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Energy Vulnerability Composite Index in Social Housing, from a Household Energy Poverty Perspective

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Abstract: In Europe, the proportion of social housing is high, and such houses tend to be inhabited by below average-income households, which are particularly vulnerable to energy poverty. This article proposes a new methodological approach for defining an index for household energy vulnerability assessment. This method can be used to improve the management of social housing. After establishing a heuristic framework for household energy poverty–which stems from different causes such as income, the characteristics of the residence, energy installations, and the energy-consumption habits of household members–multi-criteria analytical methods, based on the aggregation of indicators which reveal the conditions leading to energy poverty, have been applied, and effective means of intervention are proposed. The method is also applied to a sample of social houses and thus validated as a useful tool in decision-making processes which concern the management of social housing from a household energy-poverty perspective.

Keywords: energy poverty; social housing; indicators; energy management; socioeconomics

1. Introduction

Insufficient access to modern energy services and the lack of energy security are still important limitations to the development of poor regions [1,2] and they also affect certain social sectors in developed countries; people in these sectors struggle to afford the costs of the energy that is required for their material and social development [3–6].

The EU has demonstrated its concern for this important problem; a significant number of particularly vulnerable households in the Union have insufficient access to energy resources [6–11].

Energy poverty has, in fact, been declared a grave problem, as it is directly related to some of the Union's priority policies concerning poverty [12,13], healthcare [14–16], and energy efficiency [17,18]. European countries have launched numerous national, regional, and local initiatives to evaluate the problem posed by energy poverty, especially in those southern and eastern countries where the problem is most acute [7,19–21].

In this context, social housing has been at the centre of several studies on the impact of the rehabilitation of residential buildings on energy consumption [22–25], and the effect of improved energy installations [26–28]. Social housing tends to be inhabited by low-income households, and the buildings are often energy-inefficient.

The inadequate building features of the dwellings not only increases the energy vulnerability of the households, but is also a factor in exacerbating the relative degree of energy poverty (relative energy poverty index) suffered by vulnerable households [29–32]. However, Walker et al. [33] and others have demonstrated that the rehabilitation of the building is often not enough to solve the problem, as other factors such as the energy-consumption habits of household members [34–37], the socio-economic profile of the household [38,39], the characteristics of energy installations, and the cost of energy supply [40,41] also play a part.

Given that most social housing within the EU is publicly owned, energy vulnerability and the prevention and mitigation of household energy poverty are, to a large extent, a public concern. The application of a composite energy vulnerability index is thus a necessary tool for decision-making processes, and is also of interest when designing energy installations, when retrofitting residential buildings, and when approaching energy management from the perspective of household energy poverty.

Although it is generally accepted that the accurate identification and evaluation of the causes of energy poverty constitute the first step in solving the problem [8,42,43], no specific multi-criteria methodology for managing social housing has been developed to date. The specialised literature on energy and building has put forward interesting ideas concerning social housing [28,31,34,44–47], but an integrated analysis of household energy poverty and the management of social housing is still lacking.

Therefore, after establishing a heuristic framework for household energy poverty, the main target of the research presented in this paper is to define a multi-criteria index for the aggregation of the different factors that contribute to household energy poverty, and to define their relationship with the management of social housing and the implementation of efficient palliative measures.

The energy vulnerability index defined in the empirical stage of this research was subsequently tested on a sample of social housing, and these houses were characterised according to this index. This exercise, which is a key contribution of the present paper, aimed to assess the validity of the index as a tool in decision-making processes in the context of managing social housing.

The development of the tool constitutes, in itself, an important contribution to the generation of composite indexes that can be used to evaluate household energy poverty. The results of using the tool prove that it is highly relevant for policy makers at the local level and for public housing managers, and can be applied to mitigate and prevent the energy vulnerability of households.

The first section reviews the relevant bibliography and the background for this study. This is followed by the methodology applied when developing the energy vulnerability index and the case study, which concerns a sample of social housing in a northern Spanish city. Finally, the results and conclusions are summarised.

2. Background

Following Boardman's pioneering publication [48], according to which a household can be regarded as being in energy poverty if its members must use more than 10% of their income to cover its energy needs, other definitions and criteria have been suggested, such as the notion of 'thermal comfort' [49], a 'cold home', and 'energy debt' [11]. The International Energy Agency [50] considers that a household is energy impoverished if it has to spend an excessive proportion of its total income on energy expenses.

Based on Grevisse and Brynart [51], this study considers that a household suffers from energy poverty if the members cannot afford to pay for enough energy to satisfy basic domestic needs. On the other hand, it is considered that energy vulnerability expresses the risk of households falling into a situation of energy poverty. Through the use of the right indicators, energy vulnerability can be used as a relative index of energy poverty. Energy vulnerability can, therefore, be regarded as a spending pressure on the household income.

Energy vulnerable households, although not officially in energy poverty, are more exposed to a potential increase in energy costs/basic needs and, therefore, to becoming energy poor as a cause of a rise in energy prices [5], a decrease in household income [52], an increase in energy needs [11], and the inability to invest in increasing the residence's energy efficiency [53] or to switch to cheaper energy sources [54], as some examples.

As pointed out by Bergasse et al. [55], households that need to use an excessive proportion of their income to cover their energy needs are energy vulnerable and at risk of social exclusion [20,56]. These households need protecting and require guaranteed access to energy at stable and reasonable prices [57], as is implicitly assumed in different public policies, such as additional consumer protection measures, the implementation of financial aid packages, the launch of information campaigns, and the promotion of energy efficiency measures [51,58].

