms of energy deprivation culminate in the absence of a socially and materially necessary level of energy services in the home. Energy poverty is a multidimensional phenomenon depending on several factors [15], including: 1) the physical features and energy performances of dwellings and home appliances; 2) high energy prices and low income; 3) household members' sociodemographic characteristics and consumption habits. Therefore, energy poverty encompasses more than just the lack

of income, necessitating a multidimensional framework for understanding. In particular, *“understanding the role that energy services play within people's lives' calling for a 'people-centered approach, reaching beyond the technical issues, to deliver energy services that meet peoples' needs and priorities”* [24]. The Capability Approach posits that human development transcends mere economic growth, encompassing the expansion of individuals' freedom to pursue and achieve what they truly value being and doing in their lives. This approach shifts attention from the *“means of life”* to the *“actual opportunities that a person has”* (i.e. his functionings and capabilities). The main goal of the development process is to eradicate situations that deprive people of their substantial freedoms, such as poverty [25]. The Capability Approach offers a multidimensional perspective, providing a novel framework for evaluating human development, well-being, poverty, and energy poverty [26].

Energy availability and affordability are fundamental prerequisites for expanding human capabilities. Energy services act as crucial conversion factors in the link between material goods and an individual's capabilities to achieve essential daily functionings [27]. Therefore, energy poverty signifies the deprivation of a fundamental economic infrastructure for human well-being. Within this framework, Day et al. define energy poverty as *“an inability to realise essential capabilities as a direct or indirect result of insufficient access to affordable, reliable and safe energy services, and taking into account available reasonable alternative means of realising these capabilities”* [17]. Focusing on the instrumental importance of energy services for human well-being, the conceptualization of energy poverty within the capabilities space allows for a comprehensive understanding of its multidimensional nature, encompassing its constituents, determinants, and consequences. This understanding is crucial in devising effective policies to mitigate energy poverty [28,29].

Consequently, an increasing number of studies now adopt multidimensional frameworks to assess energy poverty [30]. The prevalent methodological preference among scholars lies in adopting a counting approach, particularly the dual cut-off identification procedure proposed by Alkire and Foster [31]. Freudenberg [32] sustains that the implicit compensation between dimensions, variables' dichotomization, and the use of less reliable and challenging-to-interpret aggregated indicators make the results of this method arbitrary and misleading. Furthermore, the prominence of the theory of partially ordered set (poset) in socio-economic inquiries is expanding owing to the wealth of non-quantitative data available across varied domains, such as inequality, poverty, economic and political sciences, and sustainable development [33]. In particular, Fattore et al. [34,35] recently proposed the poset as a non-compensative framework for ordinal evaluation of well-being and poverty, overcoming many of the limitations of the counting approach [36].

This paper aims to contribute to the literature by examining the incidence and severity of multidimensional energy poverty within the context of social housing. To achieve this objective, this article presents an Italian case study on a sample of 431 social dwellings in the northern province of Viterbo in the Lazio region, realised with the collaboration of the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA). The selected study area holds significance due to its different degrees of urbanization. Despite its considerable potential for energy efficiency improvement as a response to this phenomenon, there are currently no in-depth studies on the dissemination and determinants of energy poverty in this sector due to the low data availability [10]. This study aims to bridge this research gap by creating a unique database on energy needs and identifying energy deprivation patterns through a specific questionnaire submitted during in-person interviews. To the author's knowledge, poset has been employed in prior research for multidimensional measurement, but its application to energy poverty remains unexplored. This paper, therefore, represents a pioneering effort in using the poset to assess multidimensional energy deprivation. The remainder of the paper is structured

² https://www.mimit.gov.it/images/stories/documenti/PNIEC_finale_17012020.pdf.

³ The expenditure approach, especially the Low Income-High Costs indicator proposed by Hills [97] for United Kingdom, has inspired the measure developed by Faiella and Lavecchia [47] and currently adopted by the Italian Government.

as follows. Section 2 describes the questionnaire, as well as the main sociodemographic and energy characteristics of the sample. Then, it illustrates the methodological framework. Section 3 discusses the results. Finally, section 4 presents the concluding remarks.

2. Data and method

The investigation of energy poverty faces various challenges arising from the absence of a universal definition, as well as the limited availability of appropriate data and indicators [22]. Thomson et al. [22] underscore the lack of a specific survey on energy poverty. Due to the constrained availability of personal data, research on energy poverty has predominantly relied on aggregated public data at both macro and micro levels. Despite the NECP identifying social housing as a strategic sector, there is a general knowledge gap on energy poverty in this sector due to the scarcity of specific data on social housing in national surveys. To effectively address energy poverty and formulate more effective policies, it is imperative to conduct research at the local level [37]. Embracing this approach, the present study investigates a sample of 431 households residing in social buildings within the province of Viterbo (Italy). Through in-depth interviews with these households, the aim is to discern the potential incidence and severity of energy precariousness in social dwellings (see Appendix B for more details on data collection).

2.1. The questionnaire structure

The investigation of energy poverty at the European level has been primarily dominated by the focus on heating needs, often overlooking the fundamental significance of other energy services in determining the household's well-being, such as cooling, lighting, cooking and use of electronic devices [38]. The disproportionate emphasis on heating has resulted in the absence of comprehensive and adequate data concerning these energy services, especially in the context of cooling [6]. The ability to adequately cool dwellings during summer has been underestimated in both academic and political spheres for a considerable period. However, it is becoming an increasingly relevant problem for many European households, especially in Southern regions. Since climate change induces a gradual escalation in temperatures, the frequency and intensity of heat waves are expected to rise, reducing households' heating requirements and increasing their cooling need [39,40]. Prolonged exposure to elevated indoor temperatures poses significant health risks, including respiratory, cardiovascular, and circulatory diseases, as well as thrombosis and thermoregulatory disorders. These risks are even higher for vulnerable social groups such as children, the elderly, individuals with chronic illnesses, and low-income households residing in energy-inefficient accommodations [19]. This emerging dynamic accentuates the significance of acknowledging and addressing cooling-related energy poverty.

Cooking systems, refrigerators, and freezers are essential for preserving food, ensuring adequate nutrition, and promoting good health. Similarly, necessary for personal hygiene and clothing maintenance, domestic hot water, washing machines, and dryers facilitate presentability in public settings, active participation in community life, and interactions with others. Additionally, ownership of television, computers, mobile phones, and internet connection significantly influences social connectivity and engagement. Lastly, the importance of good indoor lighting for human well-being and health cannot be overstated [41]. It reduces stress, depression, other mental disorders and the number of domestic accidents. Furthermore, it extends the hours available for productive activities and academic pursuits, thereby enhancing overall productivity, educational performance, and social relations [42,43].

The *European Union Statistics on Income and Living Conditions* (EU_SILC) survey stands as the primary data resource for formulating poverty and social exclusion indicators within the EU [44]. While EU_SILC currently represents the most extensive data resource for

energy poverty studies [22], it has not been precisely defined to analyze this phenomenon in detail, as it does not encompass all aspects of domestic energy deprivations. The limited data available to the public agency pertained solely to the physical features of buildings and a few households' characteristics. A comprehensive questionnaire was developed to capture the energy consumption patterns of the designated households and assess the level of energy services available in the apartments for 2019. Recognizing EU_SILC as a good starting point for developing energy poverty indicators [45], the questionnaire has been created using the one used in this survey as a basis.

Comprehending the extent and the underlying factors contributing to energy insecurity is essential for designing effective policy instruments [46]. *"In Italy there is the paradox that, although there is no official measure of energy vulnerability, there have been specific tools to combat this phenomenon [...] for over five years"* [47]. They encompass two primary categories: a) social measures, exemplified by "Bonus elettrico" and "Bonus gas", and b) policies aimed at enhancing energy efficiency, notably through a tax credit on energy retrofitting (Ecobonus). Introduced in 2009, the former encompasses cumulative subsidies offered in the form of energy bill discounts for a maximum of twelve months. Conversely, the Ecobonus, presented by Law No. 296/2006, allows for a tax deduction ranging from 50% to 85% of expenses incurred for interventions increasing the energy performance of existing residential buildings stock. It is important to note the effectiveness of the Italian energy policies lacks comprehensive documentation, as pointed out by Koengkan et al. [48].

