sustainability

MDPI

Article

A Territorial Estimate for Household Energy Vulnerability: An Application for Spain

Pilar Murias *, Beatriz Valcárcel-Aguiar and Rosa María Regueiro-Ferreira

Department of Applied Economics, Faculty of Economics and Business Administration, Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Spain; beatriz.valcarcel@usc.es (B.V.-A.); rosamaria.regueiro@usc.es (R.M.R.-F.)

* Correspondence: mdelpilar.murias@usc.es; Tel.: +34-881-811-584

Received: 8 June 2020; Accepted: 19 July 2020; Published: 22 July 2020

Abstract: This paper proposes a composite indicator intended to assess territorial differences in household energy vulnerability. Although the estimation of household energy vulnerability has received less attention in scientific literature than energy poverty, it is a key element for political action as it allows for the diagnosis and subsequent action to tackle potential situations of household poverty before they actually occur. In this sense, the principal contribution of this article is a proposal for a tool designed to quantify the abstract and multidimensional phenomenon of household energy vulnerability. The technique used for constructing this synthetic indicator allows for the participation of stakeholders, especially policy makers, in defining and calculating the index. The synthetic index for energy vulnerability has been estimated for Spanish provinces. The results allow for the creation of a map providing an approximate insight into the spatial distribution of household energy vulnerability in Spain.

Keywords: energy vulnerability; energy poverty; composite indicator; goal programming; Spanish provinces

1. Introduction

Economic growth over the last two centuries has positioned energy as a basic structural asset. Access to and use of this asset by households can therefore boost prosperity or lead to poverty [1]. Rising household expenditure on energy [2] is a variable that has contributed to a general increase in poverty, and energy poverty in particular [3]. Assuming that many authors consider energy poverty as a particular form of energy injustice suffered by the final consumers [4–9], its alleviation becomes an unavoidable responsibility for political action [10]. As a result, household energy poverty has gradually been included on political agendas, which in turn is an indicator of the degree of its impact from various perspectives [11–17].

In line with these proposals and faced with the lack of mechanisms capable of contributing to the prevention of situations of this kind, multilevel public institutions have introduced palliative measures based on programs designed to tackle energy poverty and minimize its impact following detection. In general terms, these initiatives cover the cost of energy bills and/or subsidize electricity and natural gas for beneficiaries that meet a series of conditions based on key variables, in particular income [18]. Examples include the Cold Weather Payments Program in the UK and the subsidized rates known as 'social vouchers' available in a number of countries including Spain, Portugal, France, Greece, and Italy [19]. However, within a context of rising energy prices, hegemony of the electricity lobby (ibid), economic instability and the failure to formalize the concept of energy poverty, the impact of these measures has been limited and has failed to eradicate the problem [20]. The essential reason is that these measures are focused on the consequences of the problems and not on the causes.

These causes are not only conditioned by the socio-economic level of household members but also by other factors (i.e., climatic, technical, demographic, or social conditions) [21], which follow a marked spatial distribution [22,23].

Meanwhile, the concept of household energy vulnerability has made a timid appearance in international academic forums, where it is considered to be an ex ante phenomenon of a temporary and less serious nature than poverty. Prevention is seen as the principal strength of household energy vulnerability, enabling policy makers to anticipate and introduce corrective measures before the population suffers the harmful effects of energy poverty [24,25]. However, the application of the concept of household energy vulnerability for this purpose has two major difficulties. The first is related to the complexities involved in providing a precise definition of this concept [26], which is even more abstract than that of poverty. In our opinion, household energy vulnerability tends to be confused with that of the socio-economically vulnerable population, assuming that the only source of household energy vulnerability is the economic one. The second complication is related to its quantification. On the one hand, the abstract and multidimensional nature of household energy vulnerability impedes direct measurement, and it can therefore only be estimated. On the other hand, it is difficult to obtain an accurate diagnosis of household energy vulnerability in large countries because frequently they hide important territorial differences.

In the light of both the potential and the difficulties associated with the concept of energy vulnerability, this article has a threefold objective. Firstly, a review of the limited but growing scientific literature allows for an insight into the distinction between the concepts of household energy vulnerability and the socio-economically vulnerable population. Secondly, it offers a proposal for approximating the degree of household energy vulnerability in a community or region by using a synthetic indicator, which will be referred to as the Household Energy Vulnerability Index (HEVI). This proposal considers the multidimensional nature of the concept of household energy vulnerability and it allows an analysis of territorial differences, identifying geographical patterns and providing a first insight into the spatial distribution of household energy vulnerability. It would also be useful to identify particularly sensitive areas where it could be necessary to carry out an in-depth study at household level. Thirdly, the HEVI is tested in the Spanish regional context, where political action takes place at local, regional, and country level and significant spatial differences affect household energy vulnerability. The application allows for the creation of a map offering an approximate insight into the spatial distribution of household energy vulnerability in Spain.

The article is structured as follows: Section 2 reviews the literature on household energy vulnerability, focusing on the abstract and multidimensional nature of the term, thereby justifying the use of synthetic indicator methodology, and describes the theoretical background employed in drawing up the proposed Household Energy Vulnerability Index (HEVI). Section 3 presents the quantitative technique used to collect information from multiple variables under a single value, the HEVI. Section 4 includes the specific model for estimating the HEVI in the case of Spanish provinces, whilst Section 5 presents and discusses the principal results. The article ends with a series of conclusions and limitations of the study.

2. Theoretical Background

In recent years, numerous policies have attempted to offset the impact of energy poverty with measures such as subsidized rates and the promotion of energy efficiency in homes [20,27]. These subsidized rates (covering electricity and gas consumption) extend to broad sectors of the population, but the criteria fail to guarantee access for all potential beneficiaries. This situation is worsened due to a context in which energy prices are continuing to rise [20]. However, these measures, designed essentially to reduce the impact of energy poverty, fail to impact on the underlying causes. They are incapable of lifting beneficiaries out of energy poverty [11] or preventing other households from experiencing similar situations in the future. Detecting and quantifying poverty is essential in order to combat its effects, but anticipating such situations would allow for direct action on the causes and prevent situations of suffering and defenselessness [16,20].

In this sense, the concept of household energy vulnerability and its connections with energy poverty are particularly relevant in the institutional sphere. In this context, vulnerability is ex ante to poverty, anticipating potential situations, and creating conditions for planning energy needs and the degree of satisfaction with this cover, for preventive purposes [24–26,28]. The utility of the concept of household energy vulnerability should therefore be clear. Yet despite this, its estimation has received scant attention in literature, particularly in comparison with the concept of energy poverty.

Most of the research conducted into energy vulnerability to date has focused either on the vulnerability of the energy system or on analyzing groups whose social and economic circumstances place their households actually in this position of vulnerability. The first type of study understands energy vulnerability as "the degree to which an energy system is unable to cope with selected adverse events and risks falling into traps in economic, social, environmental, and institutional terms" [29]. The analysis of energy vulnerability from the perspective of a system could be very useful from a household perspective for two main reasons. Firstly, it explores the relationships among energy vulnerability and other interrelated concepts like energy resilience, security, justice, or sustainability and integrates these concepts as fundamental pillars in pluralistic approaches, which search for alternative measures of progress [30–32]. In fact, the energy system is a fundamental element of the three-axis scheme (economy, environment, and society), which must guide and be guided by new models of governance [33]. Unfortunately, the precise mechanisms connecting household energy services with broader governance of the energy system (therefore with general governance) must still be urgently addressed in the current context of climate change [22]. In this sense, household energy vulnerability is not only an economic concern for poor families and social policy but also for the whole society if it aspires to be guided by the principles of social justice and environmental sustainability. Household energy vulnerability does not have exclusively economic and household-specific drivers [23], and it must not be accepted as a bad result at the end of energy system governance and palliated exclusively a posteriori. On the contrary, as [34] argued, good governance of the energy system, considering the nexus between household energy poverty and the current socio-environmental challenges, has good potential for reducing ex ante energy vulnerability. Secondly, the analysis of energy vulnerability from the perspective of a system also offers a methodological background, such as is the case with the use of the synthetic indicators. Weighted composite measures of individual indicators have been used in assessing the vulnerability of energy systems [29,32,35] but have also been increasingly adopted to define alternatives measures of progress based on wellbeing instead of on production statistics [36]. Nardo et al. [37] consider that synthetic indicators are very useful for policy analysis because they allow identifying trends, drawing attention to particular issues, setting policy priorities, and monitoring performances.

Regarding the studies focused on the socioeconomically vulnerable population, the work of Llera-Sastresa et al. [38] should be pointed out, who centered their attention on the situation of groups living in social housing, which are particularly vulnerable to energy poverty. In their classification of energy-vulnerable groups, Gillard et al. [39] include the disabled and low-income families due to the greater difficulties they experience due to their limited earnings, high energy prices, and housing with low-quality energy levels. This is in line with the work of Bouzarovski [16], who includes other population segments in these risk groups, namely the retired, those dependent on social benefits, and single-parent families. In turn, Moore's definition of vulnerable households [13] includes those inhabited by the elderly, families with children, and household heads with some degree of disability or long-term illness. He considers them victims of social injustice as they do not possess the resources necessary for a decent lifestyle, and society fails to provide them with the necessary means. This line of research is a fundamental pillar for household energy vulnerability as these social and economic circumstances of the household members place them in a situation of energy vulnerability. Nevertheless, household energy vulnerability does not only depend on the socioeconomic circumstances. In this sense, it is necessary to take other circumstances into consideration (political, physical, climate, etc.), which may impact on future household vulnerability, regardless of the present socioeconomic circumstances [9,21,23,40]. Additionally, household energy vulnerability does not describe current circumstances of energy poverty, but rather the risk of exposure to this situation of any individual or household in the future. As a result, all households, not just those made up of individuals on low income or with greater energy needs, are subject to vulnerability, albeit to varying degrees. Accordingly, energy vulnerability is a question of degree.