This is also recognised in the Third Energy Package issued in 2009 [59], which compels EU countries to implement the necessary measures to protect vulnerable consumers. In this regard, Directive 2009/72/CE, concerning common rules for the internal market in electricity, leaves the jurisdiction and responsibility for adopting these measures which protect consumers, especially the most vulnerable ones, to the member states. Each state must, therefore, adopt its own definition of vulnerable customer and/or energy poverty and define measures which aim to protect vulnerable households from having their energy supply cut off at critical periods (art. 3.7). In the European framework, therefore, the definition of what constitutes a vulnerable consumer can be variously formulated in the different national regulations.

Although such measures as one-off money handouts and cheaper tariffs can be a short-term solution, tackling energy poverty in the long term requires confronting the underlying structural problems–for instance, low household incomes and energy-inefficient homes. The maintenance of comfortable temperatures is more costly in terms of energy in low-quality housing [19], and for this reason, measures that aim to improve the energy efficiency of homes have historically been among the most effective in reducing energy consumption.

In addition, it is not rare to find households that, although inhabiting homes with similar characteristics, have very different energy consumption profiles. According to Santamouris et al. [46], energy consumption is directly related to the socioeconomic profile of the household and the use that its members make of the energy facilities; and this is a key factor, along with the characteristics of the energy tariffs being applied, in determining energy costs [60,61]. Although the low energy efficiency of buildings may not be the main factor behind energy poverty, improving energy efficiency can go a long way to helping low-income households avoid energy poverty.

For these reasons, it is considered necessary to approach the analysis of household energy vulnerability from the perspective of a comprehensive household energy profile, which should include the building characteristics of the home, the way in which different electrical appliances–lights, air-conditioning, heating, etc.—are used, as well as consumption habits and tariffs.

At all times, we should take into consideration that energy poverty is a multidimensional issue, and that the degree of energy vulnerability of households is determined by a multiplicity of factors. The present paper embraces the main results of an analysis undertaken using a large sample of households whose energy poverty situation was certified by the social services [40], and analyses the role of the four determinant factors leading to a situation of energy poverty. These four factors are as follows:

1. The dwelling characteristics of the home related to the energy needs [31,62].
2. The performance of the energy installation and of home appliances. The use of inefficient heating and air-conditioning devices to achieve comfortable temperature conditions leads to high energy costs [63,64].
3. The cost of energy. Low-income households are more vulnerable to high energy prices, and high energy prices may compromise the household finances, resulting in a vicious circle [65–67].
4. The characteristics and consumption habits of household members [16,34,68,69].

Once the concept of energy vulnerability has been established, a quantitative analysis of the position of households in terms of energy vulnerability can be approached. This quantitative analysis requires primary data and a sound analytical methodology. In turn, the results of the quantitative analysis may be used to suggest solutions and palliative measures [8,42].

However, identifying and measuring energy poverty in this way faces an additional difficulty, which is inherent to the specific nature of the problem. We must take into consideration that energy poverty is a private domestic concern, which has a different character in different regions and which is prone to changing sharply over time; it is also a socially sensitive issue, as expectations concerning energy services are highly subjective.

Limited access to personal data has restricted the analysis of energy poverty at macro- and micro-levels, based on aggregate public data. As pointed out by Dubois and Meier [6], identifying the problem and designing more effective solutions requires research on a local scale.

Focusing on the methodology applied by other studies carried out at the local level, Brunner et al. [8], undertook a qualitative analysis based on 50 interviews in Vienna. The subjects had been selected from a larger population by sampling [70]. In France, Devalière [71] undertook a quantitative analysis of 40 households in two different regions. Santamouris et al. [12], located in Greece, divided the 598 households in the sample into two groups according to income; in this case, consumption was tracked over three years, divided into two periods. An empirical study carried out in Aragón [40] was larger both in terms of the size of the sample and the number of variables: the study involved the multi-method analysis of over 650 poverty vulnerable and poverty impoverished households.

These previous studies concluded that the characteristics of buildings and installations are a key factor, especially for low-income households, and local management can contribute to solving the problem globally. As suggested by the report "Energy poverty and vulnerable consumers in the energy sector across the EU: analysis of policies and measures" [72], social housing is at the centre of multiple initiatives since social-housing dwellers may be particularly vulnerable to energy poverty [52,54].

These studies share the same vision of the problem posed by energy poverty and also agree on the partial dimensions into which the problem can be broken down (e.g., the energy efficiency of buildings, the social characteristics of the household, the characteristics of the installations, the cost of energy, etc.), but lack a composite vulnerability index that integrates the characteristics of the home, the household's consumption habits, and the energy tariffs, and that establishes the household's degree of vulnerability.

This is why our methodological proposal is important: it offers a double, quantitative and qualitative, approach that is capable of integrating different variables in a composite index which can be used to measure the degree of energy vulnerability of households.

The methodology, as described in the following section, has been applied to a sample of rental social homes located in several publicly owned buildings.

3. Methodology

The characterisation of energy vulnerability must be based on the previously noted factors that determine energy poverty and on the conceptual framework that we have established:

1. The dwelling characteristics of the home.
2. The performance of the energy installations.
3. The cost of energy.
4. The characteristics and habits of household members.

In order to design the composite index, different variables related to energy poverty were selected and allocated to one of the four key factors, as presented in Table 1. In this way, each key factor is represented by a relatively wide array of variables.

Table 1. Classification of variables using the four key factors.