To address the aforementioned gaps, the questionnaire examines all the energy services mentioned above. It is composed of 51 inquiries, organized into six distinct sections: 1. Household's sociodemographic characteristics; 2. Energy services in dwellings and damaged/damp walls; 3. Mobility; 4. Total household disposable income and energy expenditure; 5. Self-reported difficulties in ensuring adequate energy services and the perceptions of social bonuses to offset energy costs; 6. Sentiments about energy efficiency improvements and requesting tax deductions for energy upgrading. The initial four sections primarily aim to delineate energy consumption habits and determine the incidence of energy expenditure on household income, thereby identifying energy deprivations experienced by the households. The last two sections, instead, investigate the potential effectiveness of social and energy retrofit measures in mitigating the phenomenon, exploring tenants' perceptions about the importance of energy efficiency improvement and principal obstacles hindering such initiatives.

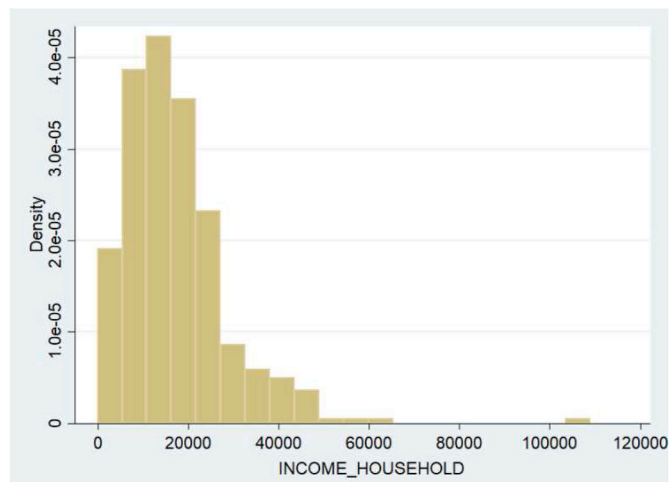
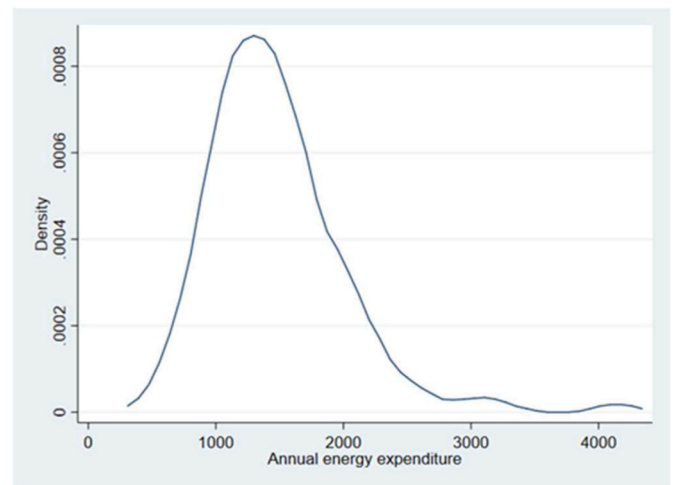
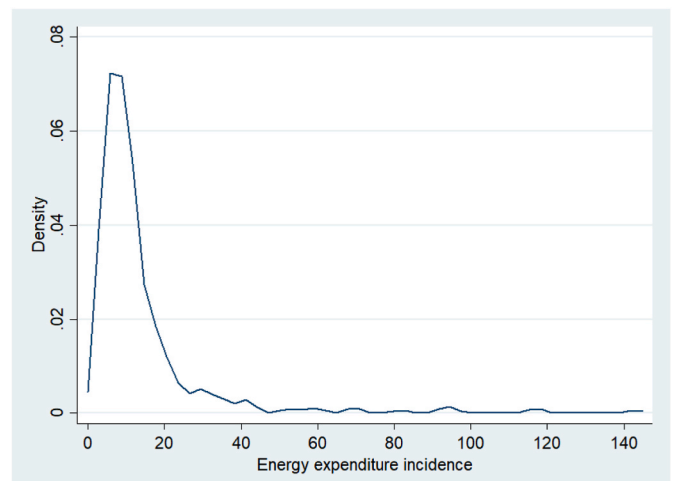
2.2. Sample characteristics

Faiella et al. [49] draw attention to the significant and persistent rise in Italian energy prices over the past decade and a half. This escalation has disproportionately impacted the most vulnerable social groups, necessitating them to dedicate an increasing proportion of their income to energy expenses due to the inelastic nature of energy consumption. Moreover, the recent price hikes triggered by the Ukraine conflict have intensified their energy vulnerability. Lannutti and Corsetti [50] identify the primary users of Italian social housing as individuals experiencing homelessness, borrowers unable to cover their debt, young adults aged between 25 and 35 years with unstable employment, elderly individuals living alone, immigrants, unemployed individuals, single-parent and low-income households due to the lower monthly fee compared to that required in the private rental market [51]. As shown in Table 1, the surveyed households primarily comprised single individuals (27.84%) and couples with at least one member aged over 65 years (25.06%). A significant proportion of these households is composed of retired elderly individuals, followed by families with one or more dependent children (21.81%) and single-parent ones (10.67%). Against an average monthly fee of €68.16, the mean household income is only €17,107.19, as expected (see Fig. 1). Italian households had an average energy expenditure of €1631 in 2019, with an income incidence of 5.1% [52].

Table 1

Absolute frequency of the sociodemographic and energy performance characteristics of the sample.

Variables	Modes	Frequency
Household type	Single	120
	Two adults over 65 years	108
	Households with one or more dependent children	94
	Single parents	46
	Two adults under 65 years	45
	Other	18
Householder's employment status	Retired	220
	Employed	112
	Unemployed	74
	Disable	25
Householder's age	20–34	8
	35–49	54
	50–64	129
	65–79	150
	>80	88
Householder's educational level	Primary school	141
	Lower secondary school	230
	Upper secondary school	51
	Graduation	9
Householder's gender	Female	227
	Male	204
Year of construction	1975	190
	1979	29
	1983	73
	1987	22
	1992	100
	1994	17
Gas boiler	Yes	287
	No	144
Alternative heating systems	Pellet stove	112
	Firewood stove	79
	Fireplace	22
	Gas bottle	12
	Other	7
Cooling system	Yes	77
	No	354

**Fig. 1.** The distribution of household income in the sample.**Fig. 2.** The distribution of total energy expenditure in the sample.**Fig. 3.** The incidence of annual energy expenditure on household income.

Conversely, tenants experienced an average energy expenditure of €1469.43 (see Fig. 2), absorbing more than 8.59% of their income (see Fig. 3).

Energy poverty is a multifaceted phenomenon involving entire households, but the literature often uses the householder's characteristics⁴ as a proxy for factors affecting household energy vulnerability. The survey revealed that the most represented age group was 65–79 years, accounting for 34.96% of the sample, followed by the age group 50–64 years at 30.07%, those over 80 years at 20.52%, and the 35–49 age group accounted for 12.59%. Furthermore, over half of the householders (51%) were retired, while only a quarter (25.98%) held stable jobs, and 17% were unemployed. A noteworthy trend among the householders was the prevalence of a low educational level, with 53.36% having completed lower secondary school. In contrast, only 11% of them had participated in high school, and a mere 2.09% had a bachelor's degree.

⁴ The questionnaire is addressed to all family members. To select the householder's data, the methodology developed by Marino et al. [98] has been modified due to the absence the variable indicating the person responsible for the accommodation in the dataset.1Selection of members over the age of 18 (adults), in particular parents;2. Among them, the employment status was examined:2aIf both work or are retired, the oldest was selected;2bIf only one is working or is retired, that individual is chosen;2cBetween an employed and a retired, the older was taken.

One feature contributing to make this study interesting is the households' gender, with more than half being women (227 out of the total 431 participants). This is particularly relevant as ENEA [53] posits that women are at a higher risk of falling into energy poverty nationally, further adding to the significance of examining energy poverty in this context.

