Multidimensional procedure for mapping and monitoring urban energy vulnerability at regional level using public data: Proposal and implementation into a case study in Spain

Jon Terés-Zubiaga a,*, Iker González-Pino a, Irantzu Álvarez-González b, Álvaro Campos-Celador c

a ENEDI Research Group, Energy Engineering Department, Faculty of Engineering of Bilbao, University of the Basque Country UPV/EHU, Plaza Ingeniero Torres Quevedo 1, 48013, Bilbao, Spain
b SAREN Research Group, Department of Graphical Expression and Engineering Projects, Faculty of Engineering of Bilbao, University of the Basque Country UPV/EHU, Rafael Moreno Pitxitegi 2, 48013, Bilbao, Spain
c ENEDI Research Group, Energy Engineering Department, Faculty of Engineering of Gipuzkoa (Eibar section), University of the Basque Country UPV/EHU, Av. Otaola 29, 20600, Eibar, Spain

A R T I C L E   I N F O

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A B S T R A C T

Energy poverty is nowadays one of the biggest challenges to be tackled in the European Union, so identifying the number of households in a situation of energy vulnerability and taking the necessary measures to protect vulnerable and energy poor customers is considered to be essential. In this study, a simple methodology for identifying and monitoring energy vulnerable areas based on information available in public databases is presented. This paper brings to light the potential of existing public data for evaluating energy vulnerability, and the nature of these data also enables the evolution of vulnerability levels and the effect of potential measures implemented to be evaluated. The proposed method allows energy vulnerability to be mapped and diagnosed, at census section level, by means of a three-dimensional index that takes into account building features and energy expenses and two socio-economic indicators, giving rise to a vulnerability traffic-light. The method is then illustrated with the evaluation of the energy vulnerability of a region located in northern Spain (Greater Bilbao), where 13% of the census sections or 93,000 inhabitants reside (11% of the total population analysed), have been identified as suffering different levels of energy vulnerability. A geographical pattern has also been clearly recognised.

1. Introduction

According to different studies, it is estimated that between 50 and 125 million people in the European Union are unable to afford proper indoor thermal comfort (García et al., 2009). As energy poverty is a widespread problem across Europe, it remains a major challenge, and lifting vulnerable citizens out of it is an urgent task for the European Union (EU) and its Member States. In fact, there is a commitment to tackle energy poverty, having been a policy priority since 2019, when Energy Poverty was in the focus of the Clean energy for all Europeans package (European Commission, 2019). This package, through the Directive (EU) 2019/944 establishes that “Member States should take the necessary measures to protect vulnerable and energy poor customers”, collecting “the right information to monitor the number of households in energy poverty”, and developing national action plans that establish an objective to decrease the number of energy poor customers. In doing so, measures could include social policies or energy efficiency improvements of the housing stock (European Commission 2019).

In short, energy poverty is the outcome of the unbalance between two household scale factors: household incomes and energy expenses allocated to cover the energy needs of the household, which, in turn, results from the combination of energy prices and energy efficiency of the buildings. In this context, the European Commission has targeted building renovations as a strategy for tackling energy poverty. In this sense, the relation between inefficient buildings and exposure to cold spells and heatwaves is highlighted by the European Commission,
pointing out the inadequate indoor comfort and sanitary conditions as a cause of lower productivity, health problems and higher mortality and morbidity (European Commission 2020).

Furthermore, as a part of the ‘Clean energy for all Europeans package’, the European Commission has developed the Commission Recommendation (EU) 2020/1563 on energy poverty (European Commission 2020), aimed to be jointly adopted with the “Renovation Wave” initiative, in order to “mutually strengthen the calls to tackle energy poverty and worst-performing buildings”. This recommendation provides “guidance on appropriate indicators for measuring energy poverty and on the definition of a significant number of households in energy poverty”. In that sense, one of the objectives of the Renovation Wave is to use renovation as a lever to address energy poverty and give access to healthy housing for all households.

Furthermore, within the ‘Fit for 55 package’, it is expected to create a new Social Climate Fund which “will provide dedicated funding to Member States to support European citizens most affected or at risk of energy or mobility poverty” (European Commission 2021).