Variable	Description of Variable	Factor
Dwell 1	Geographical area in which the building is located	Dwelling characteristics
Dwell 2	Environment surrounding the building (urban/rural)	Dwelling characteristics
Dwell 3	Year of construction of the building	Dwelling characteristics
Dwell 4	Ownership	Dwelling characteristics
Dwell 5	Type of residence	Dwelling characteristics
Dwell 6	Size	Dwelling characteristics
Dwell 7	Number of rooms	Dwelling characteristics
Instal 1	Is the home equipped with heating equipment?	Energy installations
Instal 2	Main type of heating in use	Energy installations
Instal 3	Is the home equipped with air conditioning?	Energy installations
Ebill 1	Voltage supplied	Energy bill
Ebill 2	Is the voltage supplied known by household members?	Energy bill
Ebill 3	Electric tariff applied	Energy bill
Ebill 4	Is the electric tariff applied known by household members?	Energy bill
Ebill 5	Energy expense	Energy bill
Ebill 6	Expense of other energy sources	Energy bill
Househ 1	Social service aid	Characteristics of the household
Househ 2	Household income	Characteristics of the household
Househ 3	Number of household members	Characteristics of the household
Househ 4	Number of minors in the household	Characteristics of the household

An integrated analysis of the information provided by these variables results in a composite index of energy vulnerability. The first step in this analysis is to establish measurements with which to evaluate the effect of these variables on vulnerability.

From an energy consumption-based perspective, Bouzarovski [7] put forward different measurement options:

- Directly measuring household energy consumption (heating, lighting, refrigeration, etc.) and comparing it to a given standard.
- Analysing variations in energy consumption profiles across the consumer population, both in relative and absolute terms.
- Compiling subjective perceptions of household energy consumption and supply.

Owing to the difficulties and costs associated with carrying out systematic energy audits in all the homes under scrutiny and the difficulties in tackling subjective information, the second option was chosen. It is considered that household energy consumption is defined by the previously selected set of variables; the value scored by each variable is compared to two extreme standard values, which represent the total energy poverty and no energy poverty.

A statistical analysis of the sample of Aragonese households compiled by Scarpellini et al. [40] revealed the most likely value for each variable in energy impoverished and energy non-impoverished households.

This process defines two theoretical household standards: a household that is totally energy vulnerable would score energy poverty-indicative values in all twenty variables, whereas a zero-vulnerability household would score non-energy poverty indicative values in all twenty variables.

In this way, assessing the degree of energy vulnerability of a given household, the variables of which are known, is undertaken by comparing this household and the two standards. In other words, assessing vulnerability is reduced to evaluating three alternative scenarios using an integrated analysis of different variables, some of which may conflict with each other. This is a multi-criteria analysis problem.

As noted, a qualitative approach is proposed, according to which the concept of energy vulnerability is represented by a structural model in which the four key factors are the first level of analysis and the broken-down variables are the second level of analysis. The most suitable methodology is, therefore, the Analytic Hierarchy Process (AHP).

This methodology was originally devised by Saaty [73] and is one of the most commonly used multi-criteria decision-making tools. It has been widely applied for different energy management purposes [74–76], including the energy management of buildings [77]. The process is based on the decomposition of a complex problem into different levels with a target at the top of the structure, criteria and sub-criteria at different levels and sublevels of the hierarchy, and decision alternatives at the bottom.

The different elements on each level are pairwise compared in order to evaluate their relative preference with regard to the elements in the level above. The application of the Saaty 1–9 scale is a useful exercise, regardless of whether information is qualitative or quantitative. A value of 1 indicates equal importance for the variables being compared, 3 moderately more important, 5 strongly more important, 7 very strongly more important, and 9 extremely more important. The scores 2, 4, 6, and 8 indicate intermediate values.

In order to compare pairs within a given level, a matrix is created using the result of the comparison of element i with element j in the position a_{ji}, as follows in Figure 1:

$$A = \begin{bmatrix} a_{11} a_{12} & \cdot & a_{1n} \\ a_{21} a_{22} & \cdot & a_{2n} \\ \cdot \quad \cdot & \cdot & \cdot \\ a_{n1} a_{n2} & \cdot & a_{nn} \end{bmatrix}$$

Figure 1. Structure of a pairwise comparison matrix.

Once the weight vector is known, it is multiplied by the weight coefficient of the element above (which was used as a comparison criterion). The process is repeated upwards until reaching the top of the hierarchy.

The method calculates and aggregates its own vectors until the final vector, made up of the weight coefficient of all alternatives, is obtained. The elements of this final vector reflect the relative importance of each alternative with regard to the target indicated at the top of the hierarchical structure.

A critical stage of the methodology is the assignation of relative importance values to each variable and factor—that is, the relative preference of each criteria with regard to the elements in the level above.

For the first issue, and given the lack of specific data, all variables were considered to have equal importance for the corresponding key factor.

However, it was obvious that factors had a different impact on the degree of vulnerability of households, and it was decided that a specific methodology should be used to manage subjectivity and assign different weights to each.

This was achieved by asking 65 technicians and professionals with direct or indirect experience in the management of energy poverty in Aragón to evaluate (on a scale of 0 to 10), within the framework of a semi-structured interview, the significance of each of the factors considered relevant to energy poverty.

The relative weight of each factor was calculated on the basis of the average values presented in Table 2:

Table 2. Evaluation of the four factors (in percentages) for the multi-criteria methodology (Source: authors' own).

	Average	Relative Importance for Vulnerability
Dwelling	7.18	26%
Installations	8.17	30%
Bill	7.74	28%
Household	4.48	16%

Figure 2 shows the frequency of answers and the average value for the four key factors:

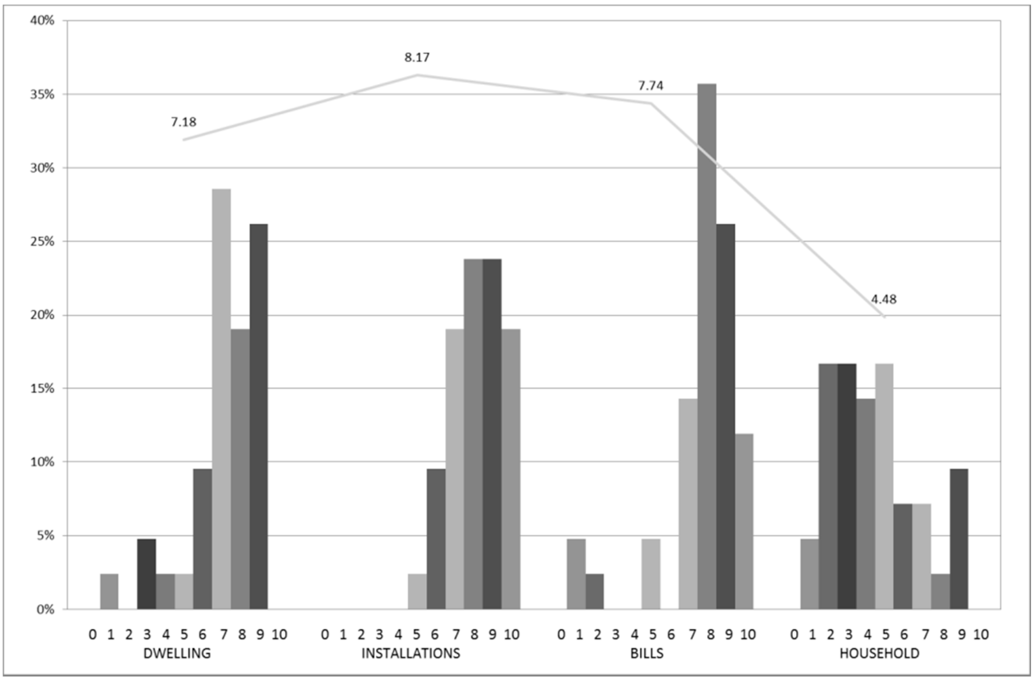

Figure 2. Qualitative analysis of the relevance of the four key factors concerning energy poverty, according to the experts (Source: authors' own).

However, the obtained value for the rated household will be relative to the individual assessment and cannot, therefore, be directly compared with those of other households. Obtaining a vulnerability index requires that the weight vectors be normalised to an absolute scale. In each analysis, the analytical values will thus be normalised to a linear scale, zero-vulnerability having a value of 0 and total vulnerability a value of 1. This system allows for an absolute value to be assigned to each household; the closer to 1 the value is, the more vulnerable the household.

The values thus obtained will be the ultimate composite index of energy vulnerability.

The following section presents and examines the results of applying the described methodology to a sample of households.

The application of the AHP to the evaluation of the degree of vulnerability of a household, using the structural model illustrated in Figure 3, results in a vector with three elements, the aggregate value of which is 1. The value of these elements determines the position of the household under scrutiny with regard to the two standards.

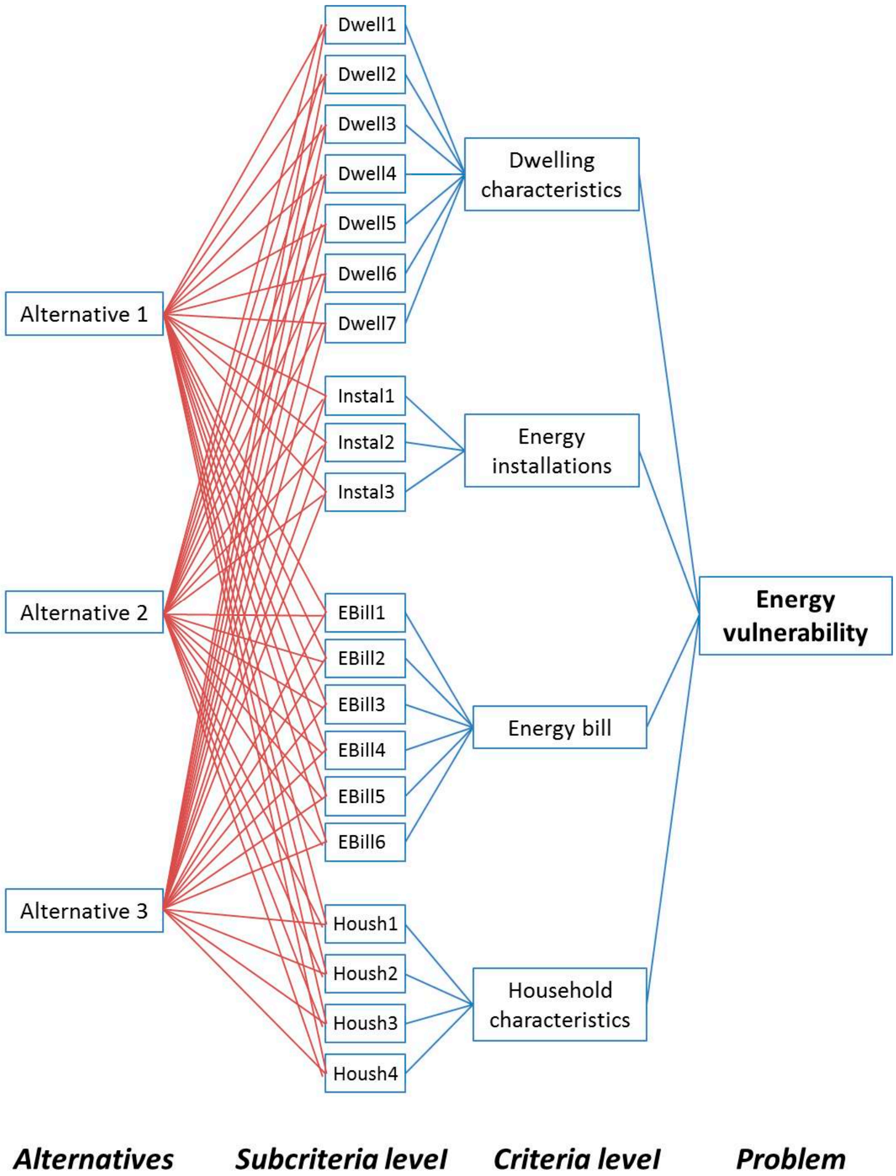

Figure 3. Structure of the decision problem.

