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Research paper

Assessment of energy poverty in Andalusian municipalities. Application of a combined indicator to detect priorities

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ABSTRACT

This study aims to assess the energy poverty risk in the municipalities in Andalusia (Spain) to know their existing differences to prioritise the aids in the municipalities with greater needs. For this purpose, a composed indicator is developed. This new indicator is based on the so-called High Energy Requirements (HER) index, where proxy indicators related to the building energy efficiency are joint and where climate severity indicators, together with the income conditions and the gender gap of the population, are included. This new indicator assesses energy poverty globally, joining the indicators related to the characteristics of the dwelling stock with other factors related to energy poverty, such as monetary poverty or gender gap. The results are analysed at a municipal level, so the cases with greater problems both in general terms and those particularly from partial aspects (such as the conservation state or the type of climate) are identified. This characterisation of the phenomenon allows the most appropriate policies to be identified according to the indicators presenting the most unfavourable values, thus constituting a useful tool to prioritise and to implement measures adapted to each municipality's needs.

1. Introduction

The progress of today's society is strongly related to energy consumption (Sorensen, 2013), which is among the main aspects on which the policies of each country should be focused (Gatto and Drago, 2021). Countries are more and more considering in their policies through energy poverty (EP) the relationship between energy and people's welfare (Day et al., 2016). EP, also known as energy vulnerability (Castaño-Rosa et al., 2019), takes place when households are not capable of keeping acceptable thermal comfort conditions or having energy services at an acceptable price, and also when it is not possible to make essential activities because of the difficulty to access to energy (Bouzarovski and Petrova, 2015).

The European Union has included the importance of EP in the main challenges that the region should address in the next years (European Commission, 2011). The creation of the European Energy Poverty Observatory (EPOV) is useful for the member countries of the European Union to control and to reduce EP. In addition, European countries are increasingly developing policies and plans to reduce EP (Kyprianou et al., 2019). In Spain, the National Strategy against Energy Poverty 2019–2024 (The Government of Spain, 2019) has established goals to reduce EP between 25 and 50% by 2025 in comparison with the current values. Thus, in the case of indicator 2M (disproportionate energy expenditure), the current value (17.3% of the population) should be reduced by between 12.9 and 8.6%. This strategy considers EP as the cases in which the family units are not capable of meeting the energy needs of their household due to their low income and the situations worsened by the deficient energy performance of dwellings, as well. Two aspects are therefore influencing EP: the energy efficiency of dwellings and the income of the family units.

An essential aspect to develop and to apply policies to reduce EP is the way of quantifying it due to its interdisciplinary character (Thomson et al., 2017) that could vary among territories (Scarpellini et al., 2015). One of the main problems to develop these policies is to determine the regions of the country that present a greater EP risk, and therefore greater financing and more specific measures are required. This aspect can be done at different territorial scales. By way of example, neighbourhoods in

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the same city may have different realities, with different levels of family income and the energy performance of buildings being common. Likewise, it is to be assumed that cities in the same region may have different characteristics. For these reasons, it is necessary to have methods for characterising energy poverty at the regional level.

Some studies, which can be grouped at district and state levels, have addresses the possibility of analysing risk areas. In relation to the former, the studies by Martín-Consuegra et al. (2020, 2019) developed a multidimensional index to assess EP in the underprivileged quarters in Madrid. A similar study was conducted by März (2018), who developed a combined methodology of multi-criteria decision analysis with a geographic information system to assess the EP risk; that methodology was based on three dimensions (heating demand, building vulnerability, and socioeconomic aspects) in the quarters in the city of Oberhausen (Germany). However, its application in other regions could be something of a challenge as complex approaches with specific data of a region are used. Therefore, Reames (2016) assessed with public data the possibility of predicting the residential heating energy use intensity in census units in Kansas. Likewise, the aspects related to EP should be redefined. Sánchez-Guevara Sánchez et al. (2019) showed the need for considering variables related to high temperatures in summer to detect the EP risk at a district scale, particularly in cities located in warm climates. In another study, Sánchez-Guevara Sánchez et al. (2020a) stressed the importance of considering the gender perspective when assessing EP.

Other regional studies have also assessed EP using various indicators. However, some works were not aimed to address EP in particular, such as Piai Paiva et al. (2019), who analysed the regions of Brazil with low-income population and the difficulties to access to energy. An approach more focused on EP are the studies by Walker et al. (2013, 2012), who performed a regional analysis of EP in Northern Ireland. The results detected areas with policies slightly adapted to their level of energy requirement. In addition, Simoes et al. (2016) and Gouveia et al. (2019) assessed the EP in the cities of Portugal using a multidimensional indicator. Recently, Pérez-Fargallo et al. (2020) developed an approach to assess the EP in Chile; this approach was based on the energy demand of climate considering an adaptive approach of users and the population in situation of monetary poverty. These aspects were considered due to the similarities of the building stock in the various Chilean municipalities, but the authors doubted about the possibility of extrapolating the methodology to developed countries.

Most research studies assessing EP are methodologies based on regional analyses or are focused on the individual analysis of municipalities. However, the way in which the most vulnerable municipalities stand out in comparison with the average values of the country is hardly included in the analysis. In addition, municipalities are not compared among themselves to identify those in a more unfavourable situation. If there is a methodology to assess the predominance of EP of one or several municipalities in a region, then the most vulnerable cases are known, and policies and financing programmes for these cases could be established (Morrison and Shortt, 2008). A recent study by Sánchez-Guevara Sánchez et al. (2020b) developed the High Energy Requirements (*HER*) index to assess the districts in Madrid where the energy requirements were greater than the average values of the city. This index contributed to identify more quickly the districts with greater energy performance in their building stock. The main advantage of the indicator is that it allows the use of aggregated data, thus allowing adequate analysis between different areas. This aspect can allow a first decision-making when evaluating the areas most affected by energy poverty, although the subsequent analysis of individual cases (through existing indicators (Siksnelyte-Butkiene et al., 2021) allows obtaining a joint assessment of energy poverty. Although this approach was developed to be applied in the districts of a city, the possibilities of extrapolating the methodology to a regional context were not studied.

This study analyses the possibility of application the *HER* index to a regional scale to assess the EP risk in the municipalities. Moreover, the *HER* index is focused on the analysis of the energy characteristics of the building stock, but without considering socioeconomic indicators. For this reason, the indicator is improved by including two socioeconomic indicators: population in monetary poverty and the existing gender gap. The latter was included because of the needs for including this dimension in the assessment of the EP at a regional level (Sánchez-Guevara Sánchez et al., 2020a). Although other social aspects can also influence the assessment of energy poverty (e.g., elderly population with low incomes (Chard and Walker, 2016) or immigrants with low incomes (Fuller and McCauley, 2016), the lack of quality data for these aspects makes their use difficult. In addition, this study also aims to broaden and to go more deeply into the regional analysis of the existing EP in one of the regions of Spain with greater predominance of EP: Andalusia (the Spanish region located to the south of the Iberian Peninsula). Although the values of state indicators, such as the number of inhabitants, unemployed people, and people in monetary poverty, are high in the region, the EP risk of this region has not been analysed in detail. Therefore, the importance of selecting Andalusia as a case study lies on two aspects: (i) it is the autonomous region with the greatest population of the country, divided into 778 municipalities; (ii) EP is estimated to be large in the region since it is one of the regions with the lowest income in Spain and with a deficient housing stock (Castaño-Rosa et al., 2020). Although Andalusia is located in a latitude with mild winters, the deficient building energy performance makes difficult to keep households adequately warm in winter, and is in turn combined with the severity of the summer conditions (Castaño-Rosa et al., 2020). Likewise, selecting Andalusia as a case study is of interest due to the situation taken place by the Covid-19 pandemic because its main economic activities are related to hotels, catering and tourism, and these activities have been therefore affected, thus reducing the number of employees and the income of the family units (The Government of Spain, 2020); and (iii) the EP in the region has not been analysed. Although some studies have analysed certain buildings of the regions, such as Bienvenido-Huertas et al. (2020a,b), Castaño-Rosa et al. (2020), Sánchez-Guevara Sánchez et al. (2017), and Vilches et al. (2017), the complex character of its building stock and the most unfavourable regions have not been studied at a regional level in a similar way as the many studies focused on the city of Madrid (Martín-Consuegra et al., 2020, 2019; Sánchez-Guevara Sánchez et al., 2020b,a).

2. Methodology

2.1. Study zone: Andalusia

Andalusia is the autonomous region in the south of the Iberian Peninsula (Fig. 1), is divided into 8 provinces and has 778 municipalities, from which 29 exceed 50,000 inhabitants and 12 exceed 100,000 inhabitants. Most municipalities with more inhabitants are each province capital (e.g., Seville) and other important municipalities, such as Algeciras or San Fernando. The demographic distribution of the autonomous region is characterised by a high concentration of population in coastal zones and valleys, which is in turn characterised by the agri-cities with populations of up to 50,000 inhabitants. Likewise, there are regions with less inhabitants, such as the areas of Grazalema, Sierra Morena or

Fig. 1. Location of the autonomous region of Andalusia.

Las Alpujarras. In terms of total population data, Andalusia is the autonomous region with the largest number of inhabitants in Spain (Fig. 2). The population data from the Spanish Institute of Statistics (2020a) shows that the number of inhabitants of the autonomous region is 9.62% greater than the second most populated autonomous region in the country (Catalonia). In demographic terms, selecting Andalusia as a case study is therefore significant because of its importance in the total number of inhabitants in Spain.

However, this aspect becomes important when the data related to the economic situation of the region are analysed in comparison with the rest of the autonomous regions. Data of employment rate (Spanish Institute of Statistics, 2020b) and the average annual income of the households (Spanish Institute of Statistics, 2020c) of each autonomous region show that Andalusia is among the autonomous regions with the lowest values (Figs. 3 and 4). In the last 10 years, the employment rate has evolved from the year with the lowest value (2013) to the year with the greatest value (2019); however, Andalusia is among the autonomous regions with the worst values. Likewise, the rate of employees in Andalusia between 2010–2019 was 6.28% lower than the national average. The income of the family units is undoubtedly affected, thus implying that the values of the average national rate in Andalusia are lower than both the national average and most autonomous regions.

Consequently, the EP risk in the region is high (Castaño-Rosa et al., 2020). The Spanish Institute of Statistics showed that the Andalusia has the highest population ratios in monetary poverty risk (13.1% greater than the national value in 2016 Spanish Institute of Statistics, 2020d). Moreover, the report written by the Spanish Environmental Science Association indicates that the Andalusian population with income levels lower than the limit considered in 2014 was between 3 and 10% greater than the national average, thus constituting one of the autonomous regions with the most unfavourable values (Tirado Herrero et al., 2016). In demographic and economic terms, Andalusia is strongly affected by EP, so tools to assess it should be available.

2.2. Index developed to assess EP in municipalities

One of the main challenges to establish policies to reduce EP is the economic distribution of the funds. The reason is that autonomous and provincial governments have funds for municipal governments to establish measures, such as the energy rehabilitation of buildings or the payment of energy bills. However, criteria for distributing funds among the municipalities are usually simple, and the reality of municipalities is not assessed. An example is the distribution of the funds of the Provincial Strategic Plan against Energy Poverty developed by the Cadiz Provincial Council in 2020 (Cadiz Provincial Council, 2020), based on the number of inhabitants of each municipality (without considering the number of inhabitants in situation of monetary poverty or the state of the building stock).