It should be noted that the topic has gradually become a widely recognised societal challenge, not only amongst practitioner and policy-making circles, but also in the academic spheres, in such a way that this increase in awareness on energy poverty in the few last years has also been reflected in the academic publications in this field. Although some publications focused on this issue can be found at the start of the 1980s, such as the work presented by Bradshaw and Hutton (1983), the first proposal for quantifying energy poverty was introduced by B. Boardman in 1991, defining it as the conditions of those households whose fuel expenditure exceeded 10% of their income (Boardman, 1991). Since then, several ways for defining fuel poverty (involving different policy implications) can be identified in the literature (Moore, 2012). Some publications dealing with this topic can be found in the following decades, but it was not until the second decade of the 21st century that it became an emerging topic and the amount of academic studies related to energy poverty started increasing yearly; approaching it from different research fields (engineering, environmental sciences, social sciences, economics, psychology, medicine...). By way of example, Fig. 1 presents the publications gathered in the Scopus platform database searching in TITLE-ABS-KEY (“energy poverty” OR “fuel poverty”)1 until 31 December 2021, including articles, reviews, book-chapters and data papers. A total amount of 178 documents published between 1983 and 2010 are provided by Scopus, while only three years later, the cumulative figure had risen to more than double (419), reaching 391 published documents in 2021 alone, thus confirming the rising interest in the topic. By regions, the UK (which is considered the pioneer on this topic, focusing on it at the beginning from a health perspective) leads the number of publications in the analysed period (26.35%), followed by the United States (11.67%) and Spain (8.01%).

Another related term also arises in this context: “energy vulnerability”. Even though it is a term that has traditionally been related to economic or energy analysis at country or supranational level and unconnected to fuel poverty; during the second decade of the 21st century some references also redefined it, applying it at an urban scale, closely related to fuel poverty. One of the first examples of this fact is the definition provided by Broto (2012), who looks at the difference between fuel poverty and energy vulnerability; while Bouzarovski et al. (2014) define energy vulnerability as “the propensity of an individual to become incapable of securing a materially and socially needed level of energy service in the home”.

A similar definition is provided by Day and Walker (2013): “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 well-being”.

In this case, publications related to this meaning of energy vulnerability, to some extent linked to fuel poverty, have increased significantly in the last few years as well (e.g., Groves et al., 2020; O’Sullivan & Howden-Chapman, 2017; Karpinska et al., 2021), even applying approaches transcending the domestic sphere, and also considering the household energy consumption and expenditure required for transport; the so called Double Energy Vulnerability (DEV) (Robinson & Mattioli, 2020).

1. State-of-the-art

There is not only one single indicator for quantifying the vulnerability level to Energy Poverty (EP) and, in fact, the methodologies and indicators proposed in the literature to identify energy poverty and vulnerable consumers are diverse.

Several authors have proposed different criteria for classifying these indicators. Heindl (2015) organised these indicators into 4 different groups: i) subjective and qualitative, developed by the individuals themselves; ii) subjective and quantitative, developed by third parties; iii) objective and quantitative, not income-expenditure based (humidity, incidence of mould in the household, epidemiological data); and iv) objective, quantitative and income-based indicators. In this sense, and by way of example, S. Tirado Herrero offers a detailed review of the most usual methods for measuring EP and identifies key conceptual and methodological challenges in this regard (Herrero, 2017); while, in a more recent review (Siksnyte-Butkiene et al., 2021), 71 indicators for evaluating EP were identified and evaluated.

In fact, regarding quantitative and income-based indicators, since Brenda Boardman first introduced the proposal of the “ten percent rule” (TPR) in 1991 (Boardman, 1991), other alternatives have been proposed. Together with the TPR, an additional “above threshold” indicator can be included in this category, the 2M, which considers that a household is energy poor when its share of energy expenditure is more than double the median of the geographical area evaluated. The opposite approach can also be found, the so-called “hidden Energy Poverty” (hEP), adopting different forms as proposed in Thema and Vondung (2020) by the EU Energy Poverty Observatory (currently, EPHA: Energy Poverty Advisory Hub). However, some authors have pointed out the limits of these indicators, such as Meyer et al. (2018) or Betto et al. (2020).

Other alternative indicators have been widely applied over the last few decades, such as the Minimum Income Standard (MIS) and the Low Income – High Costs (LIHC). The MIS was proposed by Moore (2012), applying it in the UK, and it was used in other contexts, such as in Germany (Heindl, 2015), Italy (Cambioli et al., 2021) or Spain, (Tirado Herrero et al., 2016; Romero et al., 2018). The LIHC is defined by Hills (2012) and is the basis of the current strategy in the UK on energy poverty. Some of the mentioned studies in fact use compound indices, combining some of the above-mentioned indicators, as one unique indicator does not encompass all the aspects of energy poverty.

Similarly, when energy vulnerability is addressed, there is no systematic method for determining the dimensions to be taken into consideration, and different approaches can be found in the literature. Some studies focus on demand factors, such as the thermal quality of the building envelope (Gouveia et al., 2021), whereas others authors highlight supply factors, such as energy costs or lack of access to energy carriers (Freund & Wallich, 1996). Other authors target social and demographic issues, such as F. Wright (2004) and C. Liddell (2009). Several studies also focus on building heating systems, such as Horta et al. (2019). As in the case of energy poverty indicators, these parameters can also be classified into different groups. Martín-Consuegra et al. (2020) stated that the causes of energy vulnerability are associated with building energy efficiency, energy costs, or household incomes.
evaluation, these causes can be directly assessed or considered using related indicators, which, in several cases, tend to be inter-related (building age, indicators to identify vulnerable social groups...). Meanwhile, Llera-Sastresa et al. (2017) refer to four main factors: type of home, energy efficiency, energy costs and household consumer habits, whereas Gillard et al. organise them into social, political, technical and economic factors (Gillard et al., 2017). Another comprehensive framework is presented by Bouzarovski and Simcock (2017), where four main dimensions are proposed: material deprivation, energy affordability, energy needs and misrecognition.