The energy vulnerability depends on both households' sociodemographic characteristics and buildings' energy attributes [15]. A prevalent issue is the substandard quality of the majority of apartments inhabited by the participants, with most buildings built before 1976. Additionally, 67.05% of households report moisture, mould and infiltration problems in dwellings. The low energy performance of dwellings also depends on the appliances' energy efficiency [54]. Except for two cases where heating system is lacking, 287 households use an autonomous gas boiler for heating purposes. However, 144 families resort to less efficient alternative heating systems, with pellet stoves (48.27%) and wood stoves (34.05%) being the most prevalent choices, followed by fireplaces (9%) and gas bottles (5%). Contrastingly, despite the increasing importance of cooling services in enhancing household well-being, only 17.86% of tenants possess cooling systems, which are only activated for a limited duration of 2.75 h during a typical summer day.

2.3. The partially ordered set and the evaluation of energy deprivation

Increasingly, evaluating material deprivation and well-being very often requires dealing with multidimensional systems of ordinal variables rather than numerical ones [36,55]. Focusing on the energy poverty issue, its quantification faces a significant hurdle due to the limited availability of comprehensive qualitative and quantitative data [2]. Despite accessible microdata being a fundamental source, many variables are categorical and often dichotomous [45,56]. Therefore, the ordinal nature of the standard attributes involved in the multidimensional evaluation heightens the inadequacy of aggregate tools, posing challenges in accurately evaluating and interpreting the results [35]. These methodologies based on dimension reduction (such as composite indices or Multiple Correspondence Analysis) make it almost impossible to capture the complexity of energy poverty.

Multidimensional poverty measurement entails a method of identification and a measure of aggregation [57]. When developing a multifaceted indicator of poverty (i.e. energy poverty), a key challenge arises in determining the appropriate weights determining the trade-off between different dimensions [58]. A multidimensional method now widely used in the literature to study poverty is the "counting approach", formalized by Alkire and Foster [31] in the dual cut-off identification procedure. Counting the dimensions in which individuals suffer from deprivation [59], this approach exhibits noteworthy limitations [60]. According to Guarini [61], the dichotomization of energy poverty variables prevents calculating the distribution among the poor, resulting in a significant loss of information and deflecting "in anti-poverty policy by ignoring the greater misery of the poorer among the poor". Another critical limitation is the "absence of attribute relevance", which allows for implicit compensation between different dimensions of energy poverty [61]. The compensative nature of the dual cut-off identification procedure requires the researcher to choose a weight vector introducing arbitrariness, which can significantly affect estimations [62,63].

Drawing upon Sen's idea of "partial ordering" meaning the impossibility of directly comparing individual well-being, poset has emerged as a well-suited non-compensative alternative method to examine multidimensional deprivation using cardinal data [64]. Within the capability approach, poset offers a robust conceptualization and measurement approach to overcome the limits of the dual cut-off identification procedure by estimating the incidence and severity of poverty without the need for aggregation and dimensions dichotomization [61]. This method aims to synthesize the input data through a multidimensional

comparison of statistical units, quantifying the degree to which they exhibit dominance over one another. This approach diverges from conventional methods that involve aggregating the scores of units within the input variable system into numerical values for ranking purposes [55].

2.3.1. An insightful overview of the procedure

This section does not aim to present a detailed mathematical discussion of poset, but it wants to explain the main elements of this procedure. According to Fattore [35], "a preliminary and fundamental step, in social evaluation, is the identification of the evaluation space associated to the data [...]. For multidimensional deprivation, the natural evaluation space is a partially ordered set". Given a set $V = (v_1, v_2, \dots, v_k)$ of k ordinal attributes related to deprivations with possibly different numbers of degrees $m_1, m_2, \dots, m_k$, the collection of all possible achievement profiles,⁵ such as $p_a = (p_{a1}, p_{a2}, \dots, p_{ak})$ and $p_b = (p_{b1}, p_{b2}, \dots, p_{bk})$ assigned to each statistical unit generate an achievement space denoted X . Firstly, POSET aims to sort these profiles by looking for superior combinations over others. In the context of deprivation evaluation, it compares the profiles to identify those more deprived than others, establishing a partial order relation⁶ ($\succeq$) on the set X . Introducing the following partial order, it gives rise to the corresponding partially ordered set or "basic achievement poset" denoted by $P = (X, \succeq)$:

$$p_b \succeq p_a \iff p_{bi} \succeq p_{ai} \quad \forall i = 1, 2, \dots, k \quad (1)$$

This approach aims to examine the information coming from the "order relation set on the data" organized into "a component-wise partially ordered set (or poset, for short), which is assumed as the basic data structure for the scoring and ranking process. Importantly, posets have both a "vertical" dimension (comparability/dominance between elements) as well as a "horizontal" one (incomparability)" [55]. So, the profile p_a component-wise dominates profile p_b if and only if all the scores of p_a are not lower than those of p_b and at least one of them is higher. According to Arcagni et al. [65], "two poverty profiles p_a and p_b can be ordered in terms of deprivation, only if either all the scores of p_a are not higher than those of p_b or viceversa; in this case, p_a and p_b are called comparable. On the contrary, if p_a and p_b comprise so-called conflicting scores (e.g. if $p_{a1} < p_{b1}$ and $p_{b2} < p_{a2}$), then they cannot be ordered and are called incomparable".

Secondly, the achievement poset functions as the evaluative framework for deprivation and serves as the fundamental input for generating individual metrics and composite indices of deprivation. Poset thus moves beyond the traditional confinement of poverty evaluation to a single deprivation score, and the measure respects an objective scale of deprivation. The estimation consists of a multidimensional comparison between the deprivation profiles and a set of benchmark profiles [35, 65]. Compared to the counting approach identifying a point value as the threshold, several profiles can be selected as a threshold to represent the fact that there is no unique expression of deprivation but instead has a multifaceted nature. Researchers may choose the threshold exogenously, but Fattore [35] suggests that it should represent the antichain⁷ of achievement poset, meaning that it should be composed of completed deprived and incomparable profiles. Therefore, profile falling below it are classified as completely poor, while those above or incomparable

⁵ The achievement profile is defined as "the combinations of scores of each statistical units in the basic indicators considered, describing the status of units" [96].

⁶ This partial order relation must satisfy three properties: 1) Reflexivity, meaning that each profile can be comparable with itself; 2) Antisymmetry, indicating that if an object a is better than an element b , but at the same time b is better than a , the two elements equal; 3) Transitivity, when "the units are, at least, ordinal scaled and stated the possibility of defining an order among them" [97: 5].

⁷ A partial order in which any pair of elements are comparable is termed a linear order, a complete order, or a chain. Conversely, if all pairs of elements in P are incomparable, it is defined as an antichain.

with the benchmark profile could be partially or not deprived.

Subsequently, the evaluation procedure aims to identify the degree and the intensity of deprivation of poor profiles. Thirdly, poset identifies deprived profiles in the achievement poset, introducing an identification function⁸ defined as $idn()$. Comparing all possible deprivation profiles with the threshold, it assigns to each statistical unit a *deprivation membership score* between 0 and 1, which can be interpreted as “the membership degree” of the profile to the energy-poor population:

$$idn() : P \mapsto [0, 1] \quad (2)$$

$$: p \mapsto idn(p) \quad (3)$$

Based on the reduction of the linear extensions⁹ of P [35], this function attributes 0 to non-deprived profiles at all and 1 to complete deprived ones. Define ℓ as an element of the set of linear extensions of the achievement poset $(\Omega(P))$, τ is the deprivation threshold, and $idn_\ell(p|\tau)$ is the deprivation classifier associated with linear extension ℓ . Since τ_ℓ is a deprived profile in the linear order $\succeq_\ell$ of ℓ , all profiles ordered below it are deprived, and the function attributes them a value of 1, 0 otherwise. Due to variations in profile ordering across extensions, different linear extensions may yield distinct classifications for profiles. According to Fattore and Arcagni [64], the deprivation membership score of a profile is estimated by counting the fraction of the linear extensions of achievement poset. The following equation gives the identification function:

$$idn(p|\tau) = \frac{1}{|\Omega(P)|} \sum_{\ell \in \Omega(P)} idn_\ell(p|\tau) \quad (4)$$

From equation (4), some profiles can obtain one from all the linear extensions; other ones can receive one only from some classifiers, while others may not be deprived in all linear extensions. Therefore, one of the properties of the function is to divide achievement into three groups: completely deprived, partially deprived and non-deprived units.