2.2.1. Adoption of the pre-existing methodology: the HER index

The lack of indicators to analyse EP at a regional or municipal level could contribute to the use of poor criteria to assess and to classify the distribution of funds and measures against the EP in the municipalities of a region. Pérez-Fargallo et al. (2020) indicated that many indicators to assess EP (focused on the individual analysis of the family units) make the use of indicators at a regional level something of a challenge. One of the main difficulties related to the analysis of the municipalities of a region is identifying their situation in relation to the economic poverty both in absolute terms (the influence of the phenomenon on the households located in the region) and in relative terms (in comparison with the municipalities with similar characteristics and belonging to the same region). From a simple perspective of the problem, EP is due to both the combination of high energy consumption (mainly due to a poor building energy performance) and the low income of the family units, so it is possible to establish indicators that analyse these aspects at a municipal level. Sánchez-Guevara Sánchez et al. (2020b) developed an indicator to assess the EP of the districts in Madrid: the *HER* index. This index was designed to assess the high risk in terms of energy requirement presented by the building stock of each district in Madrid in comparison with the average values of the city. The quarters with a greater risk were therefore detected. Five indirect indicators (construction year, maintenance conditions, availability of heating and cooling systems (differentiating those using electric heating systems because its use is more expensive than that of other heating systems), surface of the dwelling by household, and average temperature of the summer nights) of the building stock of each district were compared with the average values of Madrid, and a value was assigned to each indirect indicator according to the severity degree. Therefore, it could be quantitatively assessed the district that stands out in comparison with the city. Eqs. (1) and (2) show how the *HER* index used by Sánchez-Guevara Sánchez et al. (2020b) was determined. The rules established in Table 1 were applied to the five indirect indicators (V_a, V_b, V_c, V_d and V_e) to determine the value assigned to each. A value of 10 in *HER* corresponded to the most unfavourable assumption, and a value of 0 corresponded to the less unfavourable assumption in comparison with the average data of the city. Regarding the importance of each indicator, Sánchez-Guevara Sánchez et al. (2020b) justified the importance of each in comparison with the characteristics of the dwelling stock of the households in EP in Madrid: (i) V_a considered the buildings built before 1980 as these buildings were built without any requirement on energy efficiency (the first technical standard was applied from 1980 (The Government of Spain, 1979)); (ii) V_b considered buildings with bad maintenance conditions as their energy performance is usually worse (e.g., the presence of damages in the façade or interstitial condensations contribute to a greater heat transfer (Litti et al., 2015; Rotilio et al., 2018); (iii) V_c was determined by combining the other three subindicators: percentage of buildings without heating (V_1), percentage of buildings without cooling (V_2), and percentage of buildings with electric heating (V_3). Considering buildings without heating or cooling systems could imply that family units use inefficient equipment (e.g., portable radiators) and face more thermal discomfort hours, as well. Buildings with electric heating were considered because the electrical energy is more expensive than gas, thus increasing the energy bills of the family units living in buildings with these heating systems; (iv) V_d considered the dwellings with a greater surface by member of the household as

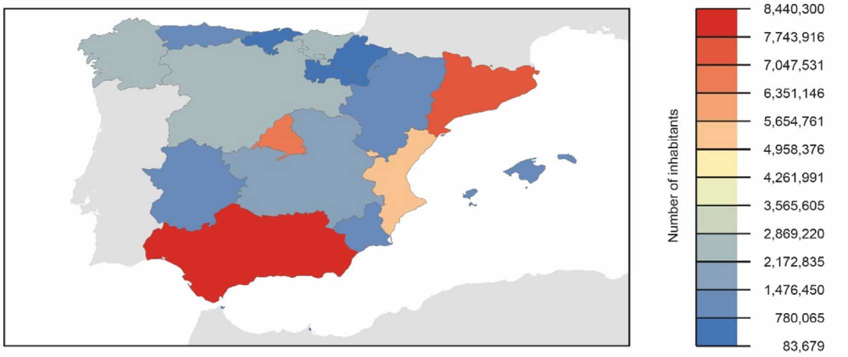

Fig. 2. Number of inhabitants in Spain by autonomous regions. Average data of the period between 2010 and 2019.
Source: Data obtained from the Spanish Institute of Statistics (2020a).

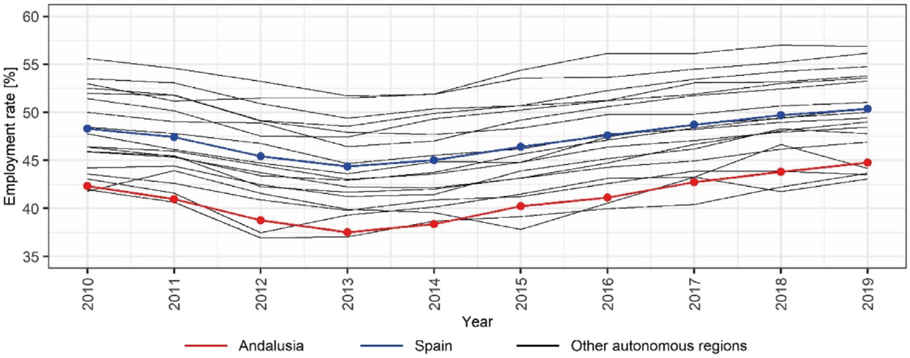

Fig. 3. Evolution of the employment rate in Spain by autonomous regions in the last 10 years.
Source: Data obtained from the Spanish Institute of Statistics (2020b).

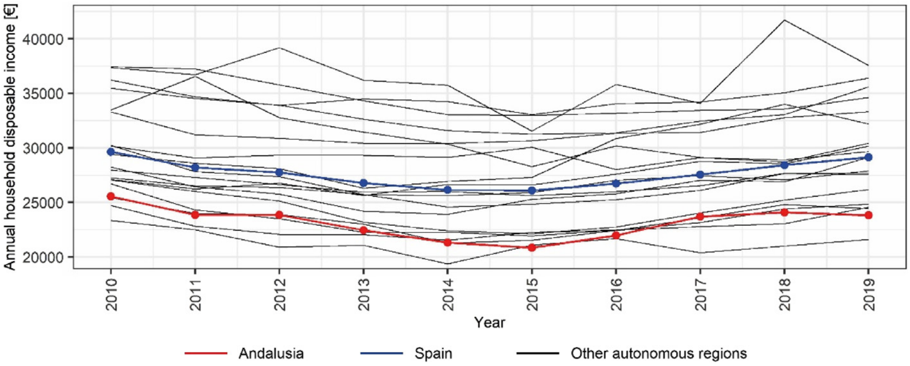

Fig. 4. Evolution of the annual net income of the Spanish households in each autonomous region in the last 10 years.
Source: Data obtained from the Spanish Institute of Statistics (2020c).

it could imply a greater energy expenditure for the family units due to the need of acclimatising a greater volume of air; and (v) V_e considered the influence of the average temperature of the summer nights to assess the thermal recovery of the family units during the night, and it is also a possible indicator of the energy expenditure in summer. The first idea of V_e was the analysis of the impact of the heat island that reduces the passive cooling capacity of dwellings in summer, although the analysis was based on the average temperature of the summer nights. As a result, the indicator could be applied in other regions where there are no specific heat island data.

$$HER = V_a + V_b + V_c + V_d + V_e \tag{1}$$

$$V_c = \frac{V_1 + V_2 + V_3}{3} \tag{2}$$

where V_a is the indicator of the percentage of buildings built before 1980; V_b is the indicator of the percentage of buildings with a deficient conservation state; V_c is the indicator of the percentage of buildings with HVAC systems and determined by Eq. (2); V_d is the indicator of the average surface of the dwelling by household member; V_e is the indicator of the average temperature of summer nights; and V_1, V_2 and V_3 are the indicators used to assess the percentage of buildings with HVAC systems and their values are also determined with Table 1.

Although the *HER* index was used to assess which districts of Madrid have a building stock with greater energy requirement, it could be used at a municipal level to carry out a regional comparative analysis as it is a methodology that aims to perform an analysis with greater disintegration and to compare territories among them. For this purpose, the approach by Sánchez-Guevara Sánchez et al. (2020b) was modified. Details are given below.

Table 1
Degree of severity and value assigned to each indicator in the classification of districts by Sánchez-Guevara Sánchez et al. (2020b).

V_e			Rest of indicators (V_a, V_b, V_d, V_1, V_2 and V_3)		
Relation	Degree of severity	Assigned value	Relation	Degree of severity	Assigned value
$DV - CA \leq 0$	Very Low	0.0	$DV \leq CA$	Very Low	0.0
$0 < DV - CA \leq 2$	Low	1.0	$CA < DV \leq 1.5 \cdot CA$	Low	1.0
$2 < DV - CA \leq 4$	Medium	1.5	$1.5 \cdot CA < DV \leq 2 \cdot CA$	Medium	1.5
$DV - CA > 4$	High	2.0	$DV > 2 \cdot CA$	High	2.0

DV: District Values; CA: City Average.

2.2.2. Modification of the HER index

The HER was modified by including two factors related to the climate characteristics and socioeconomic factors.

2.2.2.1. Inclusion of the climate variability: HDH and CDH. As mentioned above, five indirect indicators related to the characteristics of the building stock were used, and only the indicator of the average temperature of the summer nights considered the influence of the climate characteristics of the area analysed. The reason was that the climate zone of Madrid is the same in all districts, but in the case of a region or autonomous region there could be various climate zones. For this reason, indirect indicators should be included to assess the greatest heating or cooling demand that a municipality could present in comparison with the average of the region. For this purpose, two indirect indicators were designed, based on the approach of heating degree hours (HDH) and cooling degree hours (CDH) developed by the Poverty-Adaptive Degree Hourly Index (Pérez-Fargallo et al., 2020). The advantage of using HDH and CDH instead of the degree days is that the actual building behaviour could be better known according to climate (Pérez-Fargallo et al., 2020). These degrees hours are determined by considering an adaptive-based temperature according to an adaptive thermal comfort standard (Bienvenido-Huertas et al., 2021, 2020a). Adaptive thermal comfort models consider the possibility of people's adaptation when the external temperature varies and are related to lower energy consumption as the use of HVAC systems is reduced. The use of this approach is appropriate for residential buildings. The surveys by Bienvenido-Huertas et al. (2020b) showed that most family units limit the use of HVAC systems in the hours of the greatest severity. For this reason, the use of an adaptive-based approach to determine the degree hours is appropriate to assess the energy demand presented by residential buildings. The EN 16798-1:2019 standard (European Committee for Standardization, 2019) was used in this study. This standard establishes upper and lower limits among which the operative temperature should oscillate. To determine these limits, the running mean outdoor temperature (t_{rm}) (Eq. (3)) that determines the outdoor mean temperature of the days before that analysed is previously calculated. Upper and lower limits are determined with t_{rm} and using the linear correlations established in EN 16798-1:2019. To determine these limits, EN 16798-1:2019 considers several categories that vary the thermal differential between the upper and lower limit. The use of each category is established in EN 16798-1:2019, with Category III corresponding to the existing buildings. Therefore, the upper and lower limits from Category III were used (Eqs. (4) and (5)). With the values of these limits, HDH and CDH are determined by Eqs. (6) and (7).

$$t_{rm} = (1-\alpha) \cdot \sum_{d=1}^{n} \left(\alpha^{(i-1)} \cdot T_{ext,d}\right) \tag{3}$$

$$Lower\ limit = 0.33 \cdot t_{rm} + 13.8 \quad (10 \leq t_{rm} \leq 30) \tag{4}$$

$$Upper\ limit = 0.33 \cdot t_{rm} + 22.8 \quad (10 \leq t_{rm} \leq 30) \tag{5}$$

$$\begin{gathered} HDH = \sum_{i=1}^{8760} (T_{ext,i} - T_{AH,i}) \cdot X_{HA} \\ X_{HA} = 1 \ \ if \ \ T_{ext,i} < T_{AH,i} \\ X_{HA} = 0 \ \ if \ \ T_{ext,i} \geq T_{AH,i} \end{gathered} \tag{6}$$

$$\begin{gathered} CDH = \sum_{i=1}^{8760} (T_{AC,i} - T_{ext,i}) \cdot X_{CA} \\ X_{CA} = 1 \ \ if \ \ T_{ext,i} > T_{AC,i} \\ X_{CA} = 0 \ \ if \ \ T_{ext,i} \leq T_{AC,i} \end{gathered} \tag{7}$$

where $T_{ext,d}$ is the daily outdoor mean temperature [°C]; $T_{AH,i}$ is the daily adaptive-based temperature of the lower limit determined by Eq. (4) [°C]; $T_{AC,i}$ is the daily adaptive-based temperature of the upper limit determined by Eq. (5) [°C]; and X_{HA}, X_{CA} are logic values whose value is 1 if the condition given in the equations is met, and 0 if not.