Thus, as Calvo et al. (2021) identify, this phenomenon can be evaluated through three pathways: focusing on the affordability of energy expenditure in high-development countries by considering the aforementioned economic indicators; targeting geographical or technological barriers to energy by considering energy access indicators; and targeting quality, which, as argued by Urquiza et al. (2019), is a key dimension when evaluating energy poverty in territorially heterogeneous, middle-development countries.

At the same time, different methodologies can be found for data analysis when this topic is addressed. They are mainly divided into two different groups: physics-based models (e.g., Bienvenido-Huertas et al., 2021) and data-driven models (e.g., van Hove et al., 2022), or a combination of both (hybrid models). One of the differences between them can be found in the way that energy data are obtained. Physics-based models usually estimate a theoretical value of energy demand/consumption (also presented in some references as “energy needs”), which is calculated from a set of different inputs: building construction features, weather data, or user profiles, to name but a few. Data driven models, however, could use actual energy data (real consumption), or energy consumption is not directly included as input data, considering other parameters which are assumed to have an effect on the said energy consumption (buildings’ age or energy systems, for instance).

In this sense, the role of household characteristics on the probabilities of becoming energy poor has been demonstrated by several studies; even the importance of spatializing energy poverty and of paying attention to climatic and geographical conditions have been pointed out by several authors, as Calvo et al. (2021) state.

Thus, several recent publications have focused on measuring and assessing energy poverty and territorial energy vulnerability from different approaches, considering some of the dimensions previously mentioned.

Middlemiss and Gillard (2015) explored energy vulnerability from the point of view of interviewees, identifying six challenges to energy vulnerability for the fuel poor: quality of dwelling fabric, energy costs and supply issues, stability of household income, tenancy relations, social relations within the household and outside, and ill health. Encinas et al. (2022) addressed energy poverty from a spatial approach, evaluating the impact that socioeconomic, urban and climatic variables have on a territorial scale, applying the analysis to the urban area of Santiago de Chile. Pérez-Fargallo et al. (2022) evaluated energy poverty situations in a social housing district located in Chile as well, considering three different dimensions and a territorial indicator: food and hygiene issues, lighting and electrical devices related issues, indoor environment control and energy expenditure issues. Murias et al. (2020) proposed a synthetic indicator to assess territorial differences in household energy vulnerability, based on four environmental dimensions: energy, residential, physical and socio-economic.

In this context, it can be observed that the majority of studies, directly or indirectly, show the role of buildings and their energy performance for reducing or mitigating domestic energy vulnerability, and the potential of building renovation (amongst others) has frequently been explored in the literature from this perspective. Additionally, the interest of identifying vulnerable areas for prioritising specific actions has been increasing over the last few years. One example of this is the work presented by Gouveia et al. (2021), where the potential of energy renovation measures and solar photovoltaic (PV) production to address energy poverty is shown. In this sense, Geographical Information Systems (GIS) become a useful tool for implementing this sort of multidimensional analysis at city or regional scale. As far as building energy efficiency evaluation is concerned, different approaches for determining buildings’ energy demand using GIS with different approaches and different aims have been explored. These include: i) planning local energy infrastructures (Calderon et al., 2015; Lumbreras et al., 2022; Yang et al., 2020); ii) prioritising urban planning factors and priority areas for implementing energy savings measures (Yu et al., 2021; Ali et al., 2020); or iii) evaluating the potential for integrating renewable energy systems, such as geothermal (Ramos-Escudero et al., 2021) or solar (Groppi et al., 2018; Ren et al., 2022).
Several references can also be found on the use of GIS applied to energy vulnerability and fuel poverty related issues. More specifically, Fabbri and Gaspari (2021) used it to map the fuel poverty in Bologna (Italy), based on information provided by EPCs. Different studies applied to the Spanish context can also be found. Monge-Barrio and Sánchez-Ostiz Gutiérrez (2018) applied GIS to identify energy vulnerable areas at an urban level in Pamplona where energy efficiency interventions should be prioritised. The works carried out in this field by Martín-Consuegra et al. (2020), Martín-Consuegra et al. (2022), Martín-Consuegra et al. (2016), Martín-Consuegra et al. (2019) are also noteworthy; they used cadastral data focusing on the city of Madrid.