Subsequently, the poset evaluates the intensity of deprivation by attributing to profiles a degree of nonzero deprivation through a severity function $svr()$:

$$svr : D \cup A \mapsto R^+ \quad (5)$$

$$: p \mapsto svr(p) \quad (6)$$

On the set of completed or partially deprived profiles $(D \cup A)$, we can measure the distance between a poor profile and the nearest non-deprived one on its linear extension. Averaging these distances on P , a severity score is attributed to profiles in D as follows:

$$svr(p) = \frac{1}{|\Omega(P)|} \sum_{\ell \in \Omega(P)} svr_\ell(p) \quad (7)$$

This evaluation is always based on a counting procedure for the identification phase, not on individual attributes but on the linear extensions of the achievement poset [35]. Deprivation is not a sum of individual one-dimensional privations, but a global feature of the profiles, eliminating the indeterminacy of deprivation. Once identification and

severity scores are estimated for each statistical unit, results can be aggregated at the population level, computing several indicators akin to classical measures of monetary poverty, such as the HeadCount Ratio or Poverty Gap [64]. Therefore, this study computes the identification score and poverty gap for the aggregation phase: the former is used to estimate the number of energy-poor households in the sample because the average membership identification function can be considered analogous to the standard headcount ratio in the poset approach [65]. Conversely, the latter measures the average deprivation severity over the population. A sensitivity analysis has been conducted to verify the robustness of the setting (see Appendix D). Firstly, the evaluation has been replicated, removing each energy dimension at a time and recalculating the incidence and poverty gap. Then, the indicators have been disaggregated according to several significant sample characteristics to identify relevant energy-poor social groups.

2.3.2. Selection of energy poverty variables and threshold

Using poset, researchers must select energy deprivation variables and an appropriate energy poverty threshold to estimate the incidence and severity of energy poverty in social housing. Given the crucial role of all domestic energy services in alleviating energy poverty and enhancing human well-being, as discussed in Section 2.1.1, this study selects 15 energy deprivation dimensions, as outlined in Table 2. Since the poset only applies to ordinal variables, the categorical responses from questionnaires were recorded. For variables with only two possible modes, a

Table 2

Energy poverty variables and their distribution in the sample.

Variables	Levels	Frequency
Arrears on energy bills	No	351
	Yes	80
Smartphone ownership	No	406
	Yes	25
TV ownership	No	0
	Yes	431
Washing machine ownership	No	3
	Yes	428
PC ownership	No	276
	Yes	155
Dryer ownership	No	409
	Yes	22
Fridge presence	No	0
	Yes	431
Car ownership	No	137
	Yes	294
Leaking roof, damp walls/floors/foundation, or rot in window frames or floor	No	142
	Yes	289
Inability to keep home adequately warm in winter	No	120
	Yes	311
Inability to adequately cool the dwelling in summer	No	106
	Yes	325
Hot water	No	2
	Yes	429
Internet connection	No	258
	Yes	173
Type of cooking system	Gas hob	285
	Gas bottles	133
	Electric oven	8
	Induction	5
Purchased light bulb	hob	
	LED	327
	Incandescent	39
	Halogen	37
	Fluorescent	28

value of 1 was assigned to indicate the absence of the attribute, service

⁸ The identification function must satisfy two conditions: 1) order consistency, meaning it assigns lower scores to worse profiles no higher than those attributed to better ones, and 2) threshold consistency, which implies that it assigns 1 to all entirely deprived profiles.

⁹ According to Alaimo et al. [99], an extension of P is another partial order relation $(\succeq_e)$ on the same set X indicated by $P_e = (X, \succeq_e)$ composed of all the comparabilities of $\preceq$ and adds some therefore some couple of elements comparable in $\succeq_e$ are not comparable in $\preceq$. Moreover, we can define it as a linear extension of P when all the profiles of X are comparable, so it represents a complete order obtained extending the initial poset. Each linear extension functions as a binary classifier, definitively categorizing profiles into either deprivation or non-deprivation by assessing the position relative to the threshold.

inability, or inefficiency, and a value of 2 to represent possession or efficient provision of the service. For the categorical variables¹⁰ “type of cooking system” and “purchased light bulbs”, responses were ordered according to the increase in the degree of energy efficiency.

As a non-compensatory method, poset only requires the researcher to identify a deprivation threshold. Based on the Hasse diagram in Appendix C, this study determined this cut-off based on the questionnaire responses to distinguish households experiencing energy poverty from those not. To choose the threshold, this analysis considered all combinations with a value of 2 for the following attributes: “arrears on energy bills”, which means those who do not claim to have economic difficulties with the payment of bills; b) “TV ownership” and “Fridge presence”, because all the population has at least one TV and a fridge. For the “type of cooking system”, a household was considered deprived if it did not have a gas hob, which is the norm for an Italian house, or the induction hob, the system currently considered the most efficient among the four examined. For the “purchased light bulb”, a household was classified as poor if they did not purchase fluorescent or LED bulbs, given that incandescent bulbs consume significant energy. In 2009, the European Commission (Regulation No. 244/2009) progressively prohibited the use of incandescent bulbs in all Member States. Halogen lamps have lower energy efficiency than fluorescent and LED bulbs and only meet the minimum energy efficiency standard. Therefore, the selected deprivation threshold consists of the following benchmark profiles:

“22212221112112”, “222121221122112”, “222121212212112”, “22212121112222”, “22222121112222”

The established threshold enables the identification of experiencing at least five forms of energy deprivation, which encompass situations where households report arrears with bill payments, lack access to modern information and communication technologies (such as smartphones, personal computers, or internet connection), inhabit dwellings plagued by mould, dampness, and infiltration issues, as well as the inability to heat and cool their apartments adequately. Given the severity of these deprivations, it is evident that these households can unequivocally be classified as energy-poor.

3. Results

This section presents and discusses the results of the poset implementation in the sample of social buildings in the Province of Viterbo. The first subsection describes the magnitude of energy poverty experienced by these households and the main characteristics of their energy deprivations. Conversely, the second subsection endeavours to glean insights into the effectiveness of the policy instruments implemented by the Italian Government to mitigate energy poverty.

3.1. The prevalence of energy poverty

Table 3 presents the incidence and the severity of energy precariousness observed among the surveyed households, confirming the

Table 3
The incidence and severity of energy poverty in the sample.

Index	
Incidence	0.7123
Poverty Gap	0.4899812

elevated prevalence of this phenomenon within the social buildings under investigation [14].

Similar to the headcount ratio, the average identification score highlights an average membership degree of 0.7123, indicating that 307 households fall into energy poverty. Not only is the incidence high, but the intensity of energy poverty is also high, as demonstrated by the poverty gap. The average severity of deprivation in the sample equals 0.489, meaning that 71.23% of tenants are experiencing severe energy precariousness as they report deprivation in almost half the examined energy dimensions. Energy poverty primarily arises from three factors: low income, high energy prices, and low energy performance of the dwelling, which can trap households in a vicious circle [66,67]. Examining the last driver, their high energy vulnerability can be attributed to the building stock’s profound “social, performance and energy degradation” [50]. Notably, a significant portion of these buildings (about 190) were built before the introduction of Law No. 373/76 [46,72]. At the same time, the rents paid by these households are adjusted according to their income rather than market conditions, and they are barely sufficient to cover ordinary maintenance costs [11,71]. In particular, the interviewed households pay an average monthly rent of only €68.16, rendering the institution financially constrained in renewing the building stock. Moreover, since the closure of the “Gestione case per i lavoratori” (Gescal) fund in 1998, no structural financial programs have been available for this sector, making investing in energy renovations even more difficult for managing authorities. Consequently, these buildings’ energy performance and consumption have been adversely affected. In fact, 67.05% of households reported daily dampness and mould issues, leading to considerable adverse implications for their health and well-being.