If *HDH* and *CDH* are determined, the new *HER* developed in this study could be established to assess the energy requirement of the municipalities in comparison with the average values of the autonomous region. Eq. (8) shows the indicator modified to be used in municipalities. The values assigned to each indicator are obtained from Table 2, which is adapted from the values assigned by Sánchez-Guevara Sánchez et al. (2020b) at a district level. In this case, the values of the municipalities are compared with the average values of the autonomous region. As the new *HER* could obtain a maximum value of 14 in the most unfavourable assumption, the indicator was normalised to use a result scale between 0 and 1. For this purpose, a min/max normalisation was used (Eq. (9)), thus developing the Normalised High Energy Requirements (*NHER*).

$$HER = V_a + V_b + V_c + V_d + V_e + V_f + V_g \tag{8}$$

$$NHER = \frac{HER - \min(HER)}{\max(HER) - \min(HER)} \tag{9}$$

where V_f is the value assigned to the indicator of the heating degree hours considering an adaptive-based temperature obtained by Category III from EN 16798-1:2019; and V_g is the value assigned to the indicator of the cooling degree hours considering an adaptive-based temperature obtained by Category III from EN 16798-1:2019.

2.2.2.2. Inclusion of socioeconomic aspects: income and gender. Although *NHER* is an appropriate indicator to assess the energy requirements of buildings, socioeconomic aspects are not considered. Sánchez-Guevara Sánchez et al. (2020b) analysed *HER* and the population in EP independently. However, if these two aspects are combined in an indicator, the energy requirements of the building stock and the socioeconomic requirements are known. In view of this circumstance, the normalised high energy requirements with population in monetary poverty and gender gap ($NHER_{P,GG}$) index was designed. This indicator is obtained by correcting *NHER* according to both an indirect indicator of population in monetary poverty (P) and an indirect indicator of

Table 2
Degree of severity and value assigned to each indicator to be assessed at a municipal level.

V_e			Rest of indicators ($V_a, V_b, V_d, V_f, V_g, V_1, V_2$ and V_3)		
Relation	Degree of severity	Assigned value	Relation	Degree of severity	Assigned value
$\text{MV} - \text{RA} \leq 0$	Very Low	0.0	$\text{MV} \leq \text{RA}$	Very Low	0.0
$0 < \text{MV} - \text{RA} \leq 2$	Low	1.0	$\text{RA} < \text{MV} \leq 1.5 \cdot \text{RA}$	Low	1.0
$2 < \text{MV} - \text{RA} \leq 4$	Medium	1.5	$1.5 \cdot \text{RA} < \text{MV} \leq 2 \cdot \text{RA}$	Medium	1.5
$\text{MV} - \text{RA} > 4$	High	2.0	$\text{MV} > 2 \cdot \text{RA}$	High	2.0

MV: Municipality Values; RA: Region Average.

the proportion of the female population in a situation of monetary poverty in comparison with the male population (GG). Eq. (10) shows the formulation to determine $NHER_{P,GG}$. To consider the population in monetary poverty, the criterion established by Eurostat is used: this criterion is based on the fact that monetary poverty takes place when the net income of the family unit is lower than 60% of the median of income at a national level. In addition, the gender gap was considered because of the results obtained by Sánchez-Guevara Sánchez et al. (2020a) in their study on the feminisation of EP in Madrid. The results showed the significant gender gap in the households in EP in Madrid and suggested the need for establishing policies considering the gender perspective in EP. The two indirect indicators to weight the social perspective of EP modify the value obtained with $NHER$. For this purpose, the weighting values to be used should be established similarly to the indicators of the $NHER$. Data of the Andalusian population in monetary poverty (Fig. 5) and data of gender gap (Fig. 6) were collected. The data distribution shows that the interquartile range of the distribution is low, thus meaning a high concentration of data in the same values of population in monetary poverty or values of gender gap. Regarding the data of population in monetary poverty, however, interesting values are found in the municipalities located above the third quartile of the distribution. In these cases, the number of inhabitants in monetary poverty greatly oscillated, from 2786 to 171,669 inhabitants. For this reason, weightings were applied according to the location of the municipality with respect to the percentiles of the data distribution (Table 3). As the number of inhabitants in monetary poverty located below the first quartile corresponded to very low values (lower than 482 inhabitants), another correction was applied to these cases to reduce the severity of the EP of the municipality. In the gender gap, there was a distribution like that of the population in monetary poverty. Therefore, the distribution presented a low interquartile range, with low values of gender gap. From the 95th percentile, which corresponds to a gender gap of 361 inhabitants, significant values were found in the Andalusian municipalities. In this interval greater than the 95th percentile, the most significant cases of gender gap in the Andalusian municipality were concentrated. In view of this circumstance, a weighting was applied according to the rules established in Table 4. To compare the effect of the socioeconomic indicators of $NHER_{P,GG}$ in comparison with $NHER$, a same measurement scale should be established. As mentioned above, $NHER$ is normalised between 0 and 1. Therefore, $NHER_{P,GG}$ should have the same value scale. For this purpose, $NHER_{P,GG}$ was limited to obtain a maximum value of 1 if the multiplication of $NHER$ with the socioeconomic indicators obtains a greater value (Eq. (11)).

$$NHER_{P,GG} = NHER \cdot P \cdot GG \tag{10}$$

$$NHER_{P,GG} = 1 \qquad if\ NHER \cdot P \cdot GG > 1 \tag{11}$$

2.3. Data collection

To determine both $NHER$ and $NHER_{P,GG}$, data related to each indirect indicator were collected (e.g., percentage of buildings built before 1980). Different data sources were used according to the type of indirect indicator. Regarding the indicators related to the building stock and social aspects, data published by the Spanish Institute of Statistics were collected. Table 5 shows the data sources used for each indicator. As for the socioeconomic data, the statistical data sources provide data in both absolute and percentage value. Therefore, this study considered two approaches to analyse these indirect socioeconomic indicators: approach 1 for the number of inhabitants, and approach 2 for the percentages of inhabitants.

Table 3
Degree of severity and value assigned to P.

Relation	Value
MV > 99th percentile	4.0
95th percentile < MV ≤ 99th percentile	2.0
75th percentile < MV ≤ 95th percentile	1.5
25th percentile ≤ MV ≤ 75th percentile	1.0
MV < 25th percentile	0.5

Table 4
Degree of severity and value assigned to GG.

Relation	Value
MV > 95th percentile	1.5
MV ≤ 95th percentile	1.0

Regarding the climate indicators, data were obtained through METEONORM, a software constituted by a database of climate files that is composed by 8325 weather stations distributed throughout the planet. This software has been widely used because it easily obtains climate data (Bellia et al., 2015; Hatwaambo et al., 2009; Kameni et al., 2019; Osman and Sevinc, 2019). From the data of the weather stations, the hourly values of external temperature in any location of the planet are obtained by interpolations (METEONORM, 2019). The hourly data of the external temperature were obtained with METEONORM in the 778 Andalusian municipalities. Data generated by METEONORM were treated to obtain the average temperature values of the summer nights, HDH and CDH. The procedure to generate the dataset of the 778 Andalusian municipalities could be extrapolated to other regions in Spain, and even used in other countries. Obtaining data of the building stock through the statistical institutes of each country guarantees an easier workflow to obtain data than that based on an individual analysis performed by technicians and professionals of the existing buildings in each municipality. In this sense, several studies have highlighted the advantages of using this type of data (Camboni et al., 2021; Pérez-Fargallo et al., 2020). Likewise, climate data usually constitute one of the main limitations to determine the hourly degrees of a region because of the difficulties to obtain hourly data of the various climates of each municipality. For this reason, the use of METEONORM to generate hourly data implies that hourly climate data could be obtained in any place of the planet, and therefore the extrapolation of the methodology to other countries is guaranteed.

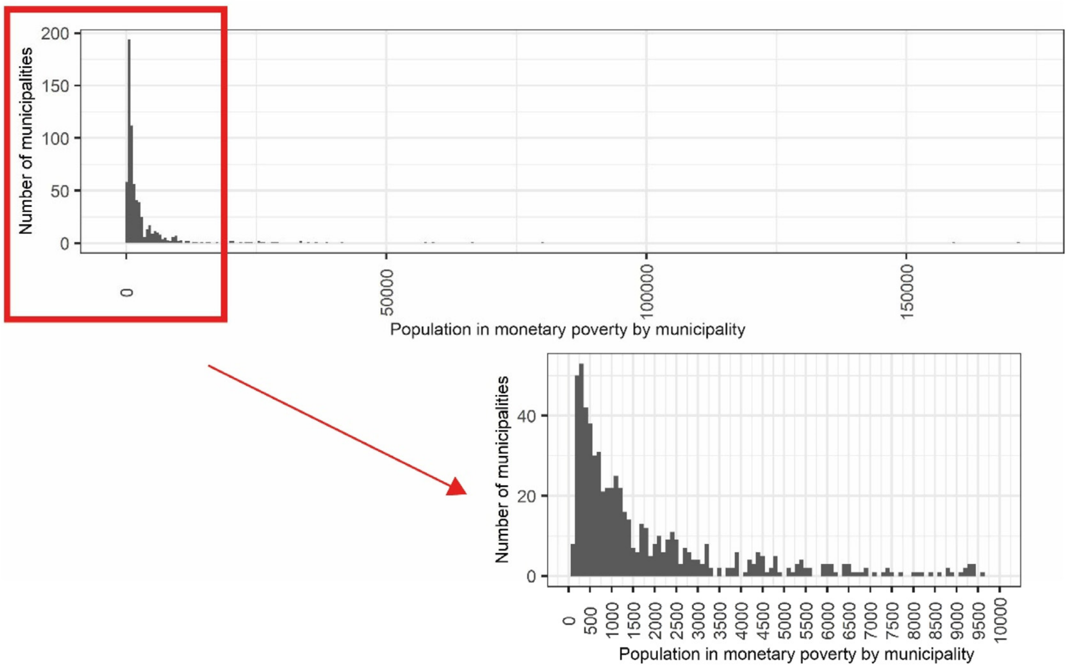

Fig. 5. Histogram of the population by municipalities in monetary poverty in 2017.
Source: Data obtained from the Spanish Institute of Statistics (2019).

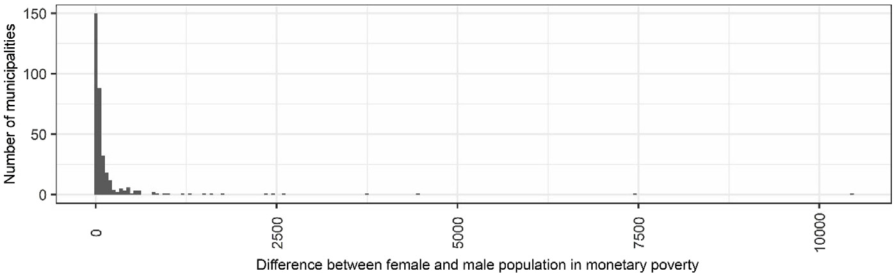

Fig. 6. Histogram of the difference between the female and male population in monetary poverty by municipalities in 2017.
Source: Data obtained from the Spanish Institute of Statistics (2019).

Table 5
Data source by indirect indicator analysed.