In the same context, there is also a growing interest in optimising and exploiting the available public data. In this sense, and related to GIS as well, the Inspire Directive 2007/2/EC, establishing an Infrastructure for Spatial Information in the European Community (European Commission 2019), boosted the emergence and development of Infrastructures for Spatial Information at both national and regional levels. In the case of Spain, the IDEE (Infraestructura de Datos Espaciales de España), on a national scale (Centro Nacional de Información Geográfica - Gobierno de España 2022), and the different autonomous regions, on a regional scale (e.g., IDENA in Navarra (Gobierno de Navarra 2022), IDEApragon in Aragon (Gobierno de Aragón 2022), IDEEx in Extremadura (Gobierno de Extremadura 2022), or GeoEuskadi in the Basque Country (Euskotren Egunerako Informatziak/Gobierno Vasco (Basque Government) 2022), to name but a few), have developed their own infrastructure of spatial information.

Traditionally, vulnerable areas have been identified through indicators derived from national statistics data available by country or region. Nevertheless, these analyses present a lack of reliable disaggregated data for focusing on inequality within cities or regions. In recent years, the amount of data of a different nature that is publicly available has grown exponentially, as well as its level of detail, and there is an increasing interest in exploiting it with different aims. In this sense, C. Sánchez-Guevara et al. present a quantification of fuel poverty at city and district level for the city of Madrid (Sánchez-Guevara et al., 2020), also analysing its incidence from a gender perspective (Sánchez-Guevara et al., 2020). For their part, several analyses to identify vulnerable areas have also been carried out by public administrations. In the case of Spain, there are examples at the national level (e.g., the Urban Vulnerability Atlas (Ministerio de Transportes 2022)) and on a regional scale (one example is the map of vulnerable areas of the Basque Country (Department of Territorial Planning 2020), developed by the Department of Territorial Planning, Housing and Transport of the Basque Government).

Finally, if national and regional statistics are a useful tool for obtaining economic and social indicators, EPCs have become a promising source of buildings’ energy performance related information in recent years (BPIE - Buildings Performance Institute Europe 2022). Introduced in response to the Energy Performance in Buildings Directive (European Commission 2002), EPCs are mandatory in the European Union for new buildings and existing buildings or apartments that are for sale or rent. The use of EPCs as a source for mapping fuel poverty can be found in different references, such as Camboni et al. (2021), who proposed a method to map fuel poverty risk by combining information from EPCs, census and survey data; or the aforementioned work carried out by Fabbri and Gaspari (2021) in Bologna (Italy) also using information from EPCs. However, EPCs also present some limitations that should be taken into consideration when using them, such as a lack of reliable energy performance information (Iribar et al., 2021), or the fact that not all buildings/apartments have it.

Based on all the aforesaid and the necessity of defining procedures aimed at identifying vulnerable areas which can be easily updated periodically, the main objective of this paper is to propose a procedure to evaluate energy vulnerability on a regional scale, thus enabling the identification of priority areas where specific measures can be implemented; as well as a first insight into the main weaknesses in those areas. This could be especially useful for prioritising areas at regional level where energy renovation in buildings should be boosted, including energy vulnerability as a criterion. The procedure should meet some requirements: i) it should be based on a limited amount of indicators; ii) the indicators used should be derived from information available in public databases and they should be updated periodically with the aim of enabling the monitoring of the evolution of energy vulnerability for a period of time and evaluating the effect of the measures implemented; and iii) the data and results should be sufficiently disaggregated to be able to determine inequalities within cities and municipalities. To do that, three main data sources are used: national and regional statistics, cadastral data and EPCs. The procedure is then implemented to evaluate the energy vulnerability in the Bilbao Metropolitan Area, carrying out a detailed analysis and identifying the vulnerable areas in this region.

It should be noted that, even though different studies can be found where some of these ideas have been partially applied to some extent, the approach herein proposed presents several novelties with respect to other existing works in the literature. Firstly, the proposed method is fully based on the use of public data already available at different levels. Secondly, the input data used are not only publicly available, but are also updated regularly, thus allowing the evolution of energy vulnerability in a given region to be assessed and making it possible to automate the updates of the territorial analysis. Thirdly, it involves a spatial analysis of the energy vulnerability using disaggregated data, so heterogeneities can be evaluated not only in supra-municipal areas, but also at municipal level. Finally, the proposed public databases are not case specific and are available in several other regions, so the proposed methodology can be easily extrapolated and used in other contexts by making minor adjustments.

Thus, the rest of the paper is organised as follows: Section 2 gives a detailed description of the proposed procedure, presenting the assumptions, data sources used and derived indicators proposed for evaluating energy vulnerability. In Section 3, a general description of the case study is presented, as well as the data sources used to analyse it. The main results obtained for the Bilbao Metropolitan Area are presented and discussed in detail in Section 4, whereas the main conclusions and remarks are addressed in Section 5.