4. Case Study

The sample under analysis includes 351 households living in social housing. Homes are located in Zaragoza, Spain, and are owned by the public agency Sociedad Municipal Zaragoza Vivienda. The sample is considered representative of rented social housing in the region.

The homes under analysis are located in three apartment blocks that were built in three different districts of the city of Zaragoza between 1990 and 1995. Their size is between 50 and 75 m^2, and the number of rooms varies. The flats are equipped with individual electrical or gas heating systems. These flats are largely allocated on the basis of economic criteria; over half of the households under scrutiny have an annual income below €9000 and 80% have an annual income below €19,000. Up to 26% of these households must dedicate over 10% of their income to pay their energy bills. The profile of the subject households in terms of the age and characteristics of household members varied greatly.

As a preliminary stage to our analysis, a comprehensive database was compiled using information on the apartment blocks under examination; the staff and management of the municipal agency that owns the buildings actively cooperated and participated in this process. Combining this information with other primary and estimated data compiled by the research team allowed for values to be allocated to the 20 selected variables.

As described in the previous section, the subject households were evaluated individually and compared to two standard households as though they were three different alternatives in a hierarchical analytical process. It must be made clear that most variables were nominal quantitative variables, and thus in order to facilitate the comparison in a multi-criteria analysis setting, they had to be transformed into discrete quantitative variables. Both these variables and the rest were categorised in order that the minimum value coincided with the most probable value in zero vulnerability households and the maximum value coincided with that in total vulnerability households.

The first step in the hierarchy analysis process is the design of the pairwise comparison matrixes of the three alternatives for each of the selected criteria. This is undertaken for each factor (criteria) which, as previously noted, is in turn defined by n-variables (sub-criteria). In this way, each factor needs n 3 × 3 matrixes.

As an example of how we can use this methodology, we can calculate the final vector for the factor or criteria 'Dwelling characteristics' for one household. According to Table 1, this factor is defined by seven variables:

- Dwell 1: Geographical area in which the building is located.
- Dwell 2: Environment where the building is located (urban/rural).
- Dwell 3: Year of construction of the building.
- Dwell 4: Ownership.
- Dwell 5: Type of residence.
- Dwell 6: Size.
- Dwell 7: Number of rooms.

The second row of Table 3 reflects the value of these variables for these households, while the first and third express the value for total- and zero-vulnerability households, respectively.

Table 3. Alternatives to be considered in the calculation of the decision problem 'Vulnerability according to the dwelling characteristics'.

Alternatives		Dwell 1	Dwell 2	Dwell 3	Dwell 4	Dwell 5	Dwell 6	Dwell 7
A1	Totally vulnerable household	3	1	1	3	1	4	5
A2	Subject household	1	1	0	2	0	2	1
A3	Zero vulnerability household	1	0	0	1	0	1	1

Given that quantitative information is available, the pairwise comparison matrixes can be based on a comparison of the value with the pair of alternatives. These will form the basis of the priority vector for each criterion, which will form the column of the alternative priority matrix for that problem.

Figures 4–10 represent the Alternative Comparison Matrix (ACM), the normalised comparison of alternatives matrix (NCM), and the priority vector (PV) for each of the seven sub-criteria (variables) that define the criterion (factor).

In the matrixes, the elements of the comparison are presented as fractions in order to demonstrate that the reciprocal comparison axiom is maintained. Obviously, the values of the diagonal that indicates the priority of each criterion with regard to itself equal 1.

	A_1	A_2	A_3
A_1	1	6	6
A_2	1/6	1	1
A_3	1/6	1	1

A_1	A_2	A_3
3/4	3/4	3/4
1/8	1/8	1/8
1/8	1/8	1/8

PV_1
0.75
0.13
0.13

Figure 4. ACM (**left**), NCM (**centre**), and PV (**right**) for sub-criterion Dwell1.

	A_1	A_2	A_3
A_1	1	1	5
A_2	1	1	5
A_3	1/5	1/5	1

	A_1	A_2	A_3
A_1	4/9	4/9	4/9
A_2	4/9	4/9	4/9
A_3	0	0	0

	PV_2
A_1	0.44
A_2	0.45
A_3	0.09

Figure 5. ACM (**left**), NCM (**centre**), and PV (**right**) for sub-criterion Dwell2.

	A_1	A_2	A_3
A_1	1	5	5
A_2	1/5	1	1
A_3	1/5	1	1

	A_1	A_2	A_3
A_1	5/7	5/7	5/7
A_2	1/7	1/7	1/7
A_3	1/7	1/7	1/7

	PV_3
A_1	0.71
A_2	0.14
A_3	0.14

Figure 6. ACM (**left**), NCM (**centre**), and PV (**right**) for sub-criterion Dwell3.

	A_1	A_2	A_3
A_1	1	5	6
A_2	1/5	1	5
A_3	1/6	1/5	1

	A_1	A_2	A_3
A_1	3/4	4/5	1/2
A_2	1/7	1/6	3/7
A_3	1/8	0	0

	PV_4
A_1	0.68
A_2	0.24
A_3	0.08

Figure 7. ACM (**left**), NCM (**centre**), and PV (**right**) for sub-criterion Dwell4.

	A_1	A_2	A_3
A_1	1	5	5
A_2	1/5	1	1
A_3	1/5	1	1

	A_1	A_2	A_3
A_1	5/7	5/7	5/7
A_2	1/7	1/7	1/7
A_3	1/7	1/7	1/7

	PV_5
A_1	0.71
A_2	0.14
A_3	0.14

Figure 8. ACM (**left**), NCM (**centre**), and PV (**right**) for sub-criterion Dwell5.