Indicator	Variable	Unit	Reference
V_a	Percentage of buildings built before 1980	%	Population and housing census in Spain (Spanish Institute of Statistics, 2011)
V_b	Percentage of buildings with dilapidated, bad or deficient maintenance conditions	%	Population and housing census in Spain (Spanish Institute of Statistics, 2011)
V_1	Percentage of dwellings without heating systems	%	Population and housing census in Spain (Spanish Institute of Statistics, 2011)
V_2	Percentage of dwellings without cooling systems	%	Population and housing census in Spain (Spanish Institute of Statistics, 2001)
V_3	Percentage of dwellings with electric heating systems	%	Population and housing census in Spain (Spanish Institute of Statistics, 2001)
V_d	Dwelling surface by household member	m^2	Population and housing census in Spain (Spanish Institute of Statistics, 2011)
P	Population in monetary poverty	No. of people, %	Distribution atlas of the household income (Spanish Institute of Statistics, 2019)
GG	Gender gap between the female and the male population in monetary poverty	No. of people, %	Distribution atlas of the household income (Spanish Institute of Statistics, 2019)

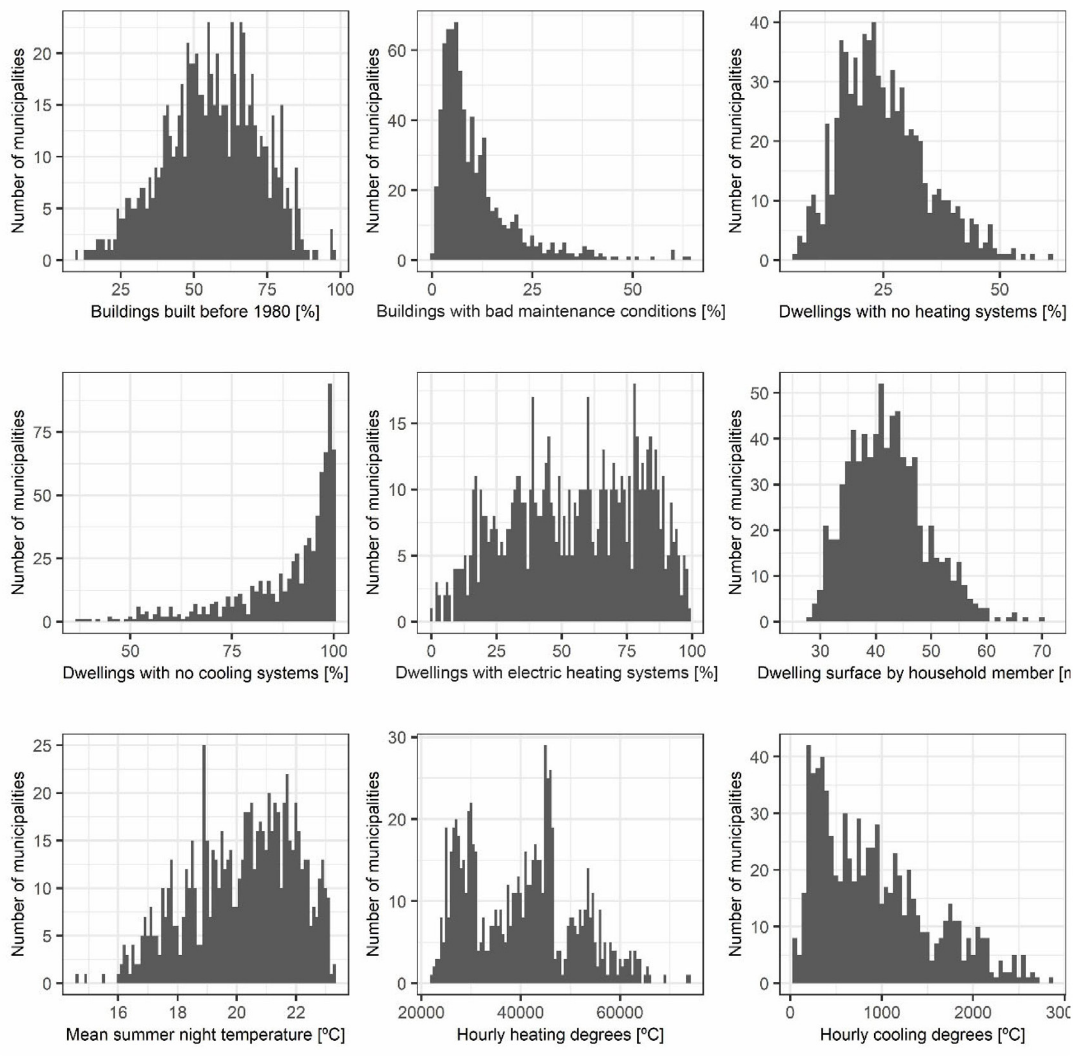

Fig. 7. Histograms of the data obtained in Andalusia in each variable considered by *NHER*.

3. Results and discussion

3.1. Analysis of the municipalities with greater EP risk due to building stock and climate indicators

Firstly, the results obtained with *NHER* were analysed. As mentioned above, *NHER* is designed to analyse the EP risk presented by municipalities according to the characteristics of their building stock. To determine the EP of municipalities, several indirect indicators were analysed. The assessment of *NHER* implies to know the requirements of different aspects in a combined way, the individual analysis of each indirect indicator could be interesting to know more in detail the building stock of the Andalusian municipalities. Although the data used to generate the NHER are partially obsolete (the census, which should be updated, is dated from 2011), they were the best source available at a state level (thus leading to a replicability) and at a desegregation level lower than the regional level. As this is a comparative study among municipalities, this last characteristic of the data is also relevant as this source is useful for establishing magnitude orders that allow that comparison to be carried out. Fig. 7 shows the histograms of the data obtained for each indicator in the 778 municipalities. In the buildings built before 1980, most municipalities had high percentages in their building stock: the first quartile (Q1) was placed in 45.5% and the third quartile (Q3) in 67.8%, recording a maximum value of 97.9%. These values were consistent with the broad development of the building stock in the period posterior to the Spanish Civil War (Domínguez-Amarillo et al., 2016; Kurtz et al., 2015). Thus, a high percentage of the buildings of the Andalusian municipalities were built before 1980, and only some municipalities had percentage values lower than 45%. However, this was not correlated to the buildings with bad maintenance conditions, as the percentage of buildings in that state were not very high. The reason is that, although it is assumed that most of the building stock previous to 1980 has deficiencies in its thermal behaviour (due to the lack of insulation as the first standard regulating it, NBE-CT-79, was not in force yet), most buildings should not necessarily have a conservation state with deficiencies. Most data were concentrated between 4.5 and 7.7%, although percentages greater than 25% were found in some municipalities. Regarding the availability of HVAC systems in dwellings, the results were diverse. In general terms, there was a greater percentage of dwellings with heating systems rather than with cooling systems. Likewise, dwellings with electric heating systems presented many percentage distributions in the building stock of the municipalities, detecting municipalities with values close to 100%, whereas other municipalities obtained values of 0.4%. The values related to the mean surface area of the dwelling by household member showed that most dwellings had average values between 36.8 and 46.17 m^2, mainly due to the fact that

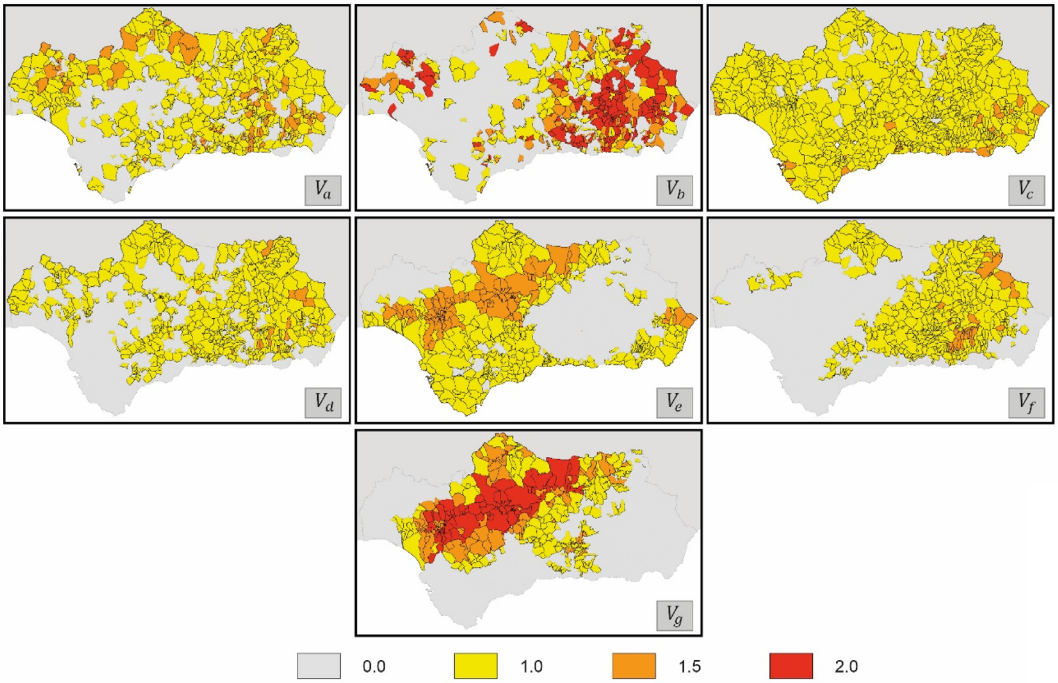

Fig. 8. Spatial distribution of the values obtained in each variable of *NHER*: V_a (buildings built before 1980); V_b (buildings with dilapidated, bad or deficient maintenance conditions); V_c (buildings with insufficient or inefficient heating and cooling systems); V_d (dwelling surface by household member); V_e (mean summer night temperature); V_f (hourly heating degrees), and V_g (hourly cooling degrees).

the average surface of dwellings and the size of the family units are similar among the Andalusian municipalities, although sometimes the values of the surface were greater than the average, obtaining values of 69.86 m^2. Finally, regarding the climate severity in Andalusia, the distribution of the degree hours presented various peaks, mainly due to the greater concentration of municipalities in geographic points with very similar characteristics of winter climate severity (e.g., the municipalities located in the Baetic Systems), whereas in summer the temperatures of cooling degree hours presented a greater concentration in the low values of the distribution because of the coastal municipalities. Likewise, the mean summer night temperature was high.

Therefore, the Andalusian municipalities generally have a building stock with characteristics that could lead to a high energy consumption in dwellings. Financing policies and measures should be established according to a criterion of classification and priorities, so the Andalusian municipalities with negative values in comparison with the average values of the autonomous region should be analysed. For this reason, the distribution of the indirect indicators in the autonomous region was studied before analysing *NHER* (Fig. 8). The spatial distribution showed various aspects related to the building stock. When V_a (buildings built before 1980) or V_d (dwelling surface by household member) had values in a high percentage of the Andalusian municipalities, the distribution in other indicators were different and geographic patterns were detected. As for V_b, there was a greater concentration of municipalities in the eastern part of the autonomous region with values greater than the Andalusian average. This could reflect the need for establishing specific plans to maintain and to repair the building stock of this region. As for the climate indicators (V_e, V_f, and V_g), the relations between the values obtained and the Baetic Systems were shown. Therefore, the municipalities at the greatest altitude of the autonomous region, such as those located in Sierra Morena or in the Penibaetic or Subbaetic System, obtained the greatest values of V_f (hourly heating degrees), and regarding V_g (hourly cooling degrees), the greatest values were obtained in the Baetic Depression (also known as the Guadalquivir Depression). Finally, as for V_e (mean summer night temperature), values equal to or greater than 1 were obtained, except in the municipalities at the greatest altitude, mainly located in the Penibaetic or Subbaetic System and some located in the Sierra de Cadiz.

This spatial distribution of the indirect indicators showed that the characteristics of the Andalusian building stock are different, so establishing political intervention criteria could be something of a challenge. Although some aspects were clear, such as the need for reducing the heating loads in the municipalities at the greatest altitude or the cooling loads in the area of the Guadalquivir Depression, the many aspects interrelated to the energy performance of the building stock of the municipalities made difficult to establish a classification criterion. As a result, *NHER* allowed all these indicators to be combined. Fig. 9 shows the spatial distribution of *NHER* in the Andalusian municipalities. As mentioned in Section 2, *NHER* had values between 0 and 1. A total of 10 classification groups could be established by intervals of 0.1. The Andalusian municipalities obtained values of *NHER* between 0 and 0.6. For the methodology designed for *NHER*, no municipality therefore met the most unfavourable combination in all the indirect indicators. A total of 21 municipalities obtained the most unfavourable values of *NHER*, with the set of municipalities with values of *NHER* between 0.3 and 0.4 being the greatest (Fig. 10). After analysing the distribution of the indirect indicators in the groups of *NHER* (Fig. 11), the indicators most influencing the most unfavourable groups (G05 and G06) were detected. In these cases, the combinations of high values of buildings built before 1980, deficient buildings, average surface and climate variables were strongly related to the most unfavourable groups.