2. Materials and methods

The evaluation procedure proposed in this work takes the work presented by F. (Martín-Consuegra et al., 2020) as a reference, extending the method, proposing some modifications and adapting it to the data available in other public databases. The method is approached at census-section level, which, as defined by the Statistical Office of the Basque Country (EUSTAT - Statistical Office of the Basque Country 2022), is the partition of the municipal area preferably characterised as being defined by easily identifiable boundaries (geographical features, permanent construction, roads...), and having a size of between 1000 and 2500 residents (except in the case of municipalities with a smaller population).

As presented in the previous section, when fuel poverty is addressed by focusing on the affordability of energy expenditure (following the categorisation presented by Calvo et al. (2021)), it can be evaluated as a result of the combination of several factors which can be gathered into three main dimensions: indicators related to the building’s features and location, which are directly related to the energy needs (construction, energy systems, urban environment, climatic variability...); socioeconomic factors, which, on the one hand, determine barriers for guaranteeing the coverage of the household energy needs (low household incomes) and, on the other, also have an effect on the way energy is used (use profiles, environmental awareness...); and household energy affordability (high energy costs). Based on this categorisation, different indices using data available in different public databases are defined and obtained, with the aim of quantifying the “exposure level” or the “vulnerability level” of every census section considering the said indicators, through a data driven analysis. It should be highlighted that the
method is not focused on determining a specific indicator (MIS, TPR or LIHC) for quantifying energy vulnerability in a given region, but on proposing a comprehensive analysis of some key parameters that have a significant effect on the input data required to calculate any of these indicators (related to household energy expenses and household incomes).

The Atlas of Urban Vulnerability, where deprived neighbourhoods in Spain are identified, is taken as the starting point. However, with the aim of defining a vulnerability index focused on fuel poverty related issues, 5 additional indicators obtainable from available public data are proposed. These representative indicators have been selected from those identified in the literature review presented in Section 1.1, and assuming the requirements established in the same section: availability in public databases updated periodically to enable the monitoring of their evolution in the studied areas. Hence, based on the previously mentioned categorisation, buildings’ features are evaluated considering their (in) efficiency (by means of the rate provided by EPCs and the building’s age, see Section 2.2) and the availability of thermal facilities for space heating and domestic hot water (DHW) - see Section 2.3. Energy affordability is assessed considering the primary energy (PE) consumption provided by the energy certificates (see Section 2.4), a parameter closely related to energy expenses; whereas socioeconomic factors are taken into consideration through income (namely, the percentage of households with incomes lower than 60% of the median of the region evaluated; see Section 2.5) and the average age of the inhabitants (see Section 2.6). The procedure proposed is summarised in Fig. 2. Taking into account these indicators, a global index to evaluate fuel poverty is proposed (see Section 2.7).

Some limitations should be taken into consideration when this method is applied, mainly related to the use of public information as input data. Firstly, the analysis of energy systems is limited to checking their existence (or not) in the residential buildings of the region evaluated (for those areas where, due to the climatic conditions, heating consumption involves a significant share of the total energy consumption), omitting more detailed aspects such as the quality of the equipment or types of fuels used. The main reason is that, in the majority of the regions evaluated, this information is not available at regional census levels. Similarly, user profiles, which play a key role in the actual energy consumption of a building (as several studies point out, such as Cuerda et al. (2019)) are beyond the scope of this paper, for similar reasons, so energy expenditures are evaluated based on theoretical energy needs, instead of using actual energy consumption (based on the buildings’ age or information provided by EPCs). Nevertheless, they are indirectly taken into account when socio-economic factors are assessed, and additional socio-economic indicators could be added in this sense (e.g., unemployment rates). Thirdly, another limitation that should be considered is that the urban morphology (including urban density), which has been included in previous studies (Zhang et al., 2022), is not considered in the procedure. However, at the same time, it should be highlighted that the aim of the procedure is to carry out assessments at regional level, in such a way that, once vulnerable areas have been mapped, more detailed analyses can be applied in those areas, including all of these considerations.

2.1. Deprived neighbourhoods

One of the first data sources to be considered is the atlas of deprived neighbourhoods (Ministerio de Transportes 2022). This presents information about urban vulnerability in all Spanish municipalities. The “Atlas of Urban Vulnerability” in Spain 2001-2011 provides statistical information -at Census Tract level, and in every Spanish municipality- and analysis tools of several variables related to urban vulnerability, allowing the creation of thematic maps of different indicators. It has been developed based on the data available from the 2001 and 2011 Spanish Population and Housing Censuses, including updated household income information in 2018.