Energy inefficiency is not limited to the dwellings but extends to their facilities. Given that more than 70% of domestic energy consumption is attributed to air conditioning [73], the choice of heating and cooling systems, as well as the type of fuels used, assumes crucial importance. In Italy, electricity and natural gas are the standard domestic energy sources [74,75], and the lack of access to these resources can significantly hinder the ability to heat homes adequately, thereby increasing energy vulnerability [76]. Moreover, households with a gas heating system tend to have approximately half the expenditure due to the lower cost of this energy source and the enhanced energy efficiency of modern boilers [77]. Findings reveal that a considerable proportion of tenants (72.16%) declare an inability to heat their homes during winter adequately because they must resort to alternative heating tools, being disconnected from the gas network. According to a 2019 ranking produced by OpenExp, commissioned by the European Climate Foundation [78], Italy ranks fifth concerning cooling deprivation. While 98% of the Italian population has a heating system, only 29.4% have access to air conditioning, and 37% of the poorest population inhabit homes that are not adequately cooled during the summer months [75]. Results seem to confirm the importance of cooling because it is still uncommon among the surveyed dwellings (77), with 75.41% of households stating their inability to adequately cool the house during the summer months. Considering the first two factors, the constant increase in energy prices over the last fifteen years has led to a progressive growth in the incidence of domestic energy expenditure on disposable income, especially among the most vulnerable categories [79]. Despite the fact that these households, on average, allocate 8.59% of their limited disposable income to meet energy expenses, only 18.56% of tenants report having overdue energy bills. However, this number could be underestimated as the energy poor often feel embarrassed to declare their inability [21]. Considering household appliance ownership, nearly all families use electronic devices, such as telephones, washing machines, televisions, and fridges daily. On the contrary, the prevalence of dryers remains relatively low (5.10%), and freezers are still widespread (28.07%). Modern communication, information, and entertainment technologies have become indispensable for ensuring a dignified life, adequate children’s education, or finding a job [42,80]. Limited financial resources,

¹⁰ In the first case, the response modes have been coded as follows: Gas bottles = 1; Electric burners = 2; Gas hob = 3; Induction hob = 4. For the light bulb, instead, as follow: Incandescent = 1; Halogen = 2; Fluorescent = 3; LED = 4.

likely a result of low educational attainment and unstable employment conditions, restrict access to them for more than half of these households. In fact, 64.04% of tenants lack a computer, and 59.86% do not have access to a fixed internet connection. Finally, 82.36% and 67.28% use LED and fluorescent bulbs, gas and induction hobs.

The sensitivity analysis reports three different degrees of relevance¹¹ of energy dimensions (see Table D1 in Appendix D): a) strong influence, b) mitigation effect, and c) limited impact on the energy precariousness of tenants. Variables with strong influence generate a significant reduction of identification and poverty gap indices. This group includes arrears on energy bills, dryer ownership, leaking roof, damp walls/floors/foundation, or rot in window frames or floor, inability to keep home adequately warm in winter, inability to adequately cool the dwelling in summer, internet connection, type of cooking system, and purchased light bulb. It is important to observe that all variables represent basic needs. Note that internet connection availability can be viewed as an essential element of households' well-being, aligning with Simcock et al. [42]. Conversely, PC and car ownership seem to have a mitigation effect on energy vulnerability in social housing because they are related to working and educational opportunities [42]. In particular, the ability to move freely facilitates the pursuit of academic and employment opportunities, access to essential services such as health-care, and participation in social activities [81]. A significant majority of respondents (68.21%) reported owning and using¹² at least one car on a daily basis, although fuel costs constitute 49% of the energy expenditure of Italian households [82]. Finally, the remaining dimensions do not impact on identification but influence the severity of household energy poverty status.

The analysis of subpopulations has highlighted some significant social groups. Considering the municipality, dwellings located in Tuscany represent the poorest group (see Table D2). This condition could be attributed to the fact that these dwellings were constructed prior to 1975. According to Csiba et al. [70], householder employment status and educational level are crucial drivers of household energy vulnerability. While employed status constitutes a small percentage of the energy poor, the more vulnerable group is represented by the unemployed, followed by the disabled and retired ones, reflecting the low level of household income shows an inverse relationship between educational level, incidence and severity of energy poverty, confirming that lower educational levels limit opportunities to achieve stable occupations and income sources [30]. Considering householder age, the poverty gap seems to be inversely related to age. Conversely, age is positively associated with the identification score, supporting the conclusion of Faiella et al. [47,83]. Finally, the gender gap seems irrelevant for the subgroup identification.

3.2. The effectiveness of Italian policy instruments in social dwellings

As illustrated in Section 2.1.1, the effectiveness of the social and energy efficiency-enhancing instruments in alleviating domestic energy poverty has not been well examined [48]. To address this research gap, the final two sections of the questionnaire aim to shed light on their effectiveness and the obstacles hindering their broader adoption.

Social bonuses are designed to alleviate the impact of energy

expenses on household income, so they could reduce the likelihood of energy poverty by making energy more affordable [79]. However, the Italian Regulatory Authority for Energy, Networks, and Environment reported that these bonuses have demonstrated limited efficacy as policy tools against energy poverty, with fewer than one-third of eligible beneficiaries formally applying for them [74,79]. Fig. 4 indicates that merely 41 out of 111 surveyed eligible households take advantage of at least one of the two aids. The primary reason for their diminished effectiveness appears to be the eligibility criteria linked to the household's wealth expressed through the Equivalent Economic Situation Indicator (ISEE) [79]. Despite belonging to low and medium-income groups, many tenants cannot access the bonuses due to exceeding the stringent legal limits of €8265 and €20,000 for households with three or more dependent children. In particular, households primarily consist of one (120) or two members (154) with an average annual disposable income of €17,107.19. Secondly, the deduction's calculation is solely based on household size and the climatic zone of residence without considering actual energy consumption, contributing to a modest impact on the household budget [74]. Specifically, the average discount applied directly to energy bills amounts to only €40.48 for the 29 households receiving both bonuses, €17.68 for those receiving the electric bonus, and €46.61 for those receiving only the gas one. Thirdly, there is a notable lack of awareness among tenants regarding the existence of these subsidies, supporting the hypothesis that energy-poor households are often uninformed about their energy consumption and the availability of affordable energy-saving opportunities [84,85]. Finally, this unawareness, in conjunction with the complexity of the application process, appears to hinder some households from submitting applications or renewal requests [86].

As described in Section 2.1.2, 144 tenants must resort to alternative heating systems to the gas boiler to meet their heating needs due to the high-cost burden. Notably, 117 of these households are not even connected to the gas network, exacerbating their energy vulnerability because they cannot take advantage of the bonus gas. In fact, this social measure is even less prevalent because eligibility is not only linked to the ISEE, but is restricted to users connected to the gas network [87]. As previously identified by Lavecchia and Stagnaro [88], low percentages of beneficiaries and reasons reported by households in interviews underscore the inadequate selectivity of the current eligibility criteria, highlighting the necessity for a comprehensive review of these criteria to render these bonuses more effective in supporting energy expenditure. Furthermore, current standards overlook essential aspects of domestic energy consumption, potentially excluding a substantial number of energy-poor individuals from the audience of potential beneficiaries [79].