Regarding the demographic characteristics of the municipalities with the greatest risk, the classifications of *NHER* did not correspond to the average economic level of the households by municipality. Table 6 shows the distributions of population in monetary poverty and gender gap in the groups of *NHER*. The groups did not consider socioeconomic factors greatly related to EP. The most outstanding aspect was the population in monetary

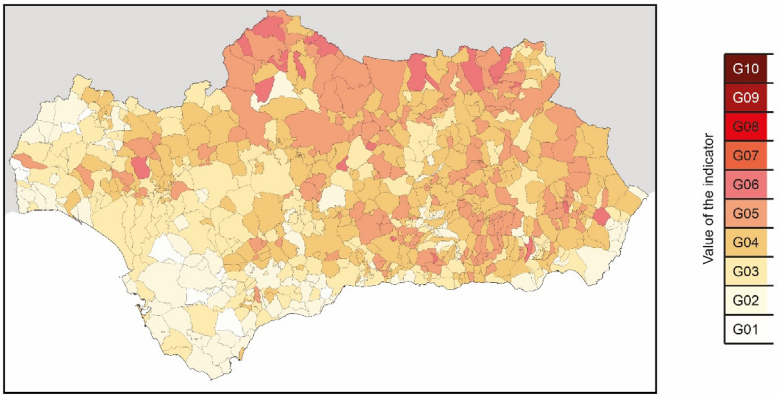

Fig. 9. Distribution of the *NHER* groups in each Andalusian municipality.

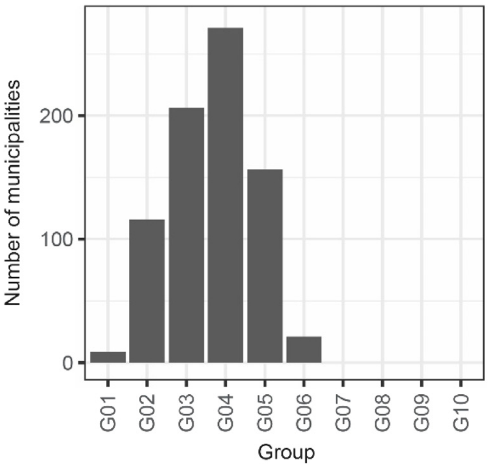

Fig. 10. Number of municipalities grouped in each *NHER* group.

poverty included in the group with the greatest risk of *NHER* as they corresponded to municipalities with a population in monetary poverty between 182 and 2036 inhabitants, and with a gender gap in monetary poverty between 1 and 50 inhabitants. In the group with the greatest risk, there were municipalities with a low population in monetary poverty, and therefore so many difficulties were not presented at a socioeconomic level in comparison with the municipalities with values of 10,333 or 66,429 inhabitants in monetary poverty found in G01 and G02. As a result, *NHER* is not a valid indicator if the state of the building stock and the income levels of the family units are together analysed. Nonetheless, it could be used to establish policies and programmes to restore the building stock and to reduce the greenhouse gas emissions (GHG) by 90% by 2050, as established in the European Union's goals. Although various studies have stressed the possible relationship between the reduction of GHG and EP (Dubois et al., 2019; Ürge-Vorsatz and Tirado Herrero, 2012), the rebound effects (Sorrell, 2015, 2007) or the variation of the energy prices (Mastropietro, 2019) could in certain cases not contribute to the removal of EP cases. Thus, *NHER* could be a valid indicator to design policies to achieve a low-carbon building stock by identifying the municipalities of a region where interventions should be prioritised because of the high energy requirements of their building stock.

3.2. Analysis of EP in the andalusian municipalities considering also population data

The limitations presented by *NHER* to assess the state of the building stock and the income of the family units together led to review the indicator. As mentioned in Section 2, $NHER_{P,GG}$ was the indicator designed to consider these two dimensions together. For this purpose, two indirect socioeconomic indicators were included: people in monetary poverty (P) and the proportion of the female population in monetary poverty in comparison with the male population (GG). When analysing the statistical population data, data of the municipalities were available in two units: the number of inhabitants or the percentage of inhabitants. Therefore, this study considered two approaches to analyse these indirect socioeconomic indicators: approach 1 for the number of inhabitants, and approach 2 for the percentages of inhabitants. Fig. 12 shows the spatial distribution of the values assigned to these indirect indicators. The approach used for the indicators varied the values assigned to each indicator. Considering the absolute population values, the municipalities with a larger number of inhabitants in monetary poverty were stressed, as well as the important cases of gender gap. Equally, as percentage values were considered, the smallest municipalities where the percentage relationships were higher due to its low number of inhabitants were stressed. Consequently, the distributions of $NHER_{P,GG}$ obtained with the two approaches were different (Fig. 13).

In approach 1, most province capitals were grouped in the groups with a greater risk because the number of inhabitants in monetary poverty was high. However, not all capitals were grouped in this group. For example, Jaen, which obtained a value of 0.87. In addition, approach 1 did not stand out big municipalities, but those with high values of population in a situation of vulnerability. This aspect can be seen in the municipalities of Jerez de la Frontera (212,915 inhabitants) and La Linea de la Concepcion (63,146 inhabitants); although the former has more inhabitants, the high number of inhabitants in monetary poverty in La Linea de la Concepcion, together with its deficient building stock, generated that its $NHER_{P,GG}$ was 0.96, whereas in Jerez de la Frontera it was 0.72. Although approach 1 grouped in the groups with a greater risk those municipalities with more inhabitants in monetary poverty or gender gap, the demographic values of the municipalities of other groups coincided (Tables 7 and 8). Increasing the degree of severity of $NHER_{P,GG}$ did not increase the population in monetary poverty in certain cases. This could be seen in group 9; although the minimum value and the first quartile of the distribution had greater values of inhabitants in

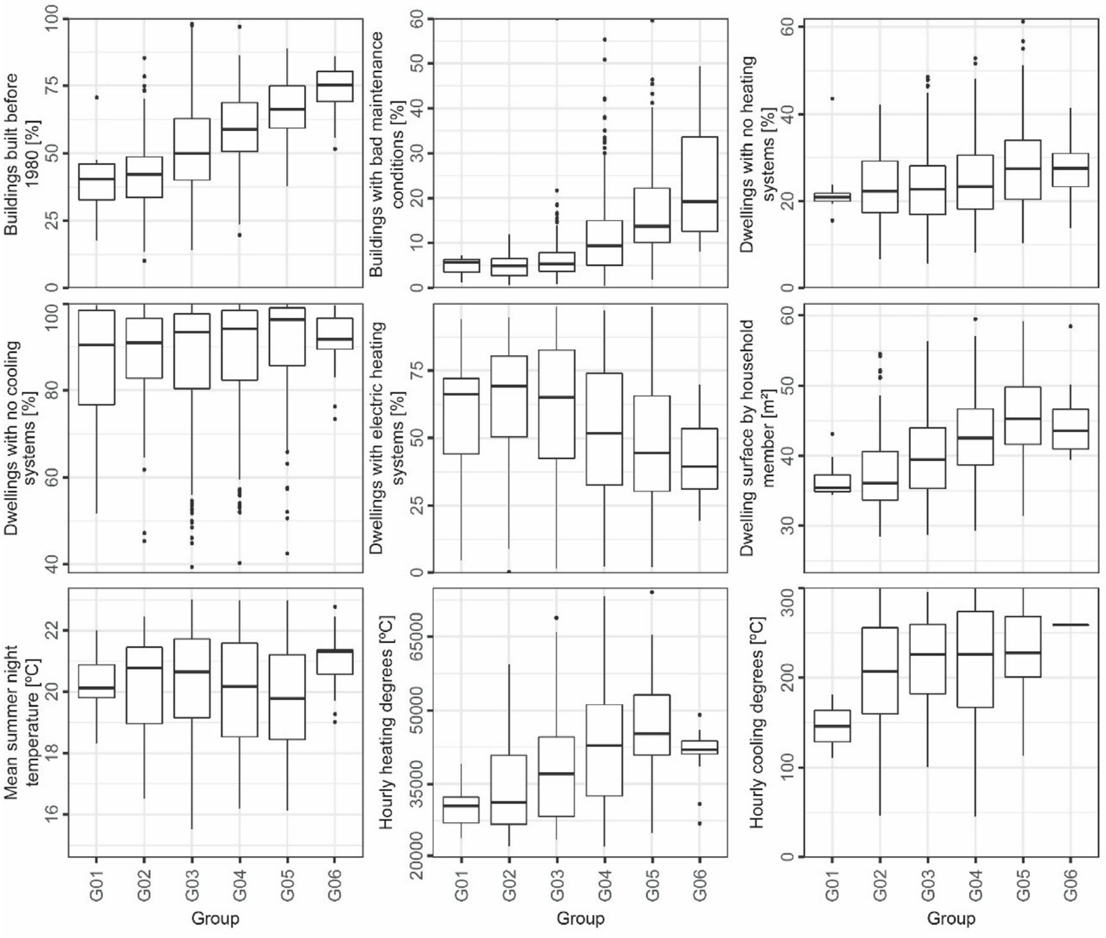

Fig. 11. Boxplots of the data related to each variable by *NHER* group.

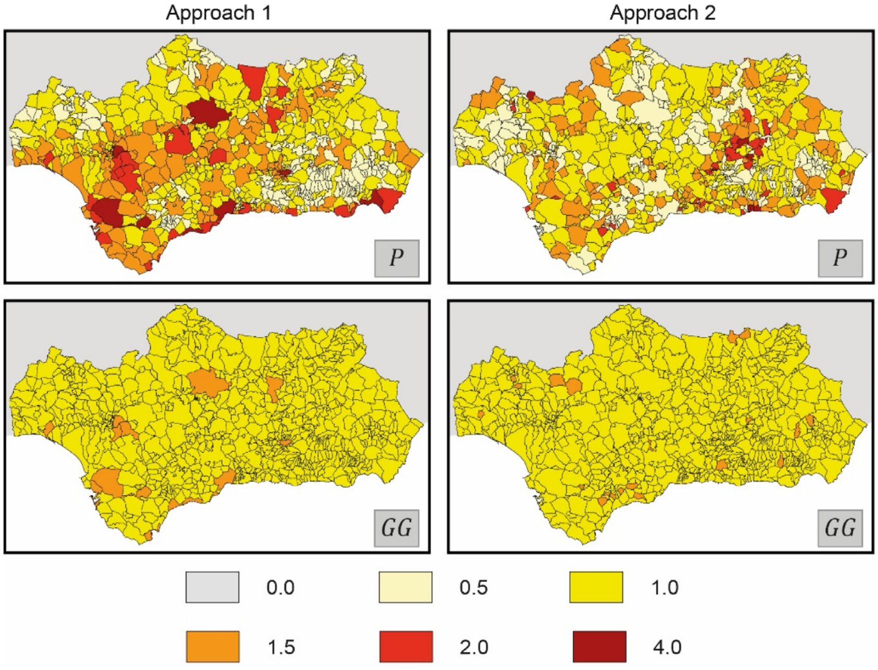

Fig. 12. Spatial distribution of the values obtained in each variable of $NHER_{P,GG}$. The values are distinguished according to the approach of $NHER_{P,GG}$.

Table 6
Distribution of the population in monetary poverty and difference of female and male population in monetary poverty in each *NHER* group.