Indeed, the definitions offered by some authors implicitly or explicitly assume a less limited and more comprehensive approach to the concept of household energy vulnerability. Bouzarovski and Simcock [23] noticed that other aspects are as significant in terms of vulnerability to energy poverty as the socio-economic characteristics of the household. An example is the case of Llera-Sastresa et al. [38], whose definition of energy vulnerability is based on the risk of a household experiencing a situation of poverty. Bouzarovski and Petrova [26] provide a similar, more detailed vision of energy vulnerability as households' likelihood of suffering limited power supplies due to insufficient income, abusive energy rates, energy inefficient homes, and a lack of awareness or information in order to adopt the correct decisions in this sense, etc. The International Federation of Red Cross and Red Crescent Societies [41] considers energy vulnerability to be a relative, dynamic, and multidimensional concept that precedes poverty, attributable to the reduced ability of individuals or groups to face and recover from (natural or human) adversity, attributable to the impact of physical, economic, social, and political factors. In turn, Day and Walker [42] (p. 15) define it as "a situation in which a person or household is unable to achieve sufficient access to affordable and reliable energy services, and as a consequence are in danger of harm to health and/or wellbeing".

Despite the variations in the definitions, all these approaches have three aspects in common. Firstly, they consider household energy vulnerability as a potentiality or risk, contrasting with energy poverty, which identifies a need or actual harmful situation [38,42]. Secondly, they consider it to be a dynamic phenomenon, dependent on space and time [39,42,43]. Finally, all the authors reviewed consider household energy vulnerability to be multidimensional in nature; in other words, conditioned by multiple factors [42,43].

At all events, improving the conditions of household vulnerability requires their prior estimation. However, detailed analysis at the household level to identify household energy conditions is frequently limited to specific places, because of the considerable costs. The mapping of household energy vulnerability covering a whole country and revealing spatial patterns in the HEVI distribution must frequently be carried out with secondary data and not too detailed. Even so, these kinds of analysis allow policy makers to obtain a macro insight into the regional differences in household energy vulnerability. Even though these analyses are less useful for informing funding allocation at household-specific level (local and regional governance), they can identify sensitive areas, which could be the object of an in-depth analysis. At the same time, they can be of interest for the governance of energy systems on a national scale, which [34] considers as important to alleviate energy poverty as those focused on the economic difficulties of some final consumers. In fact, energy system governance currently faces very important debates on, for example, energy infrastructures centralization/decentralization, and the transition from fuel or energy security [5,34,44]. By emphasizing the spatial dimension of household energy vulnerability, this article provides a previous macro insight into the territorial differences in household energy vulnerability.

The estimation of household energy vulnerability is a complex task due to its abstract and multidimensional nature, as referred to earlier. In addressing this challenge, a methodology based on synthetic indicators [37] appears to be particularly suitable as it can be used to consider the various dimensions through one or more empirical variables known as "partial indicators". These partial indicators, representative of each dimension, are weighted and included in a single measurement, known as a "synthetic indicator" [45] in an approximation of the abstract notion. In order to construct a synthetic indicator, the Organisation for Economic Co-operation and Development-Joint Research

Centre procedure [37] has been followed. This procedure can be summarized in three general stages: specification (theoretical framework, data selection, and data analysis), estimation (normalization, weighting, and aggregation), and analysis and evaluation of the results (uncertainty and sensitivity analysis and the presentation of the results).

Our starting point for the construction of the synthetic indicator is the conceptual framework explored in the anterior paragraphs and, more specifically, the definition of energy vulnerability proposed by Day and Walker [42]. Although our review of literature did not reveal a systematic study of the dimensions this notion comprises, a number of factors for determining household energy vulnerability can be deduced from definitions and empirical and theoretical studies. In this sense, some authors consider energy supply factors, such as the lack of access to electricity and natural gas or prices [46] and price-fixing strategies [47]. In turn, other authors focus on demand factors that may increase the probability of energy poverty. These include the energy requirements of household with multiple social and demographic formats [48,49]; the impact of the physical environment [50]; failure to encourage energy efficiency in the residential sector [51–53]; consumers' lifestyles [54]; the influence of variables, such as the level of energy-environmental awareness of the household members; knowledge of the home's energy requirements [55,56]; and changes to social welfare policies [55–57]. Day et al. [58] determined that energy vulnerability depends on material, socioeconomic, and political factors, set within a framework of the capability approach posited by Sen [59] and Nuusbaum [60]. Likewise, Gillard et al. [39] refer to four types of factors that determine household energy vulnerability: social, political, technical, and economic. In turn, Llera-Sastresa et al. [38] identify four reference factors that could be considered more specific than those cited in other studies, namely the type of home, energy efficiency, energy costs, and household consumer habits. Horta et al. [61] highlight the importance of technical aspects related to dwellings' isolation and heating systems as well as cultural and social factors. Probably one of the more comprehensive frameworks in this sense is that emerging from Bouzarovski and Simcock [23]. The authors present a four-axis framework of the vulnerability to energy poverty: material deprivation (based on the technical conditions of the climate and dwellings), energy affordability (based on market conditions related to prices and economic factors), energy needs (based on health and demographic conditions), and misrecognition (based on more cultural aspects configuring energy poverty perception). Moreover, the authors emphasize and argue that the four axes are of "a geographically embedded and contingent nature" [23] (p. 640), resulting in a clear spatial distribution of energy poverty and, therefore, of vulnerability to this energy poverty

Following Bouzarovski and Simcock [23], we consider a territorial approach in this study and, based on the literature review, our proposal includes a conceptual framework based on four dimensions: the energy environment, the residential environment, the physical environment, and the socioeconomic environment.

The energy environment refers to the characteristics of households' access to energy. This dimension includes two sub-dimensions: market conditions and access to renewable energies. Market conditions include utility tariffs, in particular natural gas and electricity. The tariffs for both utilities play a key role in the emergence of energy poverty [58]. In turn, access to renewable energies is important in that the higher the percentage of renewably sourced electricity in the energy mix, the greater the sustainability of the electricity system [19], thereby lowering the final kWh tariff [62].

The residential environment refers to the energy efficiency standards of buildings and households. Its inclusion is due to the positive impact of energy efficiency measures on energy poverty [21,61]. In recent decades, major improvements have been introduced to urban planning, such as wastewater management or access to potable water in towns and cities, although the measures have been insufficient in terms of the construction and conservation of homes and livability conditions, etc. [63]. The principal variables defining housing livability conditions are as follows: temperature and damp, sunlight, lighting, ventilation, and soundproofing. In the case of the interior temperature, the World Health Organization [64], indicated that there is no health risk in homes where the temperature ranges between 18 and 24 °C. This is the standard temperature range used to define interior conditions of comfort when designing buildings and installations. Calculations for air conditioning and heating facilities are normally based on a temperature of 21 °C for main rooms and 18 °C for all others [65]. However, it must be added that maintaining comfort temperatures in homes continues to be largely overlooked by public debate and publications on energy poverty [20].

The physical environment affects quality of life and well-being in multiple ways, but especially in terms of natural light and environmental temperature. Therefore, determining the environmental temperature by geographical regions [66] will allow the impact of thermal conditions to be included into the model, as extreme temperatures will boost consumption levels [67,68]. Furthermore, access to natural light impacts on habitat quality and lowers energy consumption.

The socioeconomic environment depends on two aspects: the vulnerable population incidence and the vulnerability gap or intensity of the vulnerability. In relation to the incidence of vulnerable population, it is very important to identify people belonging to vulnerable groups. A weak distribution model, a fragile labor market dominated by temporary contracts, and tensions surrounding remuneration issues all contribute to poverty and vulnerability, due to the apparent incapacity to improve society's disposable income levels [68]. Demographic vulnerability indicators are also relevant to our study due to the existence of population groups that spend a greater degree of the day at home or have specific energy requirements. This is the case for children and elderly or disabled people [26]. In relation to the vulnerability gap, its inclusion is especially important in the case of countries with wide income disparities among regions. These disparities could have important implications for the differences in energy vulnerability among households [23].

After establishing the conceptual framework for household energy vulnerability (Figure 1), the next stage is to apply observable variables to each sub-dimension, thereby determining the partial indicators. The choice of these indicators is determined by the review of the existing literature. Both data selection and data analysis are described for the estimation of household energy vulnerability in the Spanish regional context in Section 4.

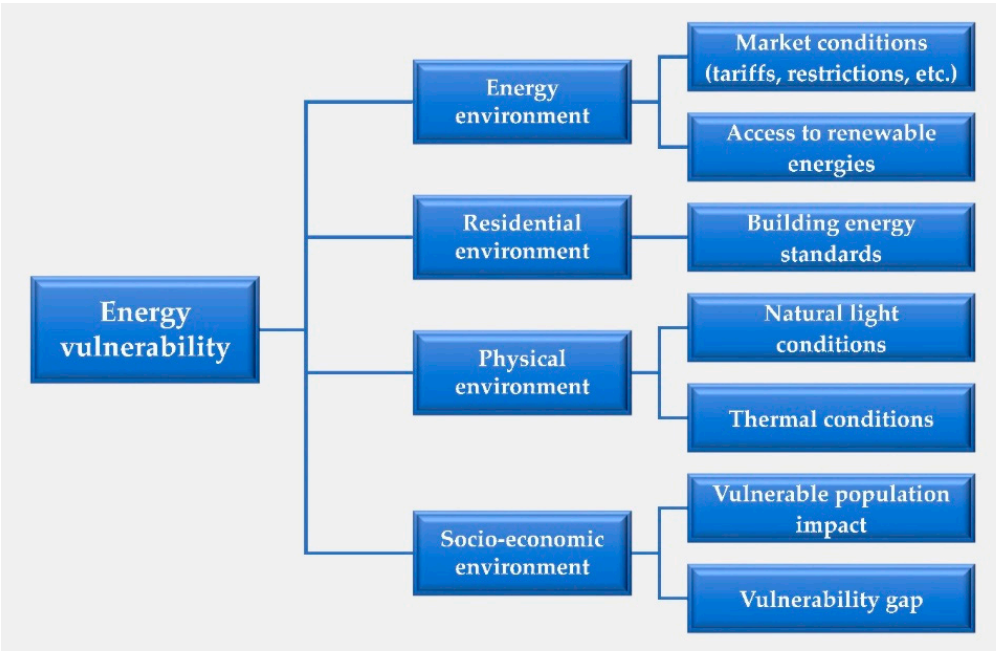

Figure 1. Conceptual framework for the Household Energy Vulnerability Synthetic Index (HEVI).