Based on these indicators, a “Catalogue of Vulnerable Neighbourhoods” (Ministerio de Transportes 2022) (included in the “Urban Vulnerability Observatory in Spain” (Ministerio de Transportes 2022)) has been developed. This catalogue is the starting point for identifying vulnerable areas, analysing all Spanish provincial capitals and those municipalities exceeding 50,000 inhabitants, that is, 1,49 municipalities out of 8131 (INE, Spanish National Statistics Institute 2022). This limit makes it necessary to look for other additional indicators to complement and extend the analysis, focusing, as previously mentioned, on fuel poverty related issues.
2.2. Building energy inefficiency

In order to identify those census sections with the greatest predominance of inefficient buildings that, as mentioned, is one of the main factors that can lead to fuel poverty, two different indicators were used as a reference: the buildings’ age and EPCs.

2.2.2. Energy rating

As far as the buildings’ age is concerned, the information can be obtained from the cadastral data. As proposed in different previous studies, e.g., (Fernandez et al., 2020; Maia et al., 2014), the year of construction could be used as an indicator of the energy performance of a given building, since the period of construction can be translated into U-Values according to the building codes in force in that moment. In the case of Spain, 1979 can be considered a milestone, when the first thermal regulation in buildings was implemented (Presidencia del Gobierno 1979) (there was, in fact, a previous thermal regulation in force since 1975 (Presidencia del Gobierno 1975), but it was very generic and focused on a methodology for calculating the thermal features of the envelope, so it did not have any real impact on the building stock characteristics). Accordingly, buildings constructed before the implementation of the NBE-CT 79 are considered significantly more inefficient than those constructed later, and consequently, the number of buildings constructed before 1979 in each census section are taken into consideration when applying the age criterion. It should be noted that, in the case of Spain, there are five different cadastres: four corresponding to the provinces of Bizkaia (Diputación Foral de Bizkaia - Bizkaiko Foru Aldundia 2022), Gipuzkoa (Diputación Foral de Gipuzkoa - Gipuzkoako Foru Aldundia 2022), Araba (Diputación Foral de Araba - Arabako Foru Aldundia 2022) and Navarra (Diputación Foral de Navarra 2022), and the Spanish Cadastre that covers the rest of the Spanish territory (Gobierno de España - Ministerio de Hacienda y Función Pública, 2022). Even though the main information (such as construction age or geometry) is provided by all of them, access to them and the level of detail present some differences. For instance, some cadastres (e.g., the Cadastre of Bizkaia) provide not only the construction year of each building, but also the renovation year in case the building has been renovated. When both values are available, it is proposed to use the latest, due to the fact that, when a building is renovated, the renovation must meet the regulation in force in that moment, at least to some extent.

Thus, the first energy efficiency indicator is defined as the percentage of buildings constructed (or renovated) before 1979 in each census section, thus selecting those census sections where this percentage is in the highest quartile of the evaluated region (Q3-Q4 = 95.5%).

2.2.2.1. Building age

Regarding thermal facilities for space heating, an indicator based on the percentage of dwellings with no heating system is considered. This indicator aims to take into consideration those apartments with no heating system at all, or if they do have one, those apartments with inadequate heating systems (i.e., punctual heaters, such as individual electric radiators or butane-gas heaters).

Three different data sources can be identified for obtaining this indicator. On the one hand, data available from the Spanish Population and Housing Censuses provided by the National Statistics Institute in Spain (INE) (INE- Spanish National Statistics Institute 2022) can be used. Moreover, the most relevant data in this sense (percentage of buildings with no heating system, amongst others) are gathered in the Atlas of Residential Buildings in Spain (Ministerio de Transportes, Movilidad y Agenda Urbana - Gobierno de España 2022), which is a web application that provides statistical information at census tract level of several variables related to residential buildings, which are updated every 10 years. The main advantage of this data source is that it provides information for every Spanish municipality desegregated at census tract level; whilst one of the main drawbacks is that, in some regions, the last available data are from 2001. As an example, the work presented by Martín-Consegra et al. (2020) uses this data source to obtain thermal facilities-related information.

Another possible data source is statistical offices at regional level. For instance, in the case of the Basque Country, the Basque Statistical Office (EUSTAT) (EUSTAT - Statistical Office of the Basque Country 2022) is the public body that collects, analyses and publishes statistical information about different aspects of the Basque society and economy. Amongst others, the Municipal Housing Statistics (EUSTAT - Statistical Office of the Basque Country 2022), which are updated yearly, include as an item “main family dwellings with a heating system” in each census section. In this item, collective and individual systems are distinguished, while mobile or fixed appliances that enable the temperature of one or all the rooms of a dwelling to be raised, including mobile electric radiators, are not considered as heating systems.

Finally, at municipal level, cadastral data could also be used in some cases. In the case of the Cadastre of Bizkaia, one of the items provided for each building is whether it is provided with a heating system. Cadastral information is updated monthly, but it should be noted that this item is exclusively based on the situation when the building was registered in registers where the access to and level of detail of the information provided vary, depending on the case. In several cases, the available public information only includes the category (from A to G), as well as the aggregated value of Primary Energy (PE) Consumption (kWh/m²-year) and the equivalent carbon dioxide emissions (kg/m²-year) provided by the energy label.