Group	Population in monetary poverty					Gender gap in monetary poverty				
	Min.	Q1	Q2	Q3	Max.	Min.	Q1	Q2	Q3	Max.
G01	136	1,346	2,073	6,363	10,333	14	14	149	330	330
G02	188	934	2,784	6,881	66,429	1	24	58	185	2,588
G03	138	626	1,329	3,907	15,871	1	14	54	105	7,474
G04	127	448	1,004	2,269	57,726	2	10	23	69	3,770
G05	160	339	704	1,226	171,669	2	8	20	47	10,449
G06	186	263	372	1,031	2,036	1	3	6	15	50

Min.: minimum value; Q1: first quartile; Q2: second quartile; Q3: third quartile; Max.: maximum value.

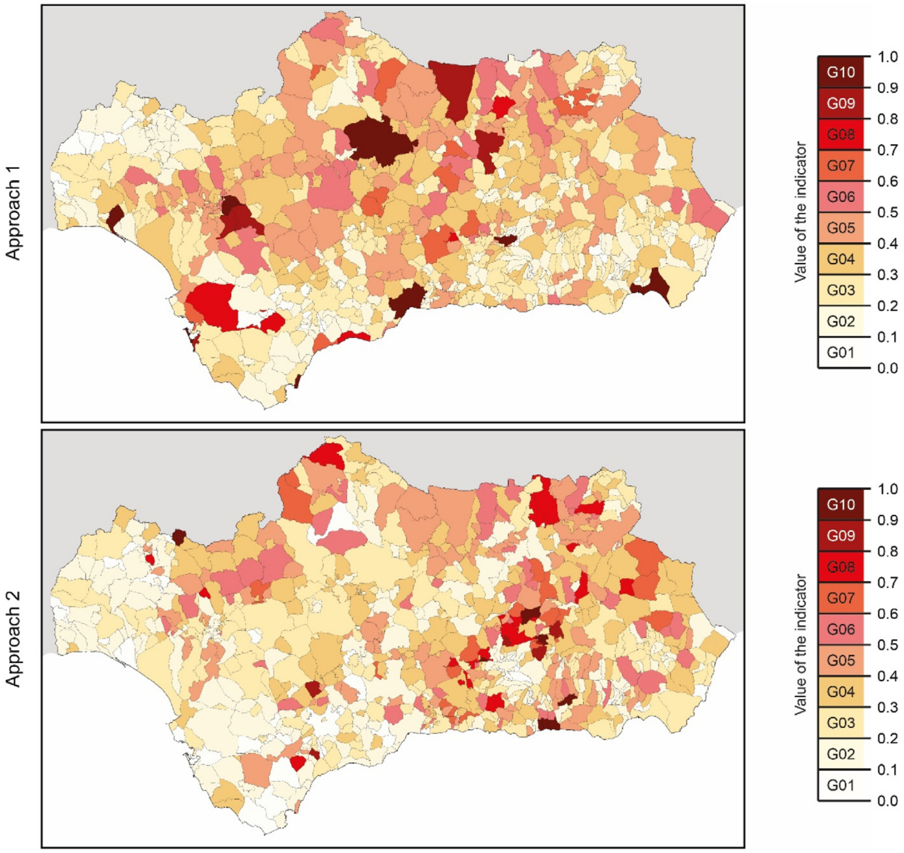

Fig. 13. Distribution of the $NHER_{P,GG}$ groups in each Andalusian municipality. The risk groups are distinguished according to the approach of $NHER_{P,GG}$.

monetary poverty than group 8, the upper quartiles had low values (as they corresponded to municipalities with a worse building stock). In addition, the municipalities with less inhabitants in monetary poverty and with less cases of gender gap were grouped in the groups with a lower risk, so the groups in EP risk were better distributed than those obtained with *NHER*.

Another important aspect is the variation of the values obtained in the municipalities in comparison with *NHER*. As for *NHER*, the maximum values were 0.6, but in $NHER_{P,GG}$ with approach 1, values of up to 1 were obtained, thus increasing the distribution of municipalities in each group (Fig. 14). The number of municipalities in the risk groups went from a high value in the groups with a lower risk to a lower number in the groups with a greater risk, thus identifying the municipalities with a greater EP risk. If the number of municipalities by risk group obtained with the two approaches of $NHER_{P,GG}$ is analysed, it could be observed that they are very similar. However, the results are different if the municipalities at a greater risk and the number of inhabitants in monetary poverty are analysed: approach 2 classified in the groups with a greater risk the municipalities with less inhabitants in a vulnerable situation. As for the group with a greater risk, the municipalities did not present situations of gender gap (i.e., the female population in monetary poverty was not greater than the male population in monetary poverty). This aspect therefore showed the possible weakness presented by $NHER_{P,GG}$ by using indirect socioeconomic indicators with percentage values. Fig. 15 shows the heatmaps of the minimum, mean and maximum values of $NHER_{P,GG}$ obtained by combining deciles of population in monetary poverty with *NHER*. The behaviour of the indicator is therefore shown by combining the cases of energy requirement of the building stock and the low-income population.

The heatmap shows that approach 1 had a more coherent behaviour with the combinations of cases of both population in monetary poverty and *NHER*. Thus, the cases with greater *NHER* and greater population in monetary poverty had the greatest values of $NHER_{P,GG}$. This aspect is particularly shown by the average values. As for the heatmaps with the maximum values of approach 1, the maximum values of decile 10 of the population in monetary poverty corresponded to municipalities with very high values of population in almost all deciles of *NHER*, thus obtaining values of 1 with $NHER_{P,GG}$. In approach 2, however, the tendency was different. The percentage populated data were

Table 7
Distribution of the population in monetary poverty in each $NHER_{P,GG}$ group. The results distinguished the approach of $NHER_{P,GG}$ used.

Group	Approach 1					Approach 2				
	Min.	Q1	Q2	Q3	Max.	Min.	Q1	Q2	Q3	Max.
G01	136	217	368	441	2,369	136	1,268	2,312	5,301	10,020
G02	127	269	393	1,180	11,401	131	592	1,651	5,478	158,751
G03	160	428	897	2,013	34,886	127	465	1,186	3,722	171,669
G04	495	797	1,315	2,323	36,582	172	548	1,051	2,302	28,747
G05	486	991	1,708	4,550	28,747	184	395	804	1,825	25,258
G06	823	3,128	4,374	7,028	26,075	186	370	804	1,419	8,025
G07	2,843	3,064	3,709	8,149	25,290	272	489	917	1,547	5,438
G08	3,869	9,912	28,730	53,966	66,429	206	305	629	1,755	4,538
G09	12,073	17,001	22,954	28,344	33,270	252	340	518	1,205	1,266
G10	23,963	31,856	58,464	119,463	171,669	280	678	926	1,646	3,785

Min.: minimum value; Q1: first quartile; Q2: second quartile; Q3: third quartile; Max.: maximum value.

Table 8
Distribution of the difference of female and male population in monetary poverty in each $NHER_{P,GG}$ group. The results distinguished the approach of $NHER_{P,GG}$ used.

Group	Approach 1					Approach 2				
	Min.	Q1	Q2	Q3	Max.	Min.	Q1	Q2	Q3	Max.
G01	2	3	9	14	17	1	13	82	229	563
G02	1	7	14	56	563	1	22	68	162	7,474
G03	1	9	26	69	598	1	13	34	80	10,449
G04	2	13	31	67	1,513	2	10	23	62	449
G05	3	23	65	144	1,001	2	4	21	62	812
G06	2	40	132	368	946	1	5	12	24	427
G07	21	74	134	818	1,280	2	3	28	68	85
G08	359	359	2,434	2,588	2,588	3	11	16	20	50
G09	323	466	835	1,407	1,606	8	8	8	8	8
G10	534	127	3,051	5,972	10,449	–	–	–	–	–

Min.: minimum value; Q1: first quartile; Q2: second quartile; Q3: third quartile; Max.: maximum value.

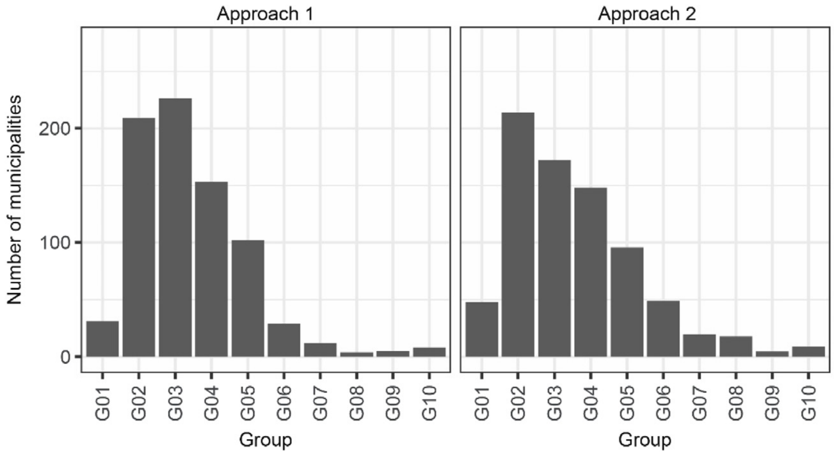

Fig. 14. Number of municipalities groups in each $NHER_{P,GG}$ group. The risk groups are distinguished according to the approach of $NHER_{P,GG}$.

assessed, and it was observed that the values of $NHER_{P,GG}$ did not follow a clear criterion in the heatmaps. Although decile 10 of *NHER* obtained high values of $NHER_{P,GG}$, high values were also obtained in lower deciles. This is useful to characterise the differences in the behaviour of both approaches. The use of approach 1 (absolute population data) therefore allowed the municipalities of the autonomous region with a greater risk to be detected, locating 8 municipalities in the group with the greatest risk. These municipalities did not coincide with the province capitals or the most populated cities, as a criterion of distribution of funds against EP based on the number of inhabitants could assume. One of the municipalities with a greater risk is La Linea de la Concepcion with 63,146 inhabitants, which had the same EP risk as Seville, with 689,434 inhabitants. The main reason was that the state of the building stock and the number of inhabitants in monetary poverty were considered. On the other hand, approach 2 considered in the analysis the municipalities that, without high values of population in monetary poverty, had significant percentage relations in comparison with the tendencies within the autonomous region. Smaller municipalities were stressed in comparison with the big municipalities presenting a high EP risk. If these municipalities are detected, measures could be established to face EP due to the human resource and economic difficulties that governments of these municipalities could have to intervene in comparison with the big cities, whose intervention could be easily made. Therefore, the use of approach 1 (absolute population data) or approach 2 (percentage population data) will allow various aspects to be addressed: approach 1 will detect the most unfavourable combinations of energy requirement and population in EP, particularly stressing the biggest municipalities, and approach 2 will detect municipalities where the energy requirements and the proportion of inhabitants in monetary poverty is high. Therefore, those responsible for decision-making could