In order to calculate the synthetic indicator value, the partial indicators must be weighted and aggregated. Although there are numerous aggregation techniques for constructing a synthetic indicator, not all of them permit the same degree of commitment by policy makers. In this case, a goal-programming-based method has been proposed. This technique is based on the definition of an aspiration level for each indicator, constructing the synthetic indicator by aggregating the distance between the observed values of the indicators and the corresponding aspiration levels. This deviation is considered as a desirable deviation if it is an improvement or as an undesirable deviation if it worsens. Goal programming has two main advantages for decisions makers. On the one hand, it is very intuitive because the fixation of aspiration levels can be equated with the setting of objectives or acceptable levels, which policy makers are familiar with. Therefore, these aspiration levels will ideally be pre-determined in accordance with the needs and goals set by decision makers. On the other hand, the use of distances is particularly useful in assessing regional or local performance, making the identification the weaknesses and strengths of each region or local area easier and allowing for comparisons among regions with similar characteristics but which show divergent results.

3. Goal Programming for the Aggregation of Partial Indicators

The origins of goal programming lie in the field of operational research [69–71]. Díaz-Balteiro and Romero [72] used this methodology to estimate synthetic indicators as part of an optimization process. Several years later, Blancas et al. [73] again applied the goal concept to the synthetic indicator context. They were followed by other authors working in various fields, such as tourism sustainability [74–76], sustainability of water supply companies [77], or urban livability [78,79].

The construction of synthetic indicators using this technique presents several advantages over other techniques. Firstly, it facilitates the work of interpretation and decision-making by territorial managers [78], as we explained before. Secondly, in contrast to other aggregation techniques that require a certain size to guarantee their discrimination capacity, goal programming may be applied even if the number of variables exceeds the number of units [73]. Thirdly, partial indicators do not have to be normalized before aggregation [72], because they are defined in terms of deviation variables in relation to an aspiration level.

Our study applies goal programming to the construction of a synthetic indicator of household energy vulnerability in territories, which is an undesirable phenomenon. In this sense, and in order to ensure that the interpretation of the index is as intuitive as possible, it must be defined as an indicator, whereby the higher the value the greater the degree of vulnerability and, therefore, the worse the result will be for the unit under consideration. In order to illustrate how this aggregation technique works in the case of a synthetic indicator of this nature, we assumed a set of N territories or regions assessed by means of M partial indicators. These indicators were divided into two types. Positive partial indicators, namely those that positively contribute to household energy vulnerability (the higher the value the greater the degree of vulnerability) and negative partial indicators, which contribute in a negative way to household energy vulnerability (the higher the value the lower the degree of vulnerability).

We, therefore, considered the existence of L positive partial indicators and K negative partial indicators, whereby L + K = M.

For each region there is a series of values for each of the partial indicators that approach the concept dimensions. The definitions are, therefore, as follows:

$X_{il}{}^{+}$ = the value of the positive partial indicator l for the region i $\forall l \; l = 1, 2, \ldots, L \; \forall i \; i = 1, 2, \ldots, N$

$X_{ik}{}^{-}$ = the value of the negative partial indicator k for the region i $\forall k \; k = 1, 2, \ldots, K \; \forall i \; i = 1, 2, \ldots, N$

An aspiration level is ideally defined by the regional managers for each of the M partial indicators, representing an acceptable level of attainment. Based on this, the following can be expressed:

$\mu_l{}^{+}$ = the aspiration level for the positive partial indicator l $\forall l \; l = 1, 2, \ldots, L$

$\mu_k{}^{-}$ = the aspiration level for the negative partial indicator k $\forall k \; k = 1, 2, \ldots, K$

Associated with each indicator m (positive or negative) and aspiration level, we can define a goal using the deviation variables. The deviation variables represent the difference between the value of a partial indicator and its corresponding aspiration level. Therefore, there are two possible types of deviation variables: negative or positive.

n_{im} = the negative deviation of indicator m regarding the aspiration level μ_m for region i. $\forall m\ m = 1,2,\ldots,M\ \forall i\ i = 1,2,\ldots,N$

p_{im} = the positive deviation of indicator m regarding the aspiration level μ_m for region i. $\forall m\ m = 1,2,\ldots,M\ \forall i\ i = 1,2,\ldots,N$

The interpretation of the deviation variables will depend on the type of indicator involved (positive or negative).

In the case of a positive partial indicator l (where higher values indicate a greater degree of vulnerability), a negative deviation variable ${n_{il}}^+$ in relation to an aspirational level ${\mu_l}^+$ represents a strength for the region i regarding household energy vulnerability, whilst a positive deviation variable ${p_{il}}^+$ in relation to an aspirational level ${\mu_l}^+$ represents a weakness for the region i regarding household energy vulnerability. Consequently, the goals are formulated as shown below:

$${X_{il}}^+ + {n_{il}}^+ - {p_{il}}^+ = {\mu_l}^+,\ \text{where}\ {n_{il}}^+,\ {p_{il}}^+ \geq 0;\ {n_{il}}^+ . {p_{il}}^+ = 0\ \forall l\ l = 1,2,\ldots,L \forall i\ i = 1,2,\ldots,N$$

In the case of a negative partial indicator k (where higher values indicate less vulnerability), a negative deviation variable ${n_{ik}}^-$ in relation to an aspirational level ${\mu_k}^-$ represents a weakness for the region i regarding energy vulnerability, whilst a positive deviation variable ${p_{ik}}^-$ in relation to an aspirational level ${\mu_k}^-$ represents a strength for the region i regarding energy vulnerability. Consequently, the goals are formulated as shown below:

$${X_{ik}}^- + {n_{ik}}^- - {p_{ik}}^- = {\mu_k}^-,\ \text{where}\ {n_{ik}}^-,\ {p_{ik}}^- \geq 0;\ {n_{ik}}^- . {p_{ik}}^- = 0\ \forall k\ k = 1,2,\ldots,K \forall i\ i = 1,2,\ldots,N$$

In order to prevent errors in the interpretation of the deviation variables, two further variables can be defined:

S_{im} = the desirable deviation variable or strength in the indicator m for the region i. This variable would be a negative deviation when m is a positive indicator (${n_{il}}^+$) or a positive deviation when m is a negative indicator (${p_{ik}}^-$).

$$\forall m\ m = 1,2,\ldots,M\ \forall i\ i = 1,2,\ldots,N$$

In this sense, a strength means that this indicator achieves a better value than the value it aspires to.

W_{im} = undesirable deviation or weakness in the indicator for the region i. This variable would be a positive deviation when m is a positive indicator (${p_{il}}^+$) or a negative deviation when m is a negative indicator (${n_{ik}}^-$).

$$\forall m\ m = 1,2,\ldots,M\ \forall i\ i = 1,2,\ldots,N$$

In this sense, a weakness means that this indicator achieves a worse value than the value it aspires to.

Consequently, the energy vulnerability synthetic indicator for each unit is defined as follows:

$$IS_i = \sum_{m=1}^{M} \frac{\omega_m \cdot W_{im}}{\mu_m} - \sum_{m=1}^{M} \frac{\omega_m \cdot S_{im}}{\mu_m} \forall i, i = 1,2,\ldots,N$$

where ω_m = weighting assigned to indicator m and $\forall m\ m = 1,2,\ldots,M$.

The synthetic indicator may adopt positive values for some units and negative values for others. In this sense, the index value will be positive, providing that the weaknesses exceed the strengths, and negative when the strengths exceed the weaknesses. As a result, the higher the synthetic indicator value of a particular region, the greater its household energy vulnerability.

4. A Territorial Approach to Household Energy Vulnerability in Spain

The proposed synthetic indicator has been estimated for the provinces of Spain. Southern and eastern EU member states like Spain have suffered a significant impact on energy poverty [22,23,80–83], mainly because of the poor quality of residential dwellings and insufficient thermal insulation [22]. However, this impact is expected to be unequal in these countries as they present important economic, climatic, or political differences [84,85]. In this sense, it is reasonable to think that these differences can lead to the existence of certain territorial patterns of energy vulnerability, whose identification could give us a first insight into the spatial distribution of the household energy vulnerability in Spain.

The province has been chosen as a territorial unit. On the one hand, it is the lowest level of aggregation for which secondary data is available. On the other hand, even though some provinces can present important internal contrasts, especially a rural–urban divide, these contrasts are less marked than those at the autonomous community level. In this sense, the use of provinces allows us to obtain a first map of household energy vulnerability in Spain, detecting potential geographical patterns. The dimensions, sub-dimensions, and partial indicators for this macro analysis are listed in Table 1 together with the measurement unit, sign, and source of partial indicators.

The proposed framework can give us a first territorial map of the household energy vulnerability as we consider that the above dimensions and partial indicators can follow territorial patterns [22,23]. This proposal could also be a basis for analyzing household energy vulnerability in other countries with large territorial differences in these dimensions.

The energy environment was approximated using three partial indicators. In the case of market conditions, the only indicators available are the tariffs for the two most commonly used types of energy: gas and electricity. Although from a theoretical perspective their inclusion in the model is essential, in the specific case of the Spanish provinces they do not allow for a distinction to be drawn between units, as tariffs are standard for the entire country. Despite this, we opted to include them, as the proposed model is intended for general application. Access to renewable energies was calculated by determining the percentage of renewable energies over the total energy production in each province.

As for the residential environment, the aim was to determine building energy quality. Unfortunately, there is no energy quality indicator for all the homes registered in Spain. Although new constructions are required to meet certain energy efficiency standards [86,87], this variable is not available for all Spanish homes. In light of these circumstances, we decided to apply two proxies: newly built homes, which supposedly meet the aforementioned energy requirements and a home ownership indicator, included under the supposition that home owners are more disposed than lessees to take on major alteration and improvement work, such as energy efficiency improvements [18,20].