As mentioned in the introduction, the 2019 NECP has identified energy retrofit of social housing as a strategic priority to address energy

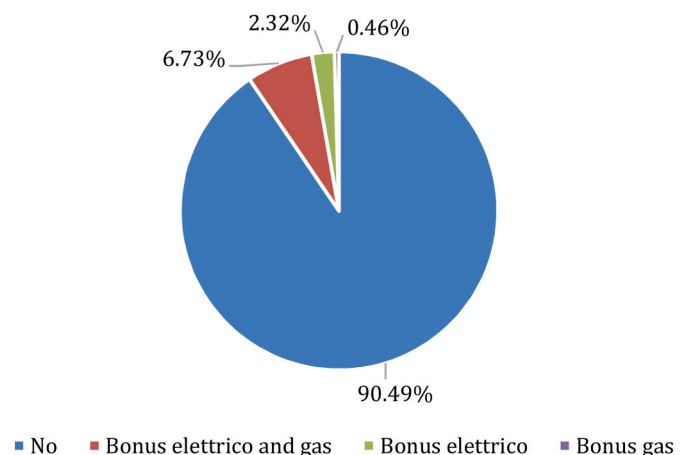


Fig. 4. The distribution of access to social bonuses among tenants.

¹¹ Note that in the model does not exist dimensions that are not relevant to the energy poverty condition of households.

¹² Tenants report that the primary users of the car are the householders themselves (212) and their spouses (149). Other household members, particularly dependent children, primarily rely on walking to reach places of interest, such as schools or other local destinations, due to the small size of the Municipalities. Most respondents indicated travelling a maximum of 5 km daily to commute to their workplaces or educational institutions. Only a limited number of individuals (30), mainly between the ages of 15 and 25, reported travelling more than 5 km daily.

poverty. While these interventions offer a long-term solution to the phenomenon acting on its structural causes [89], they require a considerable initial investment that low-income households and managing entities can hardly support. Although access to Ecobonus was only extended to public agencies through the 2018 Budget Act, it failed to address the limited investment capacity within this sector effectively, already compromised by the low revenue generated from low rents and the absence of specific financing programs. Indeed, Viterbo's agency did not avail of this measure to renovate its approximately 4000 dwellings, as the average rent of €68.16 was already insufficient to cover ordinary maintenance expenditures. In 2020, the increase of the tax deduction foreseen by the new political structure of the "Superbonus¹³" has allowed the institution to plan a series of interventions to significantly reduce management costs, enhance thermal insulation, and curb energy consumption in its building stock.

Given that the managing authority oversees both ordinary and extraordinary maintenance operations, including energy retrofitting of buildings and appliances, a limited number of households (60) have undertaken minor energy efficiency improvements.¹⁴ Despite the extension of credit transfer opportunities to low-income individuals by the 2017 Budget Law, only three tenants have applied for Ecobonus. As in the case of social measures, the application seems to be hindered by the bureaucratic complexity of the procedure, not compensated by the low cost of replacement, as well as by a lack of knowledge about this option. Interesting are the barriers these households perceive in implementing even modest energy efficiency improvements, whose understanding is fundamental to developing well-targeted policies. In line with the literature, 359 tenants indicate that the primary constraint is the high costs involved. Energy poverty tends to affect low-income households, including those in this sample, who often face the dilemma between fulfilling their energy requirements or their basic needs. Therefore, they do not possess the necessary financial resources to make the initial investment required by these interventions [90]. Despite the poor quality of the buildings, 63 respondents do not perceive a need or importance to improve the apartment's energy efficiency. This attitude may depend on two different reasons. Firstly, energy poor may have lower expectations, leading them to adapt to the circumstances without seeking any improvement [21]. Secondly, these households are less involved with the issue of energy efficiency, and they can be more reluctant to invest in an asset they do not own and may have to leave before having recovered the substantial initial expenditure [47,91]. Finally, only six users report the lack of information on energy-saving measures as a barrier to enhancing the energy performance of the houses and their systems.

4. Conclusions

In light of the heightened energy vulnerability experienced by European households due to rising energy prices and increased domestic

energy consumption resulting from the impacts of the COVID-19 pandemic and the Russian-Ukraine war, addressing energy poverty becomes a fundamental prerequisite for a fair and just transition to a climate-neutral Europe by 2050, ensuring that no one is left behind [4,6,8]. Aligned with the European Green Deal strategy, enhancing measures to address energy poverty is a priority within the 2019 Italian NECP. The strategic importance of energy retrofitting in social housing is particularly emphasized, but this sector grapples with numerous challenges. The building's obsolescence, energy inefficiency, users' precarious working and income statuses, and the limited capacity of managing authorities result in a vicious circle that exposes it to an increasing energy vulnerability.

The common expenditure approach primarily views energy poverty as a unidimensional phenomenon solely tied to energy affordability, failing to capture the complexity of essential energy services deprivation fully. Conversely, energy poverty is a multidimensional phenomenon, encompassing energy availability, well-being, housing quality and energy performance of systems appliances [92]. The Capability Approach offers a more suitable theoretical framework for studying energy poverty, valuing its multifaceted nature, overcoming the limits of expenditure measures and capturing deprivations suffered by the energy poor. Based on this conceptual framework, this paper employs the theory of partially ordered set for the first time to evaluate energy poverty. As a multidimensional and non-compensatory methodology, it avoids imposing trade-offs between energy dimensions and expands the information base without dichotomizing variables. Despite these strengths, the poset is not independent of the value judgments of the researcher, particularly in the choice of the deprivation threshold. This study's chosen threshold allows us to focus on the most severe forms of energy deprivation. Still, unfortunately, it creates a clear distinction between energy-poor and non-energy-poor households and does not highlight non-fully deprived ones. Building on the recent advancements in poset made by Fattore and Alaimo [55], future research is needed to identify benchmark profiles providing a gradual distribution of the phenomenon in the population. This property could support the definition of policy tools capable of assisting households according to the severity of their condition, prioritizing those suffering from more severe forms of deprivation.

To the best of the author's knowledge, in-depth studies on the incidence, intensity and causes of energy poverty within Italian social housing are scarce, primarily due to the absence of specific data. The local survey discussed in this paper reveals a significant incidence, but above all, a high severity of energy deprivation among the surveyed households. Beyond the lack of the most common communication and information tools, many energy-poor tenants declare daily struggles with dampness and mould issues, the inability to heat their accommodations adequately, and, notably, insufficient cooling capabilities. In line with national estimates, findings highlight that 82.14% of tenants cannot afford an air conditioner, leading to severe health and quality of life consequences. Considering the escalating frequency of heatwaves affecting Mediterranean countries annually, it is crucial to consider that Eurostat's decision to cease collecting data on indoor cooling from 2020 will result in the loss of essential information necessary for studying this critical aspect of energy deprivation. This decision will constitute a significant barrier to advancing efforts to address energy poverty at the European level [38].

The Italian approach to alleviating energy poverty exhibits a fragmented nature. Although specific policy instruments have existed for fifteen years, their effectiveness remains inadequately documented in the literature, especially if reported to social housing. The limited diffusion of social bonuses and Ecobonus among the surveyed tenants indicates their ineffectiveness in addressing the phenomenon, probably because they were not explicitly designed for this purpose and were not accessible to energy-poor households [76]. The eligibility criteria for social bonuses, particularly the ISEE, and the bureaucratic complexity appear to be significant factors contributing to the low demand. Law No.

¹³ Introduced by the so-called Relaunch Decree (No. 34/2020), this tool raises the deduction rate provided by the Ecobonus of 65%–110% of the costs incurred for interventions of: a) recovery of the building, including those aimed at seismic adjustment (Sismabonus); b) energy upgrading of buildings (Ecobonus); c) installation of photovoltaic systems and charging stations for electric vehicles. Subsequently, the Budget Act 2021 (L. No 178/2020) extended this measure to all expenditure incurred by 30 June 2022, and, for certain specific cases, to 30 June 2023. The Superbonus has been extended to cover expenditure incurred within this deadline, as well as expenditure planned by 31 December 2023, provided that at least 60% of the project has been completed.

¹⁴ The measures eligible for deduction are: a) windows; b) solar shielding; c) biomass boilers; d) condensing boilers with energy class A (<https://www.ufficienzaenergetica.enea.it/detrazioni-fiscali/ecobonus.html>). Most of these households have replaced the fixtures in order to improve the thermal insulation of their dwellings, while 14 have changed the old boiler with a more modern condensing one.