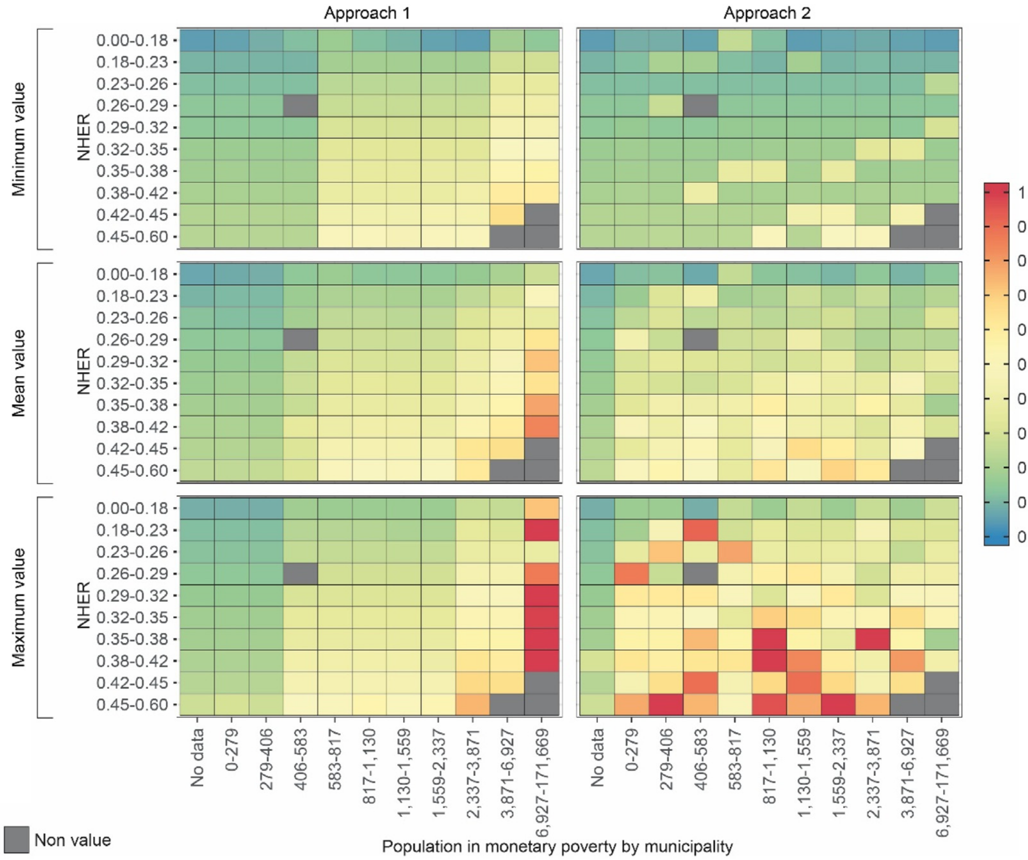

Fig. 15. Heatmap that compares the minimum, mean and maximum values of $NHER_{P,GG}$ according to the combination of *NHER* with the population in monetary poverty.

adapt the methodology designed to one approach according to their goals.

Likewise, the design of the indicator based on the combination of indirect indicators allows those formulating policies to know the weak points of the municipalities with a greater risk. Special measures could be established according to the values obtained in the technical or socioeconomic indirect indicators. In this regard, if the indicator of gender gap is considered, special programmes could be developed to reduce the female population in monetary poverty as the combination of aspects such as the family conciliation, pay inequality or the glass ceiling could contribute to a greater precariousness in the family units supported by women. Gender gap indicators should be therefore included in the assessment of the EP, as $NHER_{P,GG}$ does.

Although *NHER* is not an appropriate indicator to assess EP as socioeconomic aspects are not considered, the accurate assessment of the building stock of each municipality at a regional level would imply that it is used to design policies focused on the decarbonisation of the building stock within the goals established by the European Union for 2050. Although this decarbonisation process through the energy rehabilitation could contribute to family units in monetary poverty, the decarbonisation goals aim to intervene particularly in the building stock, and therefore the first stages should be mainly focused on the buildings generating more GHG emissions. This can imply interventions in regions with high energy consumption, although the income levels of the family units are also high.

Finally, the internationalisation of the methodology designed (to assess both the building stock and EP) and the possible limitations should be stressed. First, the methodology is based on the use of data collected by official statistical entities (in this case, Spanish entities), so it could be used in other regions. In this regard, the methodology could be used in other autonomous regions in Spain. Likewise, the methodology is based on the comparison of the individual values with the average group values, so it could be adapted to various scales; consequently, an analysis could be performed at a state level when the designer of the policies is the central government, or a regional or provincial analysis if autonomic governments are those designing the policies. Regarding the internationalisation of the methodology, the data used in other regions would be available. However, some indicators should be varied. This would be the case of the indicator related to the buildings built before the first standard on energy efficiency as the year when the first standards were established could be different in each country. However, the indirect indicators used are limited in certain ways. The main limitation is related to the data sources available as, in some cases, these data can be out of date in relation to the current situation. In this regard, the results of this study were based on the data obtained from the last Housing Census carried out in Spain (2011) and, although the increase of the building stock in recent years has been low due to the economic crisis starting in 2008 with the Lehman Brothers fall (Aguilar-Palacio et al., 2015), the percentage data of the building stock could slightly vary. Likewise, another limitation is related to the possibility of obtaining desegregated data at a municipal level from the statistical bodies of each country. In Spain, these municipal data could be obtained, although there could be limitations in other countries, thus limiting the use of the methodology.

4. Conclusions

This study aims to establishing an assessment methodology of the municipalities presenting a greater energy poverty risk. For this purpose, indicators related to both the energy requirements of the dwelling stock and the income conditions of the population are used. In addition, the energy poverty risk of the municipalities in the region of Andalusia (Spain) is quantified.

Regarding the methodology designed, the results have showed that the two indicators (*NHER* and $NHER_{P,GG}$) could be used for different objectives. Although *NHER* allows the energy requirement of the building stock of municipalities to be known, the results are not consistent with the levels of monetary vulnerability of the family units. This implies that *NHER* is not appropriate to assess the energy poverty of the municipalities. However, as the building stock performance is known, it could be used as an appropriate methodology to design policies focused on the decarbonisation of the building stock. On the other hand, $NHER_{P,GG}$ allows *NHER* to be coherently included with indirect indicators of population in monetary poverty and gender gap, so the levels of risk of energy poverty of each municipality are appropriately distributed. The approach used for the socioeconomic indicators depends on the goal established in the policies and measures designed by governments. On the one hand, the approach based on absolute population data detects the municipalities with a deficient combination of energy requirement and population in monetary poverty. This last aspect could stress the energy poverty risk in the big municipalities to the detriment of the small municipalities. However, an advantage is that the cities with a worrying situation in absolute terms are shown. In spite of this, these cities could have greater facilities in order that municipal governments self-finance measures against energy poverty, unlike the small municipalities. Therefore, the use of approach 1 could be limited to finance small municipalities. On the other hand, approach 2 detects the greatest predominance of energy poverty in the small municipalities by analysing percentage values of population in monetary poverty. The use of both approaches therefore depends on the goals established by the regional governments.

Regarding Andalusia, the analysis of the indirect indicators show that most municipalities have a building stock built before the first standard on energy efficiency, so many buildings have a deficient energy performance. Likewise, there are patterns among the most unfavourable cases of some indicators and geographic aspects of Andalusia. Most municipalities with high percentage values of buildings with a bad maintenance or damages are in the eastern side of the autonomous region. The indirect climate indicators (hourly degrees and temperature of the summer nights) show that the mountain system of the region and the climate severity are related. The design of measures adapted to these aspects would therefore improve the energy performance of the building stock. The assessment of the energy requirements by using *NHER* shows that the municipalities far from the coastal zones have a greater energy requirement. This aspect is due to two aspects: (i) the broad development of the building stock of the coastal municipalities in comparison with the indoor zones; and (ii) a greater climate severity presented by the indoor zones in comparison with coastal zones. Municipalities with a high energy poverty risk are detected by including socioeconomic indicators. This is the case of the province capitals and significant municipalities with an unfavourable situation, such as La Linea de la Concepcion. Although data of gender gap are not relatively high in most municipalities (the third quartile of the distribution of gender gap corresponds to the value of 100 inhabitants), worrying values are obtained in some municipalities. In this regard, some municipalities record values of gender gap of 10,449 inhabitants. It is therefore crucial to include measures to reduce the high number of population in comparison with the male population in monetary poverty due to the specific vulnerabilities that the female population could present to remove this situation (pay inequalities, family conciliation, etc.).

To conclude, various political implications are found. First, the methodology designed is an appropriate tool to establish policies that reduce energy poverty in all the governmental levels. Thus, the modification of the comparison scale (state, autonomous or provincial) adopts the intervention methodology of the government teams. Likewise, the possibility of obtaining additional information of the methodology through indirect indicators provides those responsible for policies with a more detailed knowledge of the municipalities' demands, so specific measures could be adapted to each municipality's needs. In this regard, if the municipality has high values in the socioeconomic indicators, several measures should be established, such as the creation of jobs, support in the payment of electricity bills or measures to remove the gender gap. In addition, the analysis of the indicators of the building stock could foster different measures, such as the incorporation of insulation in envelopes or the availability of effective cooling systems. This aspect would meet the goals established by the Spanish government in its National Strategy against Energy Poverty 2019–2024, which aims to reduce energy poverty cases between 25 and 50% by 2025. Likewise, the methodology developed with *NHER* could be useful for state and regional governments to achieve the goals of decarbonisation of the building stock established by the European Union for 2050. Regarding the energy poverty situation of Andalusia, implementing measures to reduce energy poverty is crucial. The lack of appropriate energy poverty plans in the region, together with the precariousness of the family units and the building stock (worsened by the Covid-19 pandemic), leads to the need that regional governments establish ambitious policies.

CRediT authorship contribution statement

David Bienvenido-Huertas: Conceptualisation, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Ana Sanz Fernández:** Conceptualisation, Formal analysis, Writing – review & editing. **Carmen Sánchez-Guevara Sánchez:** Conceptualisation, Formal analysis, Investigation, Validation. **Carlos Rubio-Bellido:** Conceptualisation, Visualisation, Writing – review & editing, Supervision.

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.

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References

Aguilar-Palacio, I., Carrera-Lasfuentes, P., Rabanaque, M.J., 2015. Youth unemployment and economic recession in Spain: influence on health and lifestyles in young people (16–24 years old). Int. J. Public Health 60, 427–435. http://dx.doi.org/10.1007/s00038-015-0668-9.

Bellia, L., Pedace, A., Fragliasso, F., 2015. The role of weather data files in climate-based daylight modeling. Sol. Energy 112, 169–182. http://dx.doi.org/10.1016/j.solener.2014.11.033.

Bienvenido-Huertas, D., Pulido-Arcas, J.A., Rubio-Bellido, C., Pérez-Fargallo, A., 2021. Feasibility of adaptive thermal comfort for energy savings in cooling and heating: A study on europe and the mediterranean basin. Urban Clim. 36, http://dx.doi.org/10.1016/j.uclim.2021.100807.

Bienvenido-Huertas, D., Rubio-Bellido, C., Pérez-Fargallo, A., Pulido-Arcas, J.A., 2020a. Energy saving potential in current and future world built environments based on the adaptive comfort approach. J. Clean. Prod. 249, http://dx.doi.org/10.1016/j.jclepro.2019.119306.

Bienvenido-Huertas, D., Sánchez-García, D., Rubio-Bellido, C., 2020b. Analysing natural ventilation to reduce the cooling energy consumption and the fuel poverty of social dwellings in coastal zones. Appl. Energy 279, http://dx.doi.org/10.1016/j.apenergy.2020.115845.

Bouzarovski, S., Petrova, S., 2015. A global perspective on domestic energy deprivation: Overcoming the energy poverty–fuel poverty binary. Energy Res. Soc. Sci. 10, 31–40. http://dx.doi.org/10.1016/j.erss.2015.06.007.

Cadiz Provincial Council, 2020. Provincial strategic plan against energy poverty.

Camboni, R., Corsini, A., Miniaci, R., Valbonesi, P., 2021. Mapping fuel poverty risk at the municipal level. a small-scale analysis of Italian energy performance certificate, census and survey data. Energy Policy 155, 112324. http://dx.doi.org/10.1016/j.enpol.2021.112324.

Castaño-Rosa, R., Solís-Guzmán, J., Marrero, M., 2020. Energy poverty goes south? Understanding the costs of energy poverty with the index of vulnerable homes in Spain. Energy Res. Soc. Sci 60, 101325. http://dx.doi.org/10.1016/j.erss.2019.101325.

Castaño-Rosa, R., Solís-Guzmán, J., Rubio-Bellido, C., Marrero, M., 2019. Towards a multiple-indicator approach to energy poverty in the European union: A review. Energy Build. 193, 36–48. http://dx.doi.org/10.1016/j.enbuild.2019.03.039.

Chard, R., Walker, G., 2016. Living with fuel poverty in older age: Coping strategies and their problematic implications. Energy Res. Soc. Sci. 18, 62–70. http://dx.doi.org/10.1016/j.erss.2016.03.004.