When considering the physical environment, annual hours of sunshine were used to calculate luminosity conditions and annual heating degree days for thermal conditions. The “heating degree day” variable reflects the “harshness” of the climate conditions and indicates the energy needs of a specific territory in order to face these conditions. Specifically, this indicator was taken as the annual sum of the positive daily variations between 20 °C (which guarantees comfort in the home) and the exterior temperature [66]. A low value for this variable indicates limited heating requirements and outside temperatures averaging around 20 °C, whilst a high value indicates elevated heating needs.

Finally, in the case of the socio-economic environment, the sub-dimensions discussed in the theoretical background were taken into consideration. Two partial indicators were used in order to approach the incidence of vulnerable population according to the theoretical framework and the availability of data at provincial level. On the one hand, the economically vulnerable population was approached by using the unemployed population in relation to the total population [21]. On the other hand, the demographically vulnerable population (i.e., the population that is particularly sensitive to environmental conditions for biological reasons) was approached by using the over 65s [21] and under 16s, in relation to the total population. Furthermore, per capita production (an average economic capacity for provincial populations) was used to approach the second sub-dimension: the vulnerability gap.

Table 1. List of partial indicators in the energy vulnerability synthetic indicator (EVI).

Dimensions	Sub-Dimensions	Partial Indicators	Sign	Abbreviation	Units	Database
Energy environment	Market conditions	Electricity tariff	+	ELETAR	Euros/KWh	Ministry for Energy Transition (2017)
		Natural gas tariff	+	GASTAR	Euros/KWh	Ministry for Energy Transition (2017)
	Access to alternative energies	Access to renewable energies	−	REN	%	Ministry for Energy Transition (2017)
Residential environment	Home energy quality	Home ownership	−	OWNH	% of home ownership	Spanish Statistics Agency INE (2017)
		New home	−	NEWH	% homes built after 2001	Spanish Statistics Agency INE (2011)
Physical environment	Thermal conditions	Heating degree day	+	HDD	Degrees	Spanish Statistics Agency INE (2015)
	Natural light conditions	Hours of sunshine	−	SUN	Hours	Spanish Statistics Agency INE (2015)
Socio-economic environment	Vulnerable population incidence	Unemployed	+	ECOVUL	% of the total population	Spanish Statistics Agency INE (2018)
		Under 16s and over 65s	+	DEMOVUL	% of the total population	Spanish Statistics Agency INE (2018)
	Vulnerability gap	Per capita income	−	INCOME	Euros pc	Spanish Statistics Agency INE (2015)

These indicators, which are susceptible to following territorial patterns, could be complemented with a deeper micro-analysis searching for house-specific drivers, such as the educational level, consumption habits, or health conditions of household members among others.

Table 2 shows the principal statistics for the partial indicators used to construct the household energy vulnerability index for Spanish provinces.

Table 2. Descriptive statistics for partial indicators.

Partial Indicators	Mean	Median	Maximum	Minimum	Std
ELETAR	0.23	0.23	0.23	0.23	-
GASTAR	0.07	0.07	0.07	0.07	-
REN	40.15	32.16	96.10	1.07	28.29
OWNH	78.75	79.30	85.00	67.30	4.36
NEWH	18.78	18.57	30.18	10.02	4.89
HDD	2187.13	2330.50	3733.00	333.7	857.75
SUN	2694.77	2799.50	3381.00	1491.00	482.95
ECOVUL	7.22	6.30	12.35	3.62	2.43
DEMOVUL	34.93	34.86	41.06	28.74	2.30
INCOME	13,998.78	13,541.82	18,971.36	10,413.31	2457.64

At all events, the chosen indicators can be grouped as two types. Whilst some can be considered "controllable", as in theory they are susceptible to political actions (e.g., income, economically vulnerable population, or housing energy quality), others include environmental conditions that cannot be controlled (e.g., the demographically vulnerable population, hours of sunlight, or heating requirements). This distinction is crucial from a political perspective and also when analyzing the strengths and weaknesses of the various provinces in order to calculate the index and draw a series of comparisons between them.

As was explained in the second section of the article, partial indicators do not have to be normalized in order to be aggregated, so the next steps were weighting and aggregation. In this sense, two decisions had to be taken: the choice of the weighting scheme and the fixation of the aspiration levels. The weighting of partial indicators implies a consideration of the relevance of each in constricting the index. In this regard, the decision was made to consider a certain balance between the various dimensions, whereby each had an identical weight (in this instance 0.25), which in turn was also distributed evenly among the sub-dimensions and, finally, among the indicators for each sub-dimension.

As the for the aspiration levels, and in view of the lack of external references, we opted to use standards by means of empirical analysis [88]. Although the use of these standards has some disadvantages, it is common for planners to implicitly establish aspiration levels for each of the dimensions by comparing the performance of similar or better-performing units [73,78]. On the basis of this argument, the aspiration level was set as the arithmetic mean of the value of each indicator for all 50 provinces.

It must be stressed that both in the choice of weightings and aspiration levels, goal programming methodology allows for the consideration of alternative scenarios, based on the opinion of experts who can contribute their know-how to the index construction process. In this sense, the participation of decision makers could benefit this process as they usually work by using objectives that are in fact aspiration levels for different indicators. In any case, the influence of these decisions on the final results of the HEVI were analyzed through an uncertainty and sensitivity analysis, which is described in the next section.

The following section discusses the results of the vulnerability index for the Spanish provinces, estimated in accordance with the theoretical background and the technique presented in the previous sections of this article.

5. Results and Discussion

This section presents and discusses the main results obtained from the application of the synthetic index proposal to the specific case of Spanish provinces.

Following the Organisation for Economic Co-operation and Development-JRC methodological procedure [89], an uncertainty and sensitivity analysis was conducted in order to evaluate if the ranks and scores of the index remain robust using different weights and levels of aspiration. For this, we used Monte Carlo simulation combining different choices of weights and aspiration levels and then selected a statistically representative sample comprising 16,566 combinations, with a 99% confidence level and 1% sample error. The HEVI was, therefore, estimated for each combination, resulting in 16,566 values for each of the Spanish provinces, generating an empirical probability distribution for the composite index. The results of the uncertainty analysis revealed a high degree of consistency with the principal results obtained for the model, both in terms of the HEVI values and ranking. Furthermore, the sensitivity analysis indicated that the weighting scheme has a greater impact on the results than the aspirations levels. After assessing the methodological robustness of the HEVI, its results for the 50 Spanish provinces are shown in Table 3 and Figure 2 below:

Table 3. HEVI ranking compared with the relative vulnerable population ranking (from the lowest to the highest values in both cases).

#	HEVI		#	VULNERABLE POPULATION INCIDENCE (%)	
1	Alicante/Alacant	−0.23173	1	Segovia	35.8984
2	Soria	−0.17064	2	Pontevedra	36.1099
3	Albacete	−0.14731	3	Barcelona	36.4434
4	Cuenca	−0.14094	4	Araba/Álava	36.7855
5	Badajoz	−0.13492	5	Huesca	36.9324
6	Seville	−0.12642	6	Soria	36.9889
7	Pontevedra	−0.11645	7	Cantabria	37.3133
8	Burgos	−0.09358	8	Navarra	37.8926
9	Ávila	−0.08772	9	León	38.3847
10	La Rioja	−0.07574	10	Lugo	38.8167
11	Segovia	−0.07332	11	Gipúzkoa	39.2713
12	Navarra	−0.06586	12	Valladolid	39.3600
13	Castellón/Castelló	−0.05000	13	Teruel	39.3933
14	Murcia	−0.04323	14	Guadalajara	39.4225
15	Ciudad Real	−0.03252	15	A Coruña	39.4976
16	Almeria	−0.03107	16	Balearic Islands	39.9396
17	Granada	−0.02892	17	Bizkaia	40.2330
18	Álava	−0.02622	18	Rioja. La	40.2748
19	Zaragoza	−0.02509	19	Ourense	41.1345
20	Valladolid	−0.02027	20	Murcia	41.2719
21	Jaen	−0.01391	21	Alicante/Alacant	41.4230
22	Malaga	−0.01153	22	Burgos	41.5214
23	Córdoba	−0.00509	23	Salamanca	41.5421
24	Zamora	−0.00251	24	Valencia/València	41.8748
25	Lleida	−0.00121	25	Asturias	41.9928
26	Sta. Cruz de Tenerife	−0.00098	26	Castellón/Castelló	42.4504

Table 3. *Cont.*

#	HEVI		#	VULNERABLE POPULATION INCIDENCE (%)	
27	Toledo	0.00815	27	Malaga	42.4666
28	Huelva	0.01072	28	Lleida	42.5113
29	Lugo	0.01178	29	Girona	42.7867
30	Huesca	0.02173	30	Huelva	43.0437
31	Cádiz	0.02354	31	Zamora	43.3766
32	Madrid	0.02408	32	Ávila	43.6103
33	Palencia	0.03389	33	Cuenca	43.6713
34	Girona	0.04491	34	Ciudad Real	43.7325
35	Balearic Islands	0.05258	35	Albacete	43.9179
36	Ourense	0.05652	36	Tarragona	45.1377
37	A Coruña	0.05786	37	Madrid	45.2602
38	Las Palmas	0.06322	38	Zaragoza	45.2729
39	Tarragona	0.08327	39	Almeria	45.6390
40	Cantabria	0.08452	40	Caceres	45.7065
41	Barcelona	0.09524	41	Córdoba	45.8805
42	Vizcaya	0.09530	42	Granada	45.9095
43	Valencia/Valenciá	0.09897	43	Jaen	46.2567
44	Guipúzcoa	0.10411	44	Palencia	46.4372
45	Guadalajara	0.11206	45	Toledo	46.4457
46	Teruel	0.12181	46	Seville	46.4722
47	León	0.12230	47	Palmas. Las	46.6418
48	Salamanca	0.12401	48	Cádiz	47.4187
49	Asturias	0.15193	49	Santa Cruz de Tenerife	48.0992
50	Caceres	0.15469	50	Badajoz	49.6394