	A_1	A_2	A_3
A_1	1	6	7
A_2	1/6	1	5
A_3	1/7	1/5	1

	A_1	A_2	A_3
A_1	3/4	5/6	1/2
A_2	1/8	1/7	2/5
A_3	1/9	0	0

	PV_6
A_1	0.71
A_2	0.22
A_3	0.07

Figure 9. ACM (**left**), NCM (**centre**), and PV (**right**) for sub-criterion Dwell6.

	A_1	A_2	A_3
A_1	1	8	8
A_2	1/8	1	1
A_3	1/8	1	1

	A_1	A_2	A_3
A_1	4/5	4/5	4/5
A_2	0	0	0
A_3	0	0	0

	PV_7
A_1	0.80
A_2	0.10
A_3	0.10

Figure 10. ACM (**left**), NCM (**centre**), and PV (**right**) for sub-criterion Dwell7.

This results in seven priority vectors which form each of the seven columns of the alternative priority matrix (APM) that is shown in Figure 11:

$$\mathrm{APM} = (\mathrm{VP}_1\ \mathrm{VP}_2\ \mathrm{VP}_3\ \mathrm{VP}_4\ \mathrm{VP}_5\ \mathrm{VP}_6\ \mathrm{VP}_7) \quad (1)$$

	Build1	Build2	Build3	Build4	Build5	Build6	Build7
A_1	0.75	0.45	0.71	0.68	0.71	0.71	0.80
A_2	0.13	0.45	0.14	0.24	0.14	0.22	0.10
A_3	0.13	0.09	0.14	0.08	0.14	0.07	0.10

Figure 11. Alternative priority matrix APM for the decision problem 'Vulnerability according to the dwelling characteristics.

The second step consists of constructing the criteria priority vector (CPV) according to a pairwise criteria comparison matrix. As previously noted, given the impossibility of establishing the relevance of the different explicative variables, it is assumed that no substantial difference exists between them, and therefore, all the criteria comparison elements are equal to 1. The CPV is based on this matrix; this vector has one element for each of the sub-criteria that define the level immediately below, and a value which equals the unit divided by the number of sub-criteria.

In our example, the CPV is a vector with seven identical elements as shown in Figure 12, the value of which is divided by seven, resulting in 0.14.

$$\text{CPV} = (\text{PV}_1\ \text{PV}_2\ \text{PV}_3\ \text{PV}_4\ \text{PV}_5\ \text{PV}_6\ \text{VPV}_7) \quad (2)$$

Dwell1	Dwell2	Dwell3	Dwell4	Dwell5	Dwell6	Dwell7
0.14	0.14	0.14	0.14	0.14	0.14	0.14

Figure 12. Criteria priority vector (CPV) for the decision problem 'Vulnerability according to the dwelling characteristics'.

Finally, Figure 13 displays the Global Priority Vector (GPV) that is attained by multiplying the CPV by the APM.

$$\text{GVP} = \text{CPV} \times \text{APM} \quad (3)$$

	Dwelling characteristics
A_1	0.69
A_2	0.20
A_3	0.11

Figure 13. GPV for the decision problem 'Vulnerability according to the dwelling characteristics'.

It should be observed that this final vector is made up of the weight coefficients of each of the alternatives, which in turn indicate the relative relevance of the three households considered with regard to the decision problem. In this case, the decision problem is the need to classify the energy vulnerability of the households on the basis of the dwelling characteristics. It is to be noted that the sum of the three coefficients equals 1. The result of the test indicates that, based on the dwelling characteristics, the household under examination (alternative A2) presents an intermediate degree of energy vulnerability, but is closer to zero-vulnerability coefficients than to total vulnerability coefficients.

If we apply the same process to the three remaining factors, we obtain the global priority vectors for the corresponding decision problems as summarised in Figure 14.

	Dwelling characteristics	Energy installation	Energy bill	Household characteristics
A_1	0.69	0.46	0.57	0.55
A_2	0.20	0.31	0.29	0.25
A_3	0.11	0.23	0.14	0.20

Figure 14. GPVs for the decision problems 'Vulnerability according to the different factors'.

Each column in the GPV can be considered the individual vulnerability indicators (IVI) of the three households with regard to each factor.

The problem presented in Figure 3 can be solved using the relevance factors calculated and presented in Table 2, considered a coefficient vector C whose elements can be seen in Figure 15:

	Dwelling characteristics	Energy installation	Energy bill	Household characteristics
C	0.26	0.30	0.28	0.16

Figure 15. Coefficient vector (C).

The elements on each row i of the GPV (Figure 14) and those of the coefficient vector (Figure 15) are used to calculate the Global household Vulnerability Indicator (GVI):

$$GVI = \sum GPV_i \times C_i \quad (4)$$

Figure 16 shows the result for the three alternatives of the decision problem:

	GVI
A_1	0.56
A_2	0.17
A_3	0.27

Figure 16. Global household vulnerability indicator.

At this stage, all the values obtained for the subject household are normalised (values in the row A2 in Figure 14), ranging from a value of 0 (zero vulnerability) to 1 (total vulnerability), in order to obtain a vulnerability index for each criterion, as well as a global one. The results are shown in Table 4.

Table 4. Vulnerability indexes based on the factors and the global vulnerability index in the household used as an example.

IVI Regarding Dwelling Characteristics	IVI Regarding Energy Installation	IVI Regarding Energy Bill	IVI Regarding Household Characteristics	GLOBAL VULNERABILITY
0.16	0.35	0.35	0.15	0.25

Applying these evaluation factors allows for the definition of a global energy vulnerability index based on the values of individual criteria. However, it may be mentioned that this global index is highly sensitive to weight coefficients and that it conceals the specific information supplied by relative vulnerability indexes.