157/2019 introduced the automatic payment of these bonuses through the energy bill starting in 2021, which could potentially compensate for the lack of awareness and means cited by many participants. However, maintaining the same eligibility criteria raises the concern that many energy-poor households might remain excluded from these support measures. To sustain the energy expenditure of target households effectively, eligibility criteria should be decoupled from households' wealth and directly linked to energy poverty indicators [68].

Energy subsidies provide a temporary remedy for alleviating the effects of energy poverty, whereas the fundamental causes necessitate long-term solutions focused on advancing energy efficiency policies [89]. The case study findings reveal that the main obstacle to the implementation of energy improvements in social housing is the considerable upfront investment, which is unsustainable for low-income households and public institutions. Despite the recent extension of the Ecobonus to include these subjects, it appears insufficient to address their financial constraints adequately. The interviews also disclose additional obstacles to enhancing energy efficiency in social housing, such as the reluctance of users to invest in housing for rent, low adaptive expectations, and, above all, the lack of involvement of low-income households with the issues of energy saving and lack of information. The policy instruments examined in this study aim to address only the financial resource gap. Another essential element for an effective energy retrofit project for social buildings is the active participation of all stakeholders, particularly tenants. Drawing on the Capability Approach, these households should not be treated as passive recipients but as active agents of change. By empowering them with the necessary information through awareness campaigns and focus groups, they can adopt new, sustainable consumption patterns [12,53].

Results appear to support the necessity, as already highlighted by the NECP, to enhance policy instruments aimed at mitigating energy poverty. This objective can be achieved by focusing particularly on investing in the energy renovation of residential buildings, with an emphasis on the strategic social housing sector. The National Recovery and Resilience Plan (NRRP) offers new investment opportunities for

Italy to counter the escalating prevalence of energy poverty. Component three of the Green Revolution has allocated a specific investment line to stimulate the energy renovation of over one hundred thousand private residential and social buildings. Furthermore, energy communities, prioritized in component one of the NRRP's second mission, could be a crucial instrument in achieving a fair energy transition. Grounded in the decentralization of renewable energy production, energy communities "can not only be an opportunity for technological innovation and the fight against the climate emergency, but also represent a key to combat inequality, energy poverty and to offer opportunities for development through structural interventions without assistance" [93]. With the potential to achieve significant energy savings of up to 61% [94], they could provide continuous access to affordable energy services for households residing in social housing. They could also take advantage of constant monitoring of energy consumption even when they do not have the financial resources to install expensive photovoltaic systems. These measures will powerfully boost the economy and employment, as well as promote social resilience by improving the population's living conditions and alleviating energy poverty.

CRediT authorship contribution statement

Chiara Grazini: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

Data availability

The data that has been used is confidential.

Appendix A. Energy expenditure estimation

A section of the questionnaire was devoted to recording the energy consumption of households to estimate their energy expenditure and its incidence on disposable household income (see Section 2.1.1). Participants were asked to provide the values of electricity and natural gas bills or, if unavailable, their average bimonthly amount in summer and winter, respectively. The collected information was used to estimate:

- annual electricity expenditure;
- annual natural gas expenditure for heating and cooking;
- yearly total energy expenditure.

If all the bills were available, the amounts were simply added up. In the alternative, if the average values were provided, the year was divided into two periods: a) winter, from November to April; b) summer, from May to October. This division is predicated on the fact that the Municipalities under consideration are situated within the Italian climatic zone D, where heating systems are permitted from November 1st to April 15th. Therefore, the annual expenditure on electricity was calculated using the following formula:

$$\text{annual electricity expenses} = (\text{winter bill} * 3) + (\text{summer bill} * 3) \quad (\text{A.1})$$

Regarding the annual heating expenditure, it is necessary to distinguish initially between households using natural gas and those using other fuels, such as firewood, pellets, or, in the most extreme cases, gas bottles. In the first case, the annual expenditure was estimated using the previous formula:

$$\text{annual gas expenses} = (\text{winter bill} * 3) + (\text{summer bill} * 3) \quad (\text{A.2})$$

However, in this case, the obtained value also includes the payment for cooking, which cannot be separated. In the second case, the amounts households declared they had spent purchasing different fuels were added. If they are not connected to the municipal gas network and use gas bottles to power the hob, this cost item was calculated considering the consumption of one bottle per month (with an average cost of €24 in this geographical area), according to the direct interviews with households:

$$\text{annual cooking expenses} = 24 * 12 \quad (\text{A.3})$$

To obtain the total annual household energy expenditure, expenses relating to the consumption of electricity, natural gas, and other fuels for heating and cooking were simply added, as in the following formula:

$$\text{annual energy expenditure} = \text{annual electric expenditure} + \text{annual gas expenditure} + \text{annual other fuels expenditure} + \text{annual cooking expenses} \quad (\text{A.4})$$

Appendix B. Data collection

Under the Triennial Plan 2019–2021 of the National Electricity System Research launched by the Ministry of Economic Development, the research project realised by the Economic Department of the University of Tuscia and the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) aims at the optimization of electricity consumption and the development of standardized intervention models to promote the retrofit of buildings on a district or sectoral scale. Being the second vulnerable sector at the national level, the 2019 PNIEC has identified the energy retrofit of social housing as a strategic priority to address energy poverty in Italy. However, the main limitation to the thorough investigation of the spread of this phenomenon in this area is the lack of specific surveys and the limited availability of information on energy consumption in national surveys. Extending the collaboration to the Territorial Agency for Social Housing of the Province of Viterbo, the project aims to address energy poverty in social housing by examining the technical specifications of the dwellings, as well as reconstructing the energy consumption and behaviour patterns of the resident households.

To compensate for the lack of energy information in national surveys and managing authority's databases, a survey was conducted on a sample of 431 households. The agency's building stock is composed of about 4000 accommodations located throughout the province, many of which are in a poor state of conservation and have very low energy performance. Firstly, 614 accommodations were selected, taking as a reference:

1. The year of construction, which was used as a proxy of their energy performance;
2. The area of residence, concentrating the survey in Viterbo, Tuscania and Vetralla. These municipalities present a higher concentration of social buildings (equal, respectively, to 32%, 10.18% and 3.6% of total assets);
3. The minimum number of illegal tenants due to their reluctance to participate in the project, not having any right to live in the accommodation;
4. The minimum presence of redeemed apartments purchased by the assigned households, which have lost their social housing status due to no longer being under the institution's ownership.

To build a specific database on actual energy consumption and habits, university researchers have developed a detailed questionnaire (described in section 2.1.1) and submitted it to 431 households. Since sensitive data, such as age, gender, income and amounts of bills, were requested and the questionnaire could be challenging to read for the average user, the latter was compiled during direct interviews. The survey started in February 2020 and ended in September 2021, suffering numerous interruptions due to the COVID-19 emergency. Due to the pandemic hindering access to tenants' homes, the imperative to comply with safety regulations, and the challenges faced by assigned families in obtaining suitable equipment and stable internet connections for online tasks, the establishment of dedicated help desks became necessary. In each municipality, a help desk was realised thanks to the collaboration with the managing agency, but in particular with the support of the tenants' union. The presence of this "mediator" between tenants and the institution was an essential requirement for the successful administration of the questionnaire.

As mentioned in conclusion, the involvement of tenants as active agents and their empowerment through awareness campaigns on sustainable energy consumption are fundamental to ensure the success of social building energy retrofit programs. The poor conditions of the neighbourhood and dwellings, as well as the frustration accumulated by tenants, have created a climate of distrust towards the managing authority, which could compromise the success of the project. The questionnaire administration phase was preceded by a meeting with the tenants, which provided an opportunity for university researchers to clarify the project's goals and stages, the types of data required, and the process for completing the questionnaire, while also addressing any concerns from tenants. Furthermore, ENEA researchers delivered a presentation on affordable energy-saving opportunities and disseminated informational booklets among the attendees.