So, the indicator proposed for this dimension is based on the energy rating corresponding to the modelled non-renewable primary energy consumption (kWh/m²-year), the minimum information that is generally provided, regardless of the register considered. Thus, this indicator evaluates the percentage of dwellings rated as G with respect to the total amount of dwellings with an EPC in each census section. Accordingly, the census sections considered as vulnerable are those that exceed the mean value of the entire region evaluated by 50% (i.e., 1.5 times the mean value of the entire region).

2.2.3. Global energy efficiency indicator

According to the two indicators defined, a census section is considered as vulnerable under the buildings’ (in)efficiency point of view, when the vulnerability conditions imposed for both indicators are fulfilled: the region is in the highest quartile when the percentage of buildings constructed before 1979 is evaluated, and the mean value of dwellings rated as ‘G’ exceeds the mean value of the region evaluated by 50%.

2.3. Inadequate thermal facilities

Amongst others, the Municipal Housing Statistics (EUSTAT) (EUSTAT - Statistical Office of the Basque Country 2022) is the public body that collects, analyses and publishes statistical information about different aspects of the Basque society and economy. Amongst others, the Municipal Housing Statistics (EUSTAT - Statistical Office of the Basque Country 2022), which are updated yearly, include as an item “main family dwellings with a heating system” in each census section. In this item, collective and individual systems are distinguished, while mobile or fixed appliances that enable the temperature of one or all the rooms of a dwelling to be raised, including mobile electric radiators, are not considered as heating systems.

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Once the data concerning the number of apartments with no heating system per census section has been calculated, this indicator considers a census section as vulnerable when its mean value exceeds the mean value of the entire region evaluated by 50%.

### 2.4. Energy expenses

With the aim of introducing an index related to household energy expenses, the use of the information provided by EPCs is also proposed in this case. In this sense, the value of PE consumption provided by the EPCs (i.e., PE consumption related to DHW and space heating supply) is used as an indicator of the household energy expenses.

To do that, all EPCs (for residential buildings) registered for the evaluated region are georeferenced. Focusing on the PE consumption value provided by these certificates, a screening process for removing outliers is carried out, following the criteria of other similar studies (Fabbri & Gaspari, 2021), in such a way that only those certificates with PE consumption values within the range 5 - 1000 kWh/(m²·year) are taken into account. In order to assign an average value of PE consumption to each building, the value provided by the certificate for the whole building is assumed, when available. Duplicates have also been removed, and in case more than one certificate exists for the whole building, the most recent one (considering the registering date) is to be considered.

In the case of buildings without EPC for the whole building, it is proposed that an average value is assumed for the building, calculated by considering the average PE consumption value of the certificates existing for individual apartments located in that building. Meanwhile, for those buildings without any energy certificate, the average PE consumption value of the buildings that have been constructed in the same period and are located in the census section where the building is located is proposed to be used.

Finally, once the PE consumption has been assumed for each building, the number of dwellings with a value higher than 2M has to be taken into account in each census section. Thus, based on this indicator, a census section will be considered as vulnerable when its mean PE consumption value exceeds the mean value of the entire region evaluated by 50%.

### 2.5. Incomes

One of the main socioeconomic causes of fuel poverty is low household incomes. With the aim of identifying the most vulnerable areas of a given region considering this issue, the percentage of population with income per consumption unit below certain relative thresholds is proposed to be taken as an indicator, which, in the case of Spain, is also provided by the INE (INE- Spanish National Statistics Institute 2022).

The poverty line can be fixed at a percentage of the median income level (it can be 40%, 50%, 60% or 70%, and in some cases, when severe poverty is focused, this could be 20% or 25%). EUROSTAT currently fixes the poverty threshold at 60% of the income median value per consumption unit (EUROSTAT 2022). Taking the European criterion as a reference, the percentage of population with income per consumption unit below 60% of the median is considered for every census section evaluated, so that any census section that exceeds the mean value of the entire region evaluated by 50% is considered to be vulnerable.

### 2.6. Vulnerable people

Additionally, the population age is also considered as a complementary socio-economic indicator in the evaluation of the vulnerability of each census section as a way of identifying those areas where there are higher rates of vulnerable population.

Two different cohorts are proposed for consideration: the population over 65 years of age and an infant cohort (aged from 0 to 5 years). These cohorts have been defined based on criteria used in other studies, such as Martín-Consuegra et al. (2020) or Mohan (2021). This information can also be obtained from the INE, in this case, from the continuous register statistics (INE- Spanish National Statistics Institute 2022). In particular, the percentage of population aged over 65 and below 5 has to be assessed for every census section evaluated and, based on this indicator, those census sections that present a population percentage value for one of these two age ranges (or both), exceeding the mean value of the entire region evaluated by 50%, are considered as vulnerable.