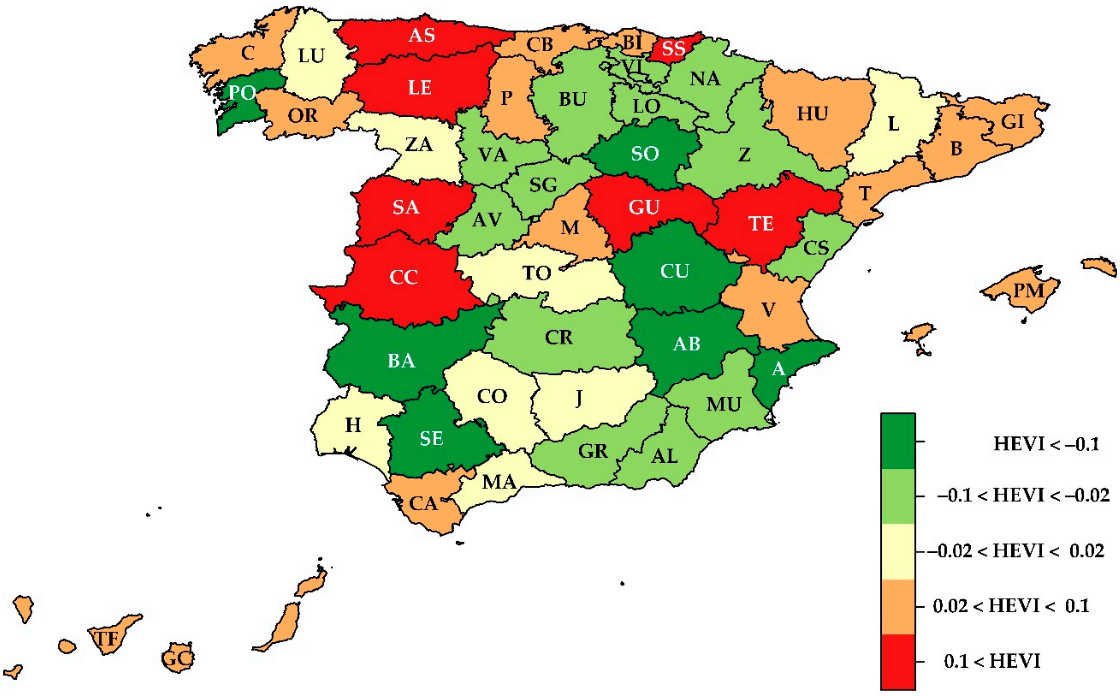

Figure 2. Geographical distribution of HEVI values. Source: authors' own.

Approximately half the provinces analyzed registered positive values, indicating that the weighted sum of partial indicator weaknesses exceeds the strengths. The highest levels of household energy vulnerability were recorded in the provinces of Caceres and Asturias, followed by Salamanca, León, and Teruel. The provinces of Guadalajara, Guipúzcoa, Barcelona, and Valencia also recorded high values. In a first approach, these provinces could be considered as priorities from a political point of view. Based on the information provided from the synthetic indicator about the causes of energy vulnerability, policy makers should focus on these regions in order to implement measures (construction of energy infrastructures, implementation of energy efficiency policies, improvement energy quality of dwelling, etc.). In addition to this, it could be recommendable to carry out a more detailed analysis in these provinces in order to identify the more vulnerable households and implement other measures at a micro level, mainly focused on final financial funding for energy dwelling improvements or coverage of energy bills.

At the other end of the scale, Alicante registered the lowest level of household energy vulnerability and the provinces of Soria, Albacete, Cuenca, Badajoz, and Seville also displayed low vulnerability. Analyzing the performance of these provinces could be quite useful for vulnerable provinces as it allows them to identify their improvement areas in order to reduce their degree of household energy vulnerability and obtain guidance on the political measures they need to implement.

Finally, a group of provinces obtained index values close to 0, indicating that the strengths of certain partial indicators offset the weaknesses registered in others. These provinces, although not being a clear political priority, should continue being assessed in order that their situation does not worsen. In addition, and conditioned to the existence of public funds, some specific measures could be implemented, depending on the weaknesses of the province.

As highlighted in the discussion of the multidimensional nature of energy vulnerability, the incidence of energy-vulnerable population is a key element, albeit not the only one. Indeed, as it was pointed in the theoretical framework, there are other factors that may contribute to the future energy vulnerability of households. In order to illustrate the contribution of our theoretical framework in this sense, Table 3 lists the Spanish provinces in accordance with their household energy vulnerability and also in terms of the percentage of vulnerable population for each province. The percentage of vulnerable population includes the two variables used in the present study to approximate both economically and demographically vulnerable population. The table shows how territories with a high percentage of vulnerable population, such as Badajoz, successfully offset this weakness thanks to the positive behavior of other indicators, thereby obtaining a good position on the global vulnerability index. In contrast, provinces whose relative vulnerable population is below average, such as Barcelona or León, score high on the household energy vulnerability indicator, which means a bad performance.

In fact, the analysis reveals that territories with similar values in the incidence of energy-vulnerable population obtain very different values in household energy vulnerability. This is due to different performance in the other partial indicators. An example of this is the case of Burgos and Asturias, whose performance in the various dimensions based on deviation variables is shown in Figure 3. This figure represents the deviation variables for each partial indicator in terms of their aspiration level. Positive deviation variables (values above the broken line) are weaknesses for the province in question, because they result in a higher value on the index. In contrast, negative deviation variables (values below the broken line) are strengths for these provinces, because they lower the score in the household energy vulnerability index.

Burgos and Asturias are both located in the north of Spain. The percentage of vulnerable population is similar in both provinces, particularly in terms of the demographically vulnerable population (and, therefore, outside the action scope of public managers). However, whilst Burgos ranks amongst the 10 provinces with the lowest household vulnerability index, Asturias has the one of the highest rates of vulnerability, second only to Caceres. In this sense, and as shown in Figure 3, Burgos performs better in all the other partial indicators, particularly in terms of access to renewable energies and the percentage of new homes—two of its greatest strengths. Asturias only performs better than Burgos in one aspect, namely the annual heating requirements, which are dependent on weather conditions and, therefore, again beyond any form of control.

The analysis of the deviation variables in relation to the aspiration levels for each indicator, and shown in the previous graph, allows for the identification of the strengths and weaknesses of each province, which in turn facilities the definition of actions aimed at improving household energy vulnerability rates in each territory. Tables 4 and 5 show the strengths and weaknesses for the least and most vulnerable provinces, respectively. The values written in italic font indicate a weakness that tends to increase the province's degree of vulnerability, whilst those written in regular font represent strengths that help to improve the general conditions of household energy vulnerability in the territory in question.

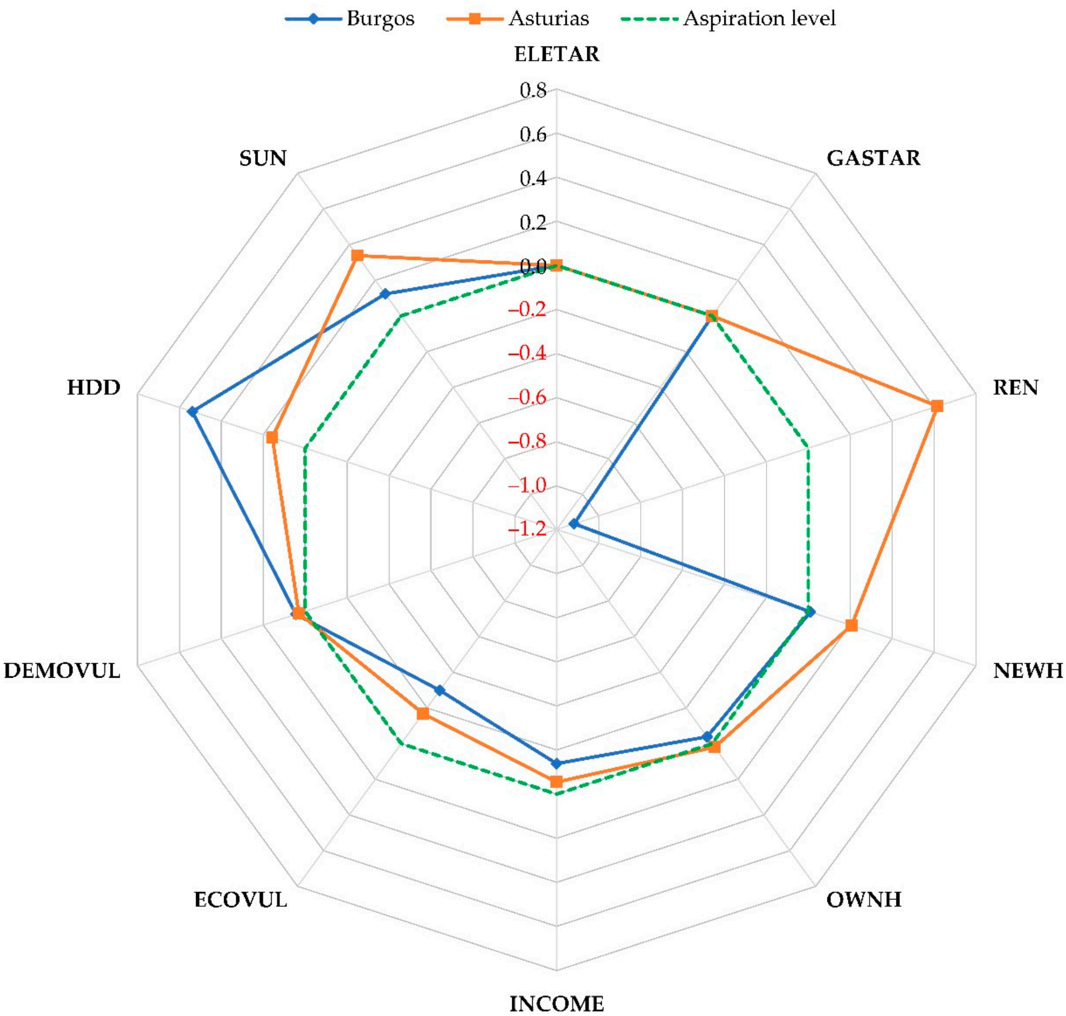

Figure 3. Comparative analysis of relative deviation variables (expressed in percentages) for Burgos and Asturias. Source: authors' own.