For descriptive purposes, the vulnerability ranges set in Table 5 (within the [0, 1] interval) will be used:

Table 5. Vulnerability ranges.

	VI
Low	0–0.25
Moderate	0.25–0.50
High	0.50–0.75
Very high	0.75–1

Based on the previous calculations, the household used as an example rates low on the vulnerability scale in general, but its rating is moderate when only the installation and energy bill-related variables are considered.

The use of a composite index made up of the four individual vulnerability indicators is proposed.

This method was applied to the 351 households in the sample, resulting in a group of indexes. These are represented in Figure 17.

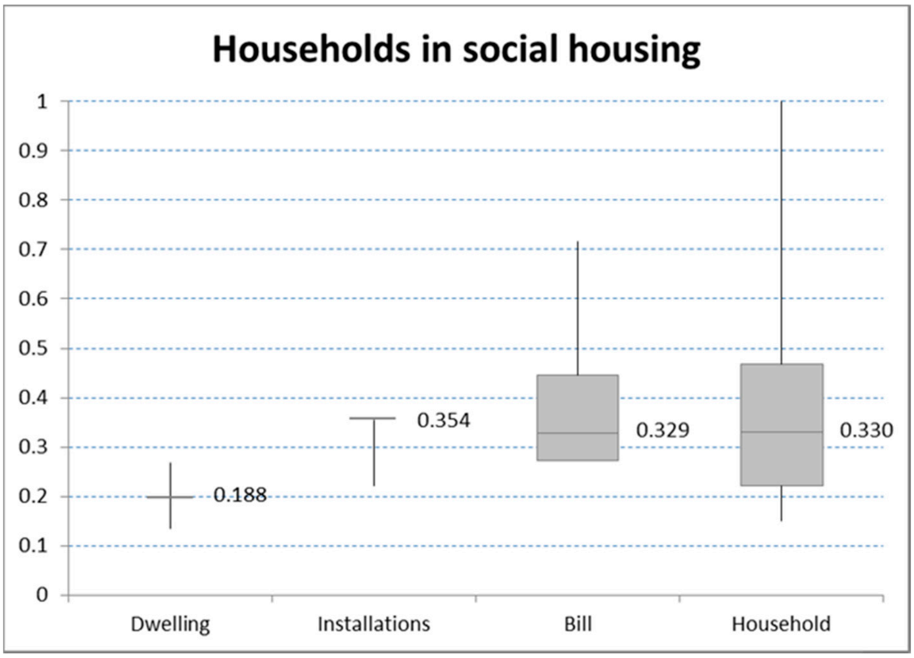

Figure 17. Distribution of the elements in the composite index for the subject sample of social houses.

Using box plots, we can identify the mean of all the sample values and graphically illustrate the interval in which the most common, and, therefore, most representative, values of the sample fall.

The similarities between the buildings under examination in terms of dwelling characteristics and energy installations are reflected in the almost negligible range of values presented by the first two indexes. Taking these factors into consideration, the sample households score a low overall vulnerability rating, whereas the global vulnerability rating (taking all four factors into consideration) for the whole sample is moderate.

The values recorded using the variables concerning energy bills and household habits, however, present a much wider range.

The application of this multi-criteria methodology indicates that the households under examination do not score high energy vulnerability ratings, despite the low average income of the households.

This positive result is, to a large extent, due to the good building characteristics of the dwellings. In contrast with other studies that deal with low-income households, this factor has little impact on the overall index because all the buildings under consideration are homogenous and are publicly owned, and thus, they are adequately maintained.

In order to demonstrate the consistency of the method and the indexes generated with it, the indexes for two additional samples were calculated: a sample of 615 certified energy impoverished households was used to establish the conceptual framework of the study (results in Figure 18); and a sample of 1340 households in Aragón (results in Figure 19), the data for which were collected in the preliminary phase of the study undertaken by Scarpellini et al. [40]. (For more details on this study, see [78]).

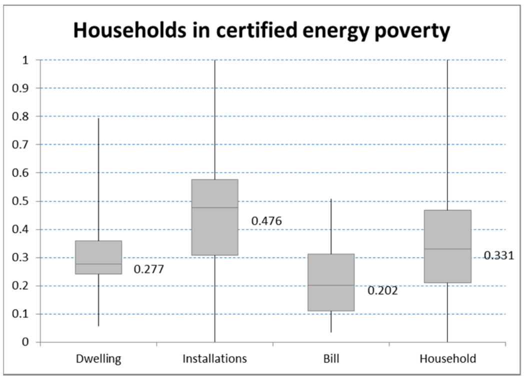

Figure 18. Distribution of the elements of the composite index for the additional samples.

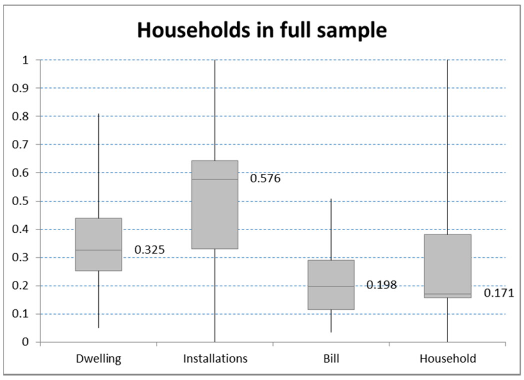

Figure 19. Distribution of the elements of the composite index for the 'Households in full sample'.

The mean and the variability range of the values concerning the characteristics of the home match those presented by certified energy impoverished households (in both cases, the households are at risk of falling below the poverty threshold); the subjects in both samples are more vulnerable than those in the third sample.