Appendix C. The Hasse diagram of poset obtained from the sample deprivation profiles

While displaying a reduced level of arbitrariness compared to the counting approach, poset demonstrates notable limitations. In particular, Alaimo, Ivaldi et al. [95] suggest computational complexity and time increase significantly as the number of observations or variables escalates, such as in this paper. For computational needs, this study estimates energy poverty on the deprivation profiles presented in the sample, which are a large number (184), as seen from the Hasse diagram in Figure C1. According to Alaimo, Fiore et al. [96], the diagram should be interpreted in a top-to-bottom way: vertical information is related to comparabilities within the partially ordered set, where two profiles are comparable if an edge connects them, while horizontal one about the incomparabilities among nodes. Notably, nodes connected by a path are deemed comparable due to transitivity.

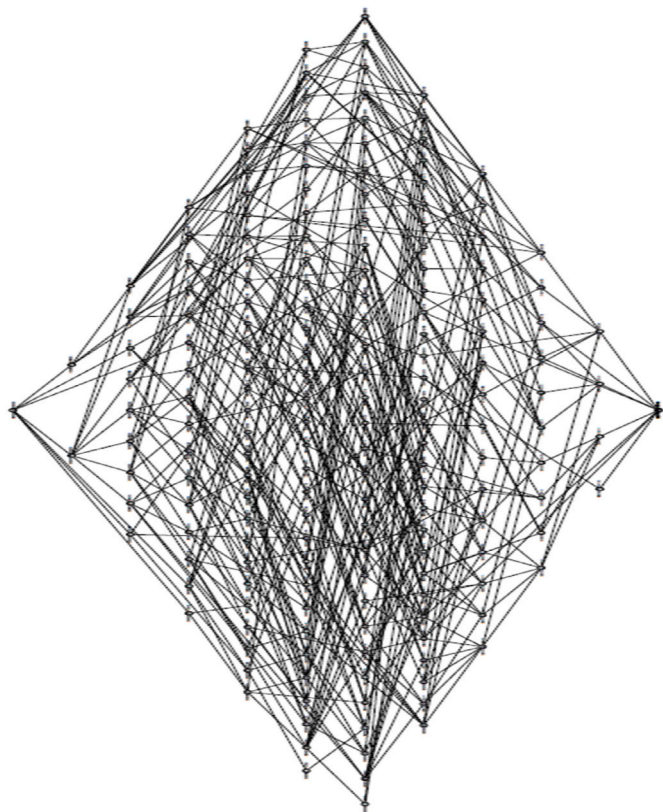


Fig. C.1. The Hasse diagram of poset obtained from the sample deprivation profiles.

Appendix D. Sensitivity analysis: the contribution of energy poverty dimensions and relevant social groups

Table D.1The impact of single energy dimension on identification score and poverty gap.

Energy Dimensions	Incidence	Poverty gap
All dimensions	0.7123 Mean = 0.72 Median = 1.00	0.4899812 Mean = 0.3614130 Median = 0.3068182
No "Arrears on energy bills"	0.675174 Mean = 0.66 Median = 1.00	0.5096649 Mean = 0.334 Median = 0.250
No "Smartphone ownership"	0.7123 Mean = 0.70 Median = 1.00	0.5153366 Mean = 0.35174 Median = 0.28750
No "TV ownership"	0.7123 Mean = 0.72 Median = 1.00	0.4899812 Mean = 0.3614130 Median = 0.3068182
No "Washing machine ownership"	0.7123 Mean = 0.71 Median = 1.00	0.4965533 Mean = 0.3591160 Median = 0.3023256
No "PC ownership"	0.7424594 Mean = 0.76 Median = 1.00	0.4610619 Mean = 0.38255034 Median = 0.34513274
No "Dryer ownership"	0.6264501 Mean = 0.65 Median = 1.00	0.4735017 Mean = 0.3303571 Median = 0.2409091
No "Fridge presence"	0.7123 Mean = 0.72 Median = 1.00	0.4899812 Mean = 0.3614130 Median = 0.3068182
No "Car ownership"	0.74942 Mean = 0.65 Median = 1.00	0.4626652 Mean = 0.3309859 Median = 0.2419355
No "Leaking roof, damp walls/floors/foundation, or rot in window frames or floor"	0.6658933 Mean = 0.67 Median = 1.00	0.4512195 Mean = 0.3391608 Median = 0.2604167
No "Inability to keep home adequately warm in winter"	0.6589327 Mean = 0.68 Median = 1.00	0.4483924 Mean = 0.3448276 Median = 0.2727273

(continued on next page)

(continued)

Energy Dimensions	Incidence	Poverty gap
No "Inability to adequately cool the dwelling in summer"	0.6589327 Mean = 0.68 Median = 1.00	0.4353727 Mean = 0.3439716 Median = 0.2708333
No "Hot water"	0.7123 Mean = 0.71 Median = 1.00	0.4927838 Mean = 0.3598901 Median = 0.3038462
No "Internet connection"	0.6682135 Mean = 0.68 Median = 1.00	0.4753125 Mean = 0.3459 Median = 0.2750
No "Type of cooking system"	0.6937355 Mean = 0.67 Median = 1.00	0.4875511 Mean = 0.3395522 Median = 0.2611111
No "Purchased light bulb"	0.7076566 Mean = 0.68 Median = 1.00	0.5111602 Mean = 0.3431373 Median = 0.2692308

Table D.2

The incidence and severity of energy poverty in each municipality.

Subpopulations	Incidence	Poverty gap
Total	0.7123 Mean = 0.72 Median = 1.00	0.4899812 Mean = 0.3614130 Median = 0.3068182
Tuscania	0.8526316 Mean = 0.80 Median = 1.00	0.540223 Mean = 0.40517241 Median = 0.38172043
Vetralla	0.2413793 Mean = 0.24 Median = 0.00	0.6190476 Mean = 0.14 Median = 0.0000
Viterbo	0.6462264 Mean = 0.71 Median = 1.00	0.446592 Mean = 0.3600000 Median = 0.3028169

Table D.3

The gendered diffusion of energy poverty

Householder gender	Incidence	Poverty gap
Male	0.4460784 Mean = 0.48 Median = 0.00	0.5147253 Mean = 0.245 Median = 0.000
Female	0.4669604 Mean = 0.40 Median = 0.00	0.492346 Mean = 0.2061069 Median = 0.0000000

Table D.4

Incidence and severity of energy poverty according to the householder employment status.

Householder employment status	Incidence	Poverty gap
Disable	0.4 Mean = 0.33 Median = 0.00	0.6285714 Mean = 0.1904762 Median = 0.000
Employed	0.1517857 Mean = 0.19 Median = 0.00	0.5196078 Mean = 0.1016 Median = 0.0000000
Retired	0.4 Mean = 0.39 Median = 0.00	0.4872506 Mean = 0.1981132 Median = 0.0000000
Unemployed	0.527027 Mean = 0.50 Median = 0.5	0.5376068 Mean = 0.25833333 Median = 0.01666667

Table D.5

The energy-poor subpopulation according to the householder age.

Householder age	Incidence	Poverty gap
20–34	0.3750 Mean = 0.38 Median = 0.00	0.66667 Mean = 0.2500000 Median = 0.000
35–49	0.5555556 Mean = 0.54 Median = 1.00	0.528 Mean = 0.28 Median = 0.10
50–64	0.6356589 Mean = 0.61 Median = 1.00	0.4430894 Mean = 0.3108108 Median = 0.1888889
65–79	0.7733333 Mean = 0.72 Median = 1.00	0.4877265 Mean = 0.3658537 Median = 0.3135593
>80	0.9090909 Mean = 0.88 Median = 1.00	0.5213235 Mean = 0.4482759 Median = 0.4411765

Table D.6

Incidence and severity of energy poverty according to the educational level of the householder.

Householder educational level	Incidence	Poverty gap
Elementary school	0.9007092 Mean = 0.85 Median = 1.00	0.5291339 Mean = 0.4329268 Median = 0.4214286
Secondary school	0.5521739 Mean = 0.56 Median = 1.00	0.4886326 Mean = 0.2857143 Median = 0.1197183
High school	0.254902 Mean = 0.32 Median = 0.00	0.5641026 Mean = 0.1710526 Median = 0.0000000
Graduated	0.2222222 Mean = 0.25 Median = 0.00	0.75 Mean = 0.188 Median = 0.0000

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