Table 4. Least vulnerable provinces. Strengths and weaknesses in relation to aspiration levels.

Provinces	ELETAR	GASTAR	REN	OWNH	NEWH	HDD	SUN	ECOVUL	DEMOVUL	INCOME
Alicante	-	-	0.9033	*0.0248*	0.4474	0.4868	0.2098	*0.0814*	0.0376	*0.1468*
Soria	-	-	1.3691	0.0387	0.2318	*0.7068*	0.0468	0.4524	0.0542	0.1322
Albacete	-	-	1.3934	*0.0172*	*0.2284*	0.1354	0.1901	*0.3512*	0.0220	*0.1302*
Cuenca	-	-	1.1305	*0.0172*	0.0563	0.0046	0.0112	0.0099	*0.0456*	*0.0401*
Badajoz	-	-	1.3656	0.0590	0.0086	0.1327	0.1110	*0.6465*	*0.0807*	*0.2340*
Seville	-	-	0.9357	0.0070	*0.1036*	0.3805	0.2547	*0.4927*	*0.0218*	*0.2055*
Pontevedra	-	-	1.0216	*0.0083*	0.1198	*0.0585*	*0.1680*	*0.0200*	0.1771	*0.0536*
Burgos	-	-	1.1164	0.0387	*0.0101*	*0.5385*	*0.1235*	0.2983	*0.0437*	0.1383
Ávila	-	-	1.1966	0.0387	0.0206	*0.4617*	0.0190	*0.0201*	*0.0376*	*0.0825*
La Rioja	-	-	0.2365	0.0628	0.3911	*0.2153*	*0.0838*	0.2919	*0.0067*	0.0720

Table 5. Most vulnerable provinces. Strengths and weaknesses in relation to aspiration levels.

Provinces	ELETAR	GASTAR	REN	OWNH	NEWH	HDD	SUN	ECOVUL	DEMOVUL	INCOME
Barcelona	-	-	*0.7600*	*0.0870*	*0.4665*	0.4369	*0.2638*	0.2183	0.1183	0.2102
Vizcaya	-	-	*0.5166*	0.0793	*0.3440*	*0.0036*	*0.4467*	0.2395	0.0054	0.3467
Valencia	-	-	*0.7770*	*0.0248*	*0.3039*	0.3635	0.0116	*0.0425*	0.0167	*0.0484*
Guipúzcoa	-	-	*0.8003*	0.0793	*0.3608*	*0.0310*	*0.3142*	0.4986	*0.0207*	0.3552
Guadalajara	-	-	*0.6515*	*0.0172*	0.4712	*0.6094*	0.0339	0.1473	0.0476	*0.2210*
Teruel	-	-	*0.6751*	0.0362	*0.2344*	*0.5207*	0.0368	0.4001	*0.0038*	0.1846
León	-	-	*0.6782*	0.0387	*0.2959*	*0.2103*	0.0160	0.2922	0.0474	*0.0186*
Salamanca	-	-	*0.8166*	0.0387	0.0545	*0.3794*	0.1144	0.1734	*0.0185*	*0.0811*
Asturias	-	-	*0.6168*	*0.0197*	*0.2070*	*0.1570*	*0.3391*	0.1681	*0.0303*	0.0552
Caceres	-	-	*0.8677*	0.0590	*0.3171*	0.0545	0.1942	*0.2958*	*0.0407*	*0.1922*

Access to renewable energies is the main strength of the provinces that obtain the best results in the energy vulnerability index: in fact, they all display an advantage in this indicator and, on average, double the aspiration level required. Furthermore, many of these areas display strengths, albeit on average more modest, in terms of housing age and hours of sunlight.

In contrast, the main weakness of provinces obtaining the best scores on the synthetic indicator is related to the economic environment. Specifically, seven provinces show weaknesses in terms of income, which is an average 12% lower than the aspiration level in the case of the economically vulnerable population.

As for the units that obtain the worst results, they all registered considerable negative deviations in terms of access to renewable energies. Other key weaknesses are related to housing age and physical heating needs reflected in the HDD variable. Nevertheless, many of these provinces do not have a particularly high incidence of economically vulnerable population. Therefore, in the case of these provinces, there is an important margin for improvement through the installation of renewable energy infrastructures and the renovation of dwellings, beyond the financial support to households.

Ultimately, the results obtained in this analysis could be of great interest for policy makers as they allow the identification of geographical patterns in the degree of household energy vulnerability, which could allow for prioritizing intervention in the more vulnerable regions and inform energy system general governance. Policy intervention has been traditionally focused on alleviating the socio-economic vulnerability of households. However, the results support that the measures to reduce the impact of household energy vulnerability should encompass other dimensions of the concept. It is the case of decentralization of energy infrastructures and improvement of renewable energy access, that [5,34] suggested as potential measures to reduce energy poverty. These measures allow not only the palliation of vulnerability situations but also increase the justice of the energy system. This macro-level study could be complemented with a micro analysis in the more vulnerable provinces, which would allow the implementation of measures for vulnerable households, such as financial funds for improving the energy quality of dwellings or providing vulnerable families with energy advice in order to optimize their consumption patterns at home.

6. Conclusions

Research into the disparities in household energy vulnerability among territories provides numerous opportunities on a political level, enabling decision makers to introduce corrective measures that will prevent situations of energy poverty, which are caused by spatial drivers. In this sense, a spatial approach allows for the identification of especially sensitive regions, which could be the object of a deeper analysis of households´ energy conditions. To do this, academia must first provide instruments capable of estimating household energy vulnerability from a comprehensive point of view, which incorporate other factors besides the identification of socially and economically vulnerable segments of the population. Important advances have been made in the definition of a multidimensional approach to energy vulnerability, both from the point of view of an energy system and from the point of view of identifying economically energy vulnerable collectives. However, little progress has been made in a multidimensional approach to household energy vulnerability that considers more factors than purely economic ones.

This article presents a proposal for a model that allows for a territorial estimation of household energy vulnerability. The abstract and multidimensional nature of household energy vulnerability was the starting point for drawing up a theoretical background based on the existing literature, which includes four dimensions with a clear spatial character: energy, residential, physical, and socio-economic. The partial indicators for estimating these dimensions were aggregated by means of a synthetic indicator based on goal programming. This aggregation technique is particularly useful for regional policy making. On the one hand, it allows policy makers to play an active role in the construction of the synthetic indicator by fixing aspiration levels in line with their needs and specific goals; and on the other hand, the technique provides a simple way of benchmarking regional performance.

The proposal was applied to Spain because it is a big territory with important economic, climatic, or political differences, which can lead to the existence of certain territorial patterns of energy vulnerability. In order to identify these spatial patterns, the province was chosen as the territorial unit in this analysis, considering that is the lowest level of aggregation for which secondary data is available. The results could, therefore, be of great use in introducing policies aimed at improving the energy conditions of the population and developing a fairer energy system. Firstly, the index values allow for the assessment of the degree of energy vulnerability by provinces, identifying which ones could be considered as priorities from a political point of view. Secondly, the results underpinned the strength of the energy vulnerability synthetic index in comparison with others that focus exclusively on the socio-economic environment. Our study showed that territories with similar values in the case of the vulnerable population indicator scored very differently in terms of energy vulnerability, due to the different performance of other dimensions affecting this concept. Finally, analyzing the deviation variables allows for the identification of the strengths and weaknesses of each province, allowing for the design of measures tailored specifically to improve energy vulnerability levels in each territory. The results of this analysis support that the measures to reduce the impact of household energy vulnerability should include other dimensions different from the economic ones, such as the decentralization of energy infrastructures and improvement of renewable energy access. These measures allow not only the palliation of vulnerability situations but also increase the justice of the energy system.

Our study also has important limitations. In the first place, we face data limitations at province level. This limitation prevents us from using certain indicators that could improve our analysis. Concerning this matter, the results obtained for the Spanish case should be interpreted with caution and, considering this, they are only useful as a first approach. Additionally, the provinces are administrative units but not homogeneous territories. For this reason, it would be recommendable to complete this general study with other ones at a provincial level in order to search for internal differences. For example, it would be interesting to assess the possible differences between urban and rural environments, as well as coastal and inland areas. Finally, as we have explained several times throughout the article, this study does not provide an accurate diagnosis of households suffering a high level of energy vulnerability. In order to obtain this diagnosis, it could be necessary to complement it with micro analysis at a household level in the most vulnerable areas.

Furthermore, the instrument proposed in this article offers numerous possibilities for further research. Firstly, and provided that the necessary data are available, a line of particular interest would be to assess the possible differences between urban and rural municipalities, as well as coastal and inland areas. We also consider that this study could be applied to European regions with differing socio-economic, physical, and energy profiles in order to test the potential of policies that could be applied in each country. Another potential line of research by using primary data is assessing the spatial differences on cultural and social factors, which could be related with the perception of energy poverty and vulnerability. This study could be complemented with the analysis of specific practices that are used at household level in order to face energy vulnerability.