Day, R., Walker, G., Simcock, N., 2016. Conceptualising energy use and energy poverty using a capabilities framework. Energy Policy 93, 255–264. http://dx.doi.org/10.1016/j.enpol.2016.03.019.

Domínguez-Amarillo, S., Sendra, J.J., Oteiza, I., 2016. La envolvente térmica de la vivienda social. El caso de sevilla, 1939 a 1979. Editorial CSIC: Madrid.

Dubois, G., Sovacool, B., Aall, C., Nilsson, M., Barbier, C., Herrmann, A., Bruyère, S., Andersson, C., Skold, B., Nadaud, F., Dorner, F., Moberg, K.R., Ceron, J.P., Fischer, H., Amelung, D., Baltruszewicz, M., Fischer, J., Benevise, F., Louis, V.R., Sauerborn, R., 2019. It starts at home? Climate policies targeting household consumption and behavioral decisions are key to low-carbon futures. Energy Res. Soc. Sci. 52, 144–158. http://dx.doi.org/10.1016/j.erss.2019.02.001.

European Commission, 2011. A roadmap for moving to a competitive low carbon economy in 2050. Brussels, Belgium.

European Committee for Standardization, 2019. EN 16798-1:2019 energy performance of buildings - ventilation for buildings - part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acous.

Fuller, S., McCauley, D., 2016. Framing energy justice: Perspectives from activism and advocacy. Energy Res. Soc. Sci. 11, 1–8. http://dx.doi.org/10.1016/j.erss.2015.08.004.

Gatto, A., Drago, C., 2021. When renewable energy, empowerment, and entrepreneurship connect: Measuring energy policy effectiveness in 230 countries. Energy Res. Soc. Sci. 78, 101977. http://dx.doi.org/10.1016/j.erss.2021.101977.

Gouveia, J.P., Palma, P., Simoes, S.G., 2019. Energy poverty vulnerability index: A multidimensional tool to identify hotspots for local action. Energy Rep. 5, 187–201. http://dx.doi.org/10.1016/J.EGYR.2018.12.004.

Hatwaambo, S., Jain, P.C., Perers, B., Karlsson, B., 2009. Projected beam irradiation at low latitudes using meteonorm database. Renew. Energy 34, 1394–1398. http://dx.doi.org/10.1016/j.renene.2008.09.011.

Kameni, M., Yvon, A., Kalameu, O., Asadi, S., Choudhary, R., Reiter, S., 2019. Impact of climate change on demands for heating and cooling energy in hospitals, : An in-depth case study of six islands located in the Indian ocean region. Sustain. Cities Soc. 44, 629–645. http://dx.doi.org/10.1016/j.scs.2018.10.031.

Kurtz, F., Monzón, M., López-Mesa, B., 2015. Energy and acoustics related obsolescence of social housing of Spain's post-war in less favoured urban areas. The case of zaragoza. Inf. la construcción 67, m021. http://dx.doi.org/10.3989/ic.14.062.

Kyprianou, I., Serghides, D.K., Varo, A., Gouveia, J.P., Kopeva, D., Murauskaite, L., 2019. Energy poverty policies and measures in 5 EU countries: A comparative study. Energy Build. 196, 46–60. http://dx.doi.org/10.1016/j.enbuild.2019.05.003.

Litti, G., Khoshdel, S., Audenaert, A., Braet, J., 2015. Hygrothermal performance evaluation of traditional brick masonry in historic buildings. Energy Build. 105, 393–411. http://dx.doi.org/10.1016/j.enbuild.2015.07.049.

Martín-Consuegra, F., Gómez Giménez, J.M., Alonso, C., Hernández, R.Córdoba., Aja, A.Hernández., Oteiza, I., 2020. Multidimensional index of fuel poverty in deprived neighbourhoods. Case study of madrid. Energy Build. 224, http://dx.doi.org/10.1016/j.enbuild.2020.110205.

Martín-Consuegra, F., Hernández-Aja, A., Oteiza, I., Alonso, C., 2019. Distribución de la pobreza energética en la ciudad de madrid (españa). Eure 45, 133–152. http://dx.doi.org/10.4067/S0250-71612019000200133.

März, S., 2018. Assessing the fuel poverty vulnerability of urban neighbourhoods using a spatial multi-criteria decision analysis for the german city of oberhausen. Renew. Sustain. Energy Rev. 82, 1701–1711. http://dx.doi.org/10.1016/J.RSER.2017.07.006.

Mastropietro, P., 2019. Who should pay to support renewable electricity? Exploring regressive impacts, energy poverty and tariff equity. Energy Res. Soc. Sci. 56, 101222. http://dx.doi.org/10.1016/j.erss.2019.101222.

METEONORM, 2019. Handbook Part II: Theory (Version 7.3.1). Bern, Switzerland.

Morrison, C., Shortt, N., 2008. Fuel poverty in Scotland: Refining spatial resolution in the scottish fuel poverty indicator using a GIS-based multiple risk index. Health Place 14, 702–717. http://dx.doi.org/10.1016/j.healthplace.2007.11.003.

Osman, M.M., Sevinc, H., 2019. Adaptation of climate-responsive building design strategies and resilience to climate change in the hot/arid region of Khartoum. Sudan. Sustain. Cities Soc. 47, 101429. http://dx.doi.org/10.1016/j.scs.2019.101429.

Pérez-Fargallo, A., Bienvenido-Huertas, D., Rubio-Bellido, C., Trebilcock, M., 2020. Energy poverty risk mapping methodology considering the user's thermal adaptability: The case of Chile. Energy Sustain. Dev. 58, 63–77. http://dx.doi.org/10.1016/j.esd.2020.07.009.

Piai Paiva, J.C., Jannuzzi, G.D.M., de Melo, C.A., 2019. Mapping electricity affordability in Brazil. Util. Policy 59, 100926. http://dx.doi.org/10.1016/J.JUP.2019.100926.

Reames, T.G., 2016. Targeting energy justice: exploring spatial, racial/ethnic and socioeconomic disparities in urban residential heating energy efficiency. Energy Policy 97, 549–558. http://dx.doi.org/10.1016/j.enpol.2016.07.048.

Rotilio, M., Cucchiella, F., Berardinis, P.De., Stornelli, V., 2018. Thermal transmittance measurements of the historical masonries: Some case studies. Energies 11 (2987), http://dx.doi.org/10.3390/en11112987.

Sánchez-Guevara Sánchez, C., Mavrogianni, A., Neila González, F.J., 2017. On the minimal thermal habitability conditions in low income dwellings in Spain for a new definition of fuel poverty. Build. Environ. 114, 344–356. http://dx.doi.org/10.1016/j.buildenv.2016.12.029.

Sánchez-Guevara Sánchez, C., Núñez Peiró, M., Taylor, J., Mavrogianni, A., Neila González, J., 2019. Assessing population vulnerability towards summer energy poverty: Case studies of madrid and London. Energy Build. 190, 132–143. http://dx.doi.org/10.1016/j.enbuild.2019.02.024.

Sánchez-Guevara Sánchez, C., Sanz Fernández, A., Núñez Peiró, M., Gómez Muñoz, G., 2020a. Feminisation of energy poverty in the city of madrid. Energy Build. 223, http://dx.doi.org/10.1016/j.enbuild.2020.110157.

Sánchez-Guevara Sánchez, C., Sanz Fernández, A., Núñez Peiró, M., Gómez Muñoz, G., 2020b. Energy poverty in madrid: Data exploitation at the city and district level. Energy Policy 144, http://dx.doi.org/10.1016/j.enpol.2020.111653.

Scarpellini, S., Rivera-Torres, P., Suárez-Perales, I., Aranda-Usón, A., 2015. Analysis of energy poverty intensity from the perspective of the regional administration: Empirical evidence from households in southern Europe. Energy Policy 86, 729–738. http://dx.doi.org/10.1016/j.enpol.2015.08.009.

Siksnelyte-Butkiene, I., Streimikiene, D., Lekavicius, V., Balezentis, T., 2021. Energy poverty indicators: A systematic literature review and comprehensive analysis of integrity. Sustain. Cities Soc. 67, http://dx.doi.org/10.1016/j.scs.2021.102756.

Simoes, S.G., Gregório, V., Seixas, J., 2016. Mapping fuel poverty in Portugal. Energy Procedia 106, 155–165. http://dx.doi.org/10.1016/J.EGYPRO.2016.12.112.

Sorensen, B., 2013. A history of energy: Northern Europe from the stone age to the present day. Routledge.

Sorrell, S., 2007. Improving the evidence base for energy policy: The role of systematic reviews. Energy Policy 35, 1858–1871. http://dx.doi.org/10.1016/j.enpol.2006.06.008.

Sorrell, S., 2015. Reducing energy demand: A review of issues, challenges and approaches. Renew. Sustain. Energy Rev. 47, 74–82. http://dx.doi.org/10.1016/j.rser.2015.03.002.

Spanish Institute of Statistics, 2001. Census of population and housing (2001).

Spanish Institute of Statistics, 2011. Census of population and housing (2011) [www document]. URL https://www.ine.es/censos2011_datos/cen11_datos_resultados.htm.

Spanish Institute of Statistics, 2019. Atlas of distribution of household income [www document]. URL https://www.ine.es/experimental/experimental.htm.

Spanish Institute of Statistics, 2020a. Official population figures from the revision of the municipal register. [www document]. URL https://www.ine.es/jaxiT3/Tabla.htm?t=2915.

Spanish Institute of Statistics, 2020b. Employment rates by autonomous community [www document]. URL https://www.ine.es/jaxiT3/Tabla.htm?t=4942 & L=0.

Spanish Institute of Statistics, 2020c. Income per household by autonomous communities [www document]. URL https://www.ine.es/jaxiT3/Tabla.htm?t=9949.

Spanish Institute of Statistics, 2020d. Poverty risk rate by autonomous communities [www document]. URL https://www.ine.es/jaxiT3/Tabla.htm?t=9963.

The Government of Spain, 1979. Royal decree 2429/79. Approving the basic building norm NBE-CT-79, about the thermal conditions in buildings. Normas básicas de la edificación.

The Government of Spain, 2019. National strategy against energy poverty 2019–2024 (Spain).

The Government of Spain, 2020. Employment regulation statistics advance. 2020–2020 [www document]. URL http://www.mites.gob.es/estadisticas/Reg/reg20ene_ago/reg_08_2020.pdf.

Thomson, H., Bouzarovski, S., Snell, C., 2017. Rethinking the measurement of energy poverty in europe: A critical analysis of indicators and data. Indoor Built. Environ. 26, 879–901. http://dx.doi.org/10.1177/1420326X17699260.

Tirado Herrero, S., Jiménez Meneses, L., López Fernández, J.L., Perero Van Hove, E., Irigoyen Hidalgo, V.M., Savary, P., 2016. Pobreza, vulnerabilidad y desigualdad energética. Nuevos enfoques de análisis. Asociación de ciencias ambientales. Madrid.

Ürge-Vorsatz, D., Tirado Herrero, S., 2012. Building synergies between climate change mitigation and energy poverty alleviation. Energy Policy 49, 83–90. http://dx.doi.org/10.1016/j.enpol.2011.11.093.

Vilches, A., Barrios Padura, Á., Molina Huelva, M., 2017. Retrofitting of homes for people in fuel poverty: Approach based on household thermal comfort. Energy Policy 100, 283–291. http://dx.doi.org/10.1016/j.enpol.2016.10.016.

Walker, R., Liddell, C., McKenzie, P., Morris, C., 2013. Evaluating fuel poverty policy in Northern Ireland using a geographic approach. Energy Policy 63, 765–774. http://dx.doi.org/10.1016/j.enpol.2013.08.047.

Walker, R., McKenzie, P., Liddell, C., Morris, C., 2012. Area-based targeting of fuel poverty in Northern Ireland: An evidenced-based approach. Appl. Geogr 2012 (34), 639–649. http://dx.doi.org/10.1016/j.apgeog.2012.04.002.