A comparison of the vulnerability indexes of the social houses in our sample (Figure 17) with the values calculated for the two other samples (Figures 18 and 19) indicates that the social houses are the least vulnerable in terms of architectural characteristics and energy installations.

However, the social houses are markedly more vulnerable than the other two samples in terms of energy bills. In any case, the close match of the mean calculated for this factor with that calculated for the installations suggests that this is a consequence of the kind of energy used by these installations.

Considering these results, the only actions that the public agencies can take in order to reduce the energy vulnerability of these households is to intervene in energy supply contracts, which is beyond their jurisdiction (energy supply contracts are bilateral agreements between the utility company and the customer), or to lead public campaigns to raise awareness.

Finally, these indicators also point to the source of energy poverty in the subject households, which, given the similarity of the results concerning the building, installation, and tariff characteristics, lies in the profile of the household. The difference between the installation and the bill indexes may be due to the need to excessively constrain energy consumption in response to low income levels.

Energy efficiency in buildings and installations is not a major cause of energy poverty in the social houses in the sample. Priority should be given to actions that aim to reduce the difference between the installation and energy bill-related vulnerability indexes. The vulnerability index concerning energy bills suggests that the implementation of improved energy contracts would reduce the risk of energy vulnerability in these households.

Using this methodology to study individual households may assist in decision-making processes and also facilitate a prediction of the effect of a given change in the variables on the household's energy vulnerability rating.

As presented in Figure 20, the global vulnerability index in the three samples does not present substantial differences.

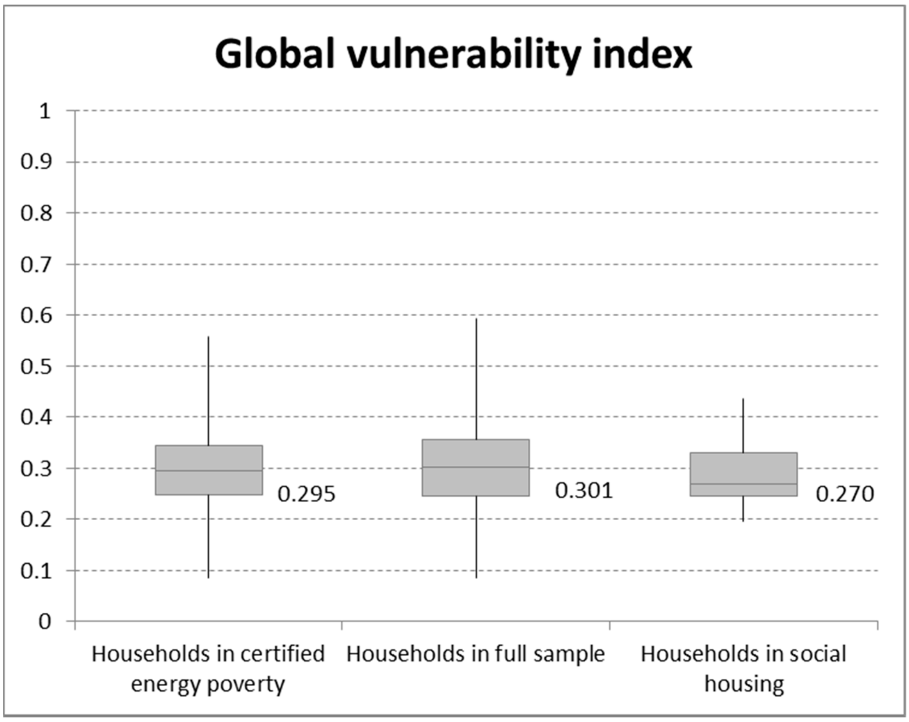

Figure 20. Distribution of global vulnerability index in the three samples.

We may conclude that the information provided by a single index is, therefore, partial and incomplete, and that it contributes to concealing the causes of household energy poverty. In addition, the use of a single index wastes the interesting information provided by partial indexes, which is enormously useful, for instance, for the management of social housing. On the other hand, the proposed composite index can be used to evaluate whether a specific household falls within a given vulnerability typology range.

5. Conclusions

The EU has adopted numerous initiatives in order to evaluate the problem posed by energy poverty at local, regional, and national levels, and to define the most effective palliative actions. The most effective measures to prevent or mitigate household energy poverty, however, are those targeted at the household level. For these measures to be effective, frameworks need to be put into place to guarantee that information on consumption is kept private and to develop methodologies with which to examine the problem from all its different angles.

Within the framework of the debate on the relationship between household energy poverty and energy vulnerability associated with the buildings in which these households live, this study has defined the most significant factors for household energy poverty. This has led to the determination of a series of indicators which are accessible to the public agencies and which are used to generate a composite index of energy vulnerability. This index is a tool that can be used to holistically manage social housing from the perspective of energy poverty. The index considers the four key factors for energy poverty (aside from the socio-professional position of household members): the characteristics of the building, the characteristics of the energy installation, the energy bill, and the energy habits of household members.

The proposed methodology achieves three goals. Firstly, it can be used to assign a relative weight to different indicators of household energy vulnerability. Secondly, the resulting index is a heuristic tool, which can increase our understanding of how attributes, and combinations of attributes, can lead to similar degrees of vulnerability. Thirdly, it reveals new data with which to design and monitor action in more efficient ways.

The household vulnerability index proposed, understood as a heuristic tool, offers a new insight into the causes and structure of vulnerability among populations with a similar level of exposure. This makes it a very useful tool for decision-making processes concerning the management of household energy poverty in social housing, e.g., the rehabilitation of buildings, maintenance, or the management of energy supply.

These results are not free of limitations, especially regarding the size of the sample and the number of data variables. Similarly, the lateral nature of the study leaves many questions open: for instance, the evolution of a sample over several years and the possibility of analysing larger samples which include homes of different types and located in different climatic areas.

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