Author Contributions: Conceptualization, P.M., B.V.-A. and R.M.R.-F.; methodology, P.M., B.V.-A.; software, B.V.-A.; validation, P.M.; formal analysis, P.M., B.V.-A.; investigation, P.M., B.V.-A. and R.M.R.-F.; data curation, P.M., B.V.-A. and R.M.R.-F.; writing—original draft preparation, P.M., B.V.-A. and R.M.R.-F.; writing—review and editing, P.M., B.V.-A.; visualization, P.M., B.V.-A.; supervision, P.M.; project administration, P.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors would like to thank David Rodríguez-González for their valuable technical support.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Sovacool, B. Conceptualising urban household energy use: Climbing the "energy services leader". *Energy Policy* **2011**, *39*, 1659–1668. [CrossRef]
2. Grave, K.; Breitschopf, B.; Ordonez, J.; Wachsmuth, J.; Boeve, S.; Smith, M.; Schubert, T.; Friedrichsen, N.; Herbst, A.; Eckartz, K.; et al. *Prices and Costs of EU Energy*; ECOFYS: Utrecht, The Netherlands, 2016.
3. Tirado-Herrero, S.; Jiménez-Meneses, L.; López-Fernández, J.L.; Perero-Van Hove, E.; Irigoyen-Hidalgo, V.M.; Savary, P. *Pobreza, Vulnerabilidad y Desigualdad Energética. Nuevos Enfoques de Análisis*; Asociación de Ciencias Ambientales: Madrid, Spain, 2016.
4. Bickerstaff, K.; Walker, G.; Bulkeley, H. *Introduction: Making sense of energy justice. In Energy Justice in a Changing Climate*; Bickerstaff, K., Walker, G., Bulkeley, H., Eds.; Zed Books: London, UK, 2013.
5. Sovacool, B.K.; Sidortsov, R.V.; Jones, B.R. *Energy Security, Equality and Justice*; Routledge: London, UK, 2014.
6. Sovacool, B.K.; Heffron, R.J.; McCauley, D.; Goldthau, A. Energy decisions reframed as justice and ethical concerns. *Nat. Energy* **2016**, *1*, 16024. [CrossRef]
7. Sovacool, B.K.; Dworkin, M.H. Energy justice: Conceptual insights and practical applications. *Appl. Energy* **2015**, *142*, 435–444. [CrossRef]
8. Walker, G.; Day, R. Fuel poverty as injustice: Integrating distribution, recognition and procedure in the struggle for affordable warmth. *Energy Policy* **2012**, *49*, 69–75. [CrossRef]
9. Christman, B.; Russell, H. Readjusting the political thermostat: Fuel poverty and human rights in the UK. *J. Hum. Rights Commonw.* **2016**, *2*, 14–31. [CrossRef]
10. de Vita, Á. Inequality and poverty in global perspective. In *Freedom from Poverty as a Human Right*; Pogge, T., Ed.; Oxford University Press: Oxford, UK, 2007; pp. 103–132.
11. Boardman, B. *Fuel Poverty: From Cold Homes to Affordable Warmth*; Belhaven: London, UK, 1991.
12. Hills, J. *Getting the Measure of Fuel Poverty*; Department of Energy and Climate Change: London, UK, 2012.
13. Moore, R. Definitions of fuel poverty: Implications for policy. *Energy Policy* **2012**, *49*, 19–26. [CrossRef]

14. Heidl, P. *Measuring Fuel Poverty: General Considerations and Application to German Household Data*; Zentrum für Europäische Wirtschaftsforschung GmbH: Mannheim, Germany, 2013.
15. Romero, J.C.; Linares, P.; López-Otero, X. *Pobreza Energética en España. Análisis Económico y Propuestas de Actuación*; Economics for Energy: Vigo, Spain, 2014.
16. Bouzarovski, S. *Energy Poverty*; Springer: Cham, Switzerland, 2018.
17. United Nations Development Programme. *Delivering Sustainable Energy in a Changing Climate*; United Nations Development Programme: New York, NY, USA, 2017.
18. Linares, P.; Romero, J.C.; López-Otero, X. *Pobreza Energética en España. Análisis Económico y Propuestas de Actuación*; Economics for Energy: Vigo, Spain, 2015.
19. Regueiro, R.M.; Doldán, X.R.; Varela, C. Desde la desigualdad energética al bienestar energético: El impacto del Bono Social en España. In Proceedings of the XVI Jornadas de Economía Crítica, León, Spain, 20–21 September 2018; Asociación de Economía Crítica: León, Spain, 2018.
20. Tirado-Herrero, S.; Jiménez-Meneses, L.; López-Fernández, J.L.; Irigoyen-Hidalgo, V.M. *Pobreza Energética en España. Hacia un Sistema de Indicadores y una Estrategia de Actuación Estatales*; Asociación de Ciencias Ambientales: Madrid, Spain, 2018.
21. Gouveia, J.P.; Palma, P.; Simoes, S. Energy poverty vulnerability index: A multidimensional tool to identify hotspots for local action. *Energy Rep.* **2019**, *5*, 187–201. [CrossRef]
22. Bouzarovski, S. Energy poverty in the European Union: Landscapes of vulnerability. *WIREs Energy Environ.* **2014**, *3*, 276–289. [CrossRef]
23. Bouzarovski, S.; Simcock, N. Spatializing energy justice. *Energy Policy* **2017**, *107*, 640–648. [CrossRef]
24. *Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 Concerning Common Rules for the Internal Market in Electricity and Repealing Directive 2003/54/EC*; European Parliament: Brussels, Belgium, 2009.
25. *Directive 2009/73/EC of the European Parliament and of the Council of 13 July 2009 Concerning Common Rules for the Internal Market in Natural Gas and Repealing Directive 2003/55/EC*; European Parliament: Brussels, Belgium, 2009.
26. Bouzarovski, S.; Petrova, S. A global perspective on domestic energy deprivation: Overcoming the energy poverty–fuel poverty binary. *Energy Policy* **2011**, *39*, 1659–1668. [CrossRef]
27. Energy Poverty Observatory. Action in Low-Income Households to Improve Energy Efficiency through Visits and Energy Diagnosis (ACHIEVE). Available online: https://www.energypoverty.eu/measure-policy/action-low-income-households-improve-energy-efficiency-through-visits-and-energy (accessed on 3 June 2020).
28. Bouzarovski, S.; Sarlamanow, R.; Petrova, S. Energy poverty policies in the EU: A critical perspective. *Energy Policy* **2012**, *49*, 76–82. [CrossRef]
29. Gatto, A.; Busato, F. Energy vulnerability around the world: The global energy vulnerability index (GEVI). *J. Clean. Prod.* **2020**, *253*, 118691. [CrossRef]
30. Gatto, A.; Drago, C. A taxonomy of energy resilience. *Energy Policy* **2020**, *136*, 111007. [CrossRef]
31. Gatto, A.; Drago, C. Measuring and modelling energy resilience. *Ecol. Econ.* **2020**, *172*, 106527. [CrossRef]
32. Gnansounou, E. Assesing the energy vulnerability: Case of industrialised countries. *Energy Policy* **2008**, *36*, 3734–3744. [CrossRef]
33. Gatto, A. A pluralistic approach to economic and business sustainability: A critical meta-synthesis of foundations, metrics, and evidence of human and local development. *Corp. Soc. Responsib. Environ. Manag.* **2020**, *27*, 1525–1539. [CrossRef]
34. Hiteva, R.P. Fuel poverty and vulnerability in the EU low-carbon transition: The case of renewable electricity. *Local Environ.* **2013**, *18*, 487–505. [CrossRef]
35. Genave, A.; Blancard, S.; Garabedian, S. An assessment of energy vulnerability in Small Island Developing States. *Ecol. Econ.* **2020**, *171*, 106595. [CrossRef]
36. Costanza, R.; Kubiszewski, I.; Giovannini, E.; Lovins, H.; McGlade, J.; Pickett, K.E.; Ragnarsdóttir, K.V.; Roberts, D.; de Vogli, R.; Wilkinson, R. Development: Time to leave GDP behind. *Nat. News* **2014**, *505*, 283. [CrossRef]
37. Nardo, M.; Saisana, M.; Saltelli, A.; Tarantola, S.; Hoffman, A.; Giovannini, E. *Handbook on Constructing Composite Indicators: Methodology and User Guide*; Organisation for Economic Co-operation and Development: Paris, France, 2008.

38. Llera-Sastresa, E.; Scarpellini, S.; Rivera-Torres, P.; Aranda, J.; Zabalza-Bribián, I.; Aranda-Usón, A. Energy Vulnerability Composite Index in Social Housing, from a Household Energy Poverty Perspective. *Sustainability* **2017**, *9*, 691. [CrossRef]
39. Gillard, R.; Snell, C.; Bevan, M. Advancing an energy justice perspective of fuel poverty: Household vulnerability and domestic retrofit policy in the United Kingdom. *Energy Res. Soc. Sci.* **2017**, *29*, 53–61. [CrossRef]
40. Middlemiss, L.; Gillard, R. Fuel poverty from the bottom-up: Characterising household energy vulnerability through the lived experience of the fuel poor. *Energy Res. Soc. Sci.* **2015**, *29*, 146–154. [CrossRef]
41. International Federation of Red Cross. ¿Qué es la Vulnerabilidad? Available online: https://www.ifrc.org/es/introduccion/disaster-management/sobre-desastres/que-es-un-desastre/que-es-la-vulnerabilidad/) (accessed on 3 June 2020).
42. Day, R.; Walker, G. Household energy vulnerability as an "assemblage". In *Energy Justice in a Changing Climate*; Bickerstaff, K., Walker, G., Bulkeley, H., Eds.; Zed Books: London, UK, 2013.
43. Bouzarovski, S.; Thompson, H. Energy Vulnerability in the Grain of the City: Toward Neighborhood Typologies of Material Deprivation. *Ann. Am. Assoc. Geogr.* **2018**, *108*, 695–717. [CrossRef]
44. Bridge, G.; Bouzarovski, S.; Bradshaw, M.; Eyre, N. Geographies of energy transition: Space, place and the low-carbon economy. *Energy Policy* **2013**, *53*, 331–340. [CrossRef]
45. Saisana, M.; Tarantola, S. *State-of-the-Art Report on Current Methodologies and Practices for Composite Indicator Development*; European Commission-Joint Research Centre: Ispra, Italy, 2002.
46. Freund, C.; Wallich, C. The Welfare Effects of Raising Household Energy Prices in Poland. *Energy J.* **1996**, *17*, 53–77. [CrossRef]
47. Jones, S. Social causes and consequences of energy poverty. In *Energy Poverty Handbook*; Csiba, K., Bajomi, A., Gosztonyi, A., Eds.; European Union: Brussels, Belgium, 2016.
48. Wright, F. Old and cold: Older people and policies failing to address fuel poverty. *Soc. Policy Adm.* **2004**, *38*, 488–503. [CrossRef]
49. Liddel, C. The Health Impacts of Fuel Poverty on Children. Available online: https://www.energypoverty.eu/publication/health-impacts-fuel-poverty-children (accessed on 3 June 2020).
50. Wang, B.; Ke, R.-Y.; Yuan, X.-C.; Wei, Y.-M. China's regional assessment of renewable energy vulnerability to climate change. *Renew. Sustain. Energy Rev.* **2014**, *40*, 185–195. [CrossRef]
51. Healy, J.D.; Clinch, J.P. Quantifying the severity of fuel poverty, its relationship with poor housing and reasons for non-investment in energy saving measures in Ireland. *Energy Policy* **2004**, *32*, 207–220. [CrossRef]
52. Buzar, S. The 'hidden' geographies of energy poverty in post-socialism: Between institutions and households. *Geoforum* **2007**, *2*, 24–240. [CrossRef]
53. Scarpellini, S.; Rivera-Torres, P.; Suárez-Perales, I.; Aranda-Usón, A. Analysis of energy poverty intensity from the perspective of the regional administration: Empirical evidence from households in southern Europe. *Energy Policy* **2015**, *86*, 729–738. [CrossRef]
54. Van der Horst, H.; Hovorka, A. Reassessing the "energy ladder": Household energy use in Maun, Botswana. *Energy Policy* **2008**, *36*, 3333–3344. [CrossRef]
55. Buchs, M.; Bardsley, N.; Duwe, S. Who bears the brant? Distributional effects of climate change mitigation policies. *Crit. Soc. Policy* **2011**, *31*, 285–307. [CrossRef]
56. Bouzarovski, S.; Tirado-Herrero, S.; Petrova, S. *Energy Vulnerability in Europe: New Perspectives on the Relationships among Household Expenditure, Living Conditions and Deprivation*; DG Energy: Brussels, Belgium, 2014.
57. Maxim, A.; Mihai, C.; Apostoaie, C.M.; Popescu, C.; Istrate, C.; Bostan, I. Implications and Measurement of Energy Poverty across the European Union. *Sustainability* **2016**, *8*, 483. [CrossRef]
58. Day, R.; Walker, G.; Simcock, N. Conceptualising energy use and energy poverty using acapabilities framework. *Energy Policy* **2016**, *93*, 255–264. [CrossRef]
59. Sen, A. Capability and well-being. In *The Quality of Life*; Sen, A., Nuusbaum, M.C., Eds.; Oxford University Press: Oxford, UK, 1993; pp. 30–53.
60. Nuusbaum, M.C. *Creating Capabilities: The Human Development Approach*; Harvard University Press: Cambridge, MA, USA, 2011.
61. Horta, A.; Gouveia, J.; Schmidt, L.; Sousa, J.; Palma, P.; Simões, S. Energy poverty in Portugal: Combining vulnerability mapping with household interviews. *Energy Build.* **2019**, *203*, 109423. [CrossRef]

62. Ministry for Ecological Transition. Estrategia Nacional Contra la Pobreza Energética 2019–2024. Available online: https://www.miteco.gob.es/es/prensa/estrategianacionalcontralapobrezaenergetica2019-2024_tcm30-496282.pdf (accessed on 3 June 2020).
63. Spanish Red Cross. *Informe Sobre Vulnerabilidad Social*; Spanish Red Cross: Madrid, Spain, 2018.
64. World Health Organisation. *Health Impact of Low Indoor Temperatures: Report on a WHO Meeting, Copenhagen, Denmark, 11–14 November 1985*; World Health Organization: Geneve, Switzerland, 1985.
65. Ecologists in Action. Estudio Técnico Sobre Pobreza Energética en la Ciudad de Madrid. Available online: https://www.madrid.es/UnidadesDescentralizadas/Consumo/NuevaWeb/pobreza%20energ%C3%A9tica/Estudio%20Pobreza%20energ%C3%A9tica%204%20febrero%202017.pdf (accessed on 3 June 2020).
66. Instituto para el Ahorro y la Diversificación Energética (IDAE). *Guia Técnica Instalaciones de Climatización con Equipos Autónomos*; IDAE: Madrid, Spain, 2010.
67. Cuchí, A.; Arcas-Abella, J.; Pagès-Ramon, A. Estudio de la Distribución del Consume Energético Residencial Para Calefacción en España. Available online: https://www.fomento.gob.es/NR/rdonlyres/53E31468-1B09-4123-A05B-0FBEB86B858E/149686/201804_Estudio_distribucion_consumo_energetico_res.pdf (accessed on 3 June 2020).
68. Foessa. VIII Informe Sobre Exclusión y Desarrollo Social en España. Available online: http://www.plataformatercersector.es/sites/default/files/20190612%20VIII%20Informe-FOESSA-2019-completo.pdf (accessed on 3 June 2020).
69. Charnes, A.; Cooper, W. *Management Models and Industrial Applications of Linear Programming*; Wiley: New York, NY, USA, 1961.
70. Lee, S.M. *Goal Programming for Decision Analysis*; Auerbach: Philadelphia, PA, USA, 1972.
71. Ignizio, J.P. *Goal Programming and Extensions*; Lexington Books: Lexington, UK, 1976.
72. Díaz-Balteiro, L.; Romero, C. Sustainability of forest management plans: A discrete goal programming approach. *J. Environ. Manag.* **2004**, *71*, 351–359. [CrossRef]
73. Blancas, F.J.; Caballero, R.; González, M.; Lozano-Oyola, M.; Pérez, F. Goal programming synthetic indicators: An application for sustainable tourism in Andalusian coastal counties. *Ecol. Econ.* **2010**, *69*, 2158–2172. [CrossRef]
74. Lozano-Oyola, M.; Blancas, F.J.; González, M.; Caballero, R. Sustainable tourism indicators as planning tools in cultural destinations. *Ecol. Indic.* **2012**, *18*, 659–675. [CrossRef]
75. Pérez, V.; Hernández, A.; Guerrero, F.; León, M.A.; da Silva, C.L.; Caballero, R. Sustainability ranking for Cuban tourist destinations based on composite indexes. *Soc. Indic. Res.* **2016**, *129*, 425–444. [CrossRef]
76. Blancas, F.J.; Lozano-Oyola, M.; González, M.; Caballero, R. A dynamic sustainable tourism evaluation using multiple benchmarks. *J. Clean. Prod.* **2018**, *174*, 1190–1203. [CrossRef]
77. Molinos-Senante, M.; Marques, R.C.; Pérez, F.; Gómez, T.; Sala-Garrido, R.; Caballero, R. Assessing the sustainability of water companies: A synthetic indicator approach. *Ecol. Indic.* **2016**, *61*, 577–587. [CrossRef]
78. Valcárcel-Aguiar, B.; Murias, P. Evaluation and management of urban liveability: A goal programming based composite indicator. *Soc. Indic. Res.* **2019**, *142*, 689–712. [CrossRef]
79. Valcárcel-Aguiar, B.; Murias, P.; Rodríguez-González, D. Sustainable urban liveability: A practical proposal based on a composite indicator. *Sustainability* **2019**, *11*, 86. [CrossRef]
80. Bouzarovski, S.; Tirado Herrero, S. Geographies of injustice: The socio-spatial determinants of energy poverty in Poland, Czechia and Hungary. *Post Communist Econ.* **2017**, *29*, 27–50. [CrossRef]
81. Healy, J.D.; Clinch, P. Fuel poverty in Europe: A cross-country analysis using a new composite measure. In *Environmental Studies Research Series WP*; University College Dublin: Dublin, Ireland, 2002.
82. Thomson, H.; Snell, C. Quantifying the prevalence of fuel poverty across the European Union. *Energy Policy* **2013**, *52*, 563–572. [CrossRef]
83. Scarpellini, S.; Sanz Hernández, M.A.; Moneva, J.M.; Portillo-Tarragona, P.; Rodríguez, M.E.L. Measurement of spatial socioeconomic impact of energy poverty. *Energy Policy* **2019**, *124*, 320–331. [CrossRef]
84. Aristondo, O.; Onaindia, E. Counting energy poverty in Spain between 2004 and 2015. *Energy Policy* **2018**, *113*, 420–429. [CrossRef]
85. Bednar, D.J.; Reames, T.G.; Keoleian, G.A. The intersection of energy and justice: Modeling the spatial, racial/ethnic and socioeconomic patterns of urban residential heating consumption and efficiency in Detroit, Michigan. *Energy Build.* **2017**, *143*, 25–34. [CrossRef]

86. Ministry for the Presidency. Real Decreto 235/2013, de 5 de abril, por el que se Aprueba el Procedimiento Básico Para la Certificación de la Eficiencia Energética de los Edificios.BOE núm. 89, de 13 de abril de 2013, páginas 27548 a 27562. Available online: https://www.boe.es/eli/es/rd/2013/04/05/235 (accessed on 3 June 2020).
87. Ministry for the Presidency and Territorial Administrations. Real Decreto 564/2017, de 2 de junio, por el que se modifica el Real Decreto 235/2013, de 5 de abril, por el que se Aprueba el Procedimiento Básico Para la Certificación de la Eficiencia Energética de los Edificios.BOE» núm. 134, de 6 de junio de 2017, páginas 45935 a 45937. Available online: https://www.boe.es/eli/es/rd/2017/06/02/564 (accessed on 3 June 2020).
88. Cicerchia, A. Measures of optimal centrality: Indicators of city effect and urban overloading. *Soc. Indic. Res.* **1999**, *46*, 273–299. [CrossRef]
89. Saisana, M.; Saltelli, A.; Tarantola, S. Uncertainty and Sensitivity Analysis as Tools for the Quality Assessment of Composite Indicators. *J. R. Stat. Soc. A Stat.* **2005**, *168*, 1–17. [CrossRef]