### 2.7. Global vulnerability index

Based on the evaluation of the afore-defined 5 indicators (inefficient buildings, inadequate thermal facilities, high energy expenses, household incomes and population age), vulnerable areas are categorised considering different priority levels.

Census sections are firstly classified according to the three previously defined categories: building features (including inefficient buildings and inadequate thermal facilities), energy expenses and socioeconomic factors. Secondly, taking this categorisation as a reference, a global index for prioritising those census areas, considering three vulnerability levels,
is proposed. In the following, the criteria for this classification are presented, and the approach is graphically depicted in Fig. 3.

2.7.1. Building features

Two different levels are taken into account for assessing this category: L1 (orange), which includes those areas identified as vulnerable, considering the “inefficient buildings” indicator (see Section 2.2) or the “inadequate thermal facilities” (see Section 2.3); and L2 (red), which comprises the areas that fulfil both vulnerability indicators.

2.7.2. Energy expenses

This category is evaluated directly based on the indicator “Energy Expenses”, which is calculated through EPCs. A single vulnerability level is defined in this case (L1, red) for those census sections that meet the requirement defined in Section 2.4.

2.7.3. Socio-economic factors

In this case, two different levels are established: L1 (orange), which includes those areas identified as vulnerable when household incomes are considered (see Section 2.5); and L2 (red), which comprises the areas identified as vulnerable when household incomes and population age are taken into consideration. Thus, the population age criterion, per se, is not considered to be indicative of vulnerability, except for those cases when the household income requirements are also met.

2.7.4. Global index

According to the three categories established, a global energy vulnerability is defined, as explained graphically in Fig. 3. This global index splits the overall energy vulnerability into three different exposure levels:

- Level I (red): categorised as severe, this label is obtained when a red light is obtained in at least two of the three afore-defined

![Fig. 4. Layout of Greater Bilbao, showing the municipalities and urban areas.](image)

![Fig. 5. Number of buildings of Greater Bilbao according to the construction or last renovation year.](image)
vulnerability categories (L1 in energy expenses and L2 in socio-economic factors). Furthermore, if this level is reached and there is an overlap with the deprived neighbourhoods identified in red in the Atlas of Deprived Neighbourhoods (section 2.1), the vulnerability level is considered to be critical.

- Level II (orange): categorised as moderate, this label is obtained when L1 (orange) is obtained for the buildings’ features and “high socio-economic factors” categories, and “high energy expenses” is also detected.
- Level III (yellow): categorised as mild, this label applies to those census sections where caution is required and further detailed analysis is needed. It implies the detection of one “red light” and one “orange light” in the aforementioned three dimensions.

3. Case study: Bilbao Metropolitan Area (Greater Bilbao)

In order to identify and show the potentials and constraints of the proposed method, it is implemented in a case study: the Bilbao Metropolitan Area (Greater Bilbao). This region is located in Northern Spain, in the Basque Autonomous Community (Basque Country), in the province of Bizkaia (see Fig. 4).

Greater Bilbao is the conurbation around the city of Bilbao made up of 26 municipalities situated along the Nervion River. It is the fifth most populous metropolitan area in Spain, with approximately 900,000 inhabitants spread over an area of approximately 370 km², with a mean population density of 2344 inhabitant/km². The region includes more than 433,000 dwellings located in 42,900 residential buildings, whose distribution according to the year of construction or last renovation is shown in Fig. 5, and is divided into 703 census sections.

In terms of demography, it can be stated that the Nervion River is not only a geographical division of the metropolitan area, but also has socio-economic implications. The left bank of the river (Barakaldo, Sestao, Portugalete and Santurtzi), in addition to the Mining Zone, was the heart of the intense industrialisation of Bizkaia during the 19th and 20th centuries, with large shipbuilding and steel industries, that subsequently suffered the crisis of the industry. Currently, some differences can be found when socio-economic indicators are evaluated. By way of example, the municipalities with the highest rates in the percentage of the population with income per consumption unit of under 60% of the median according to the data provided by the INE (INE- Spanish National Statistics Institute 2022) are located in the left bank (Sestao 19.6%, Barakaldo 15.7%, or Santurtzi 14.7%); in contrast to the right bank, where the lowest rates can be found (Larrabetzu 7.5%, Lezama 7.6%, Derio 8.7% or Loiu 9.5%).

3.1. Data sources

Different public databases have been used to collect the input data required for analysing this area. The cartography of the census sections was obtained from the National Statistics Institute of Spain (INE) (INE-Spanish National Statistics Institute 2022), the limits of the municipalities and the region were obtained from GeoEuskadi, the Spatial Data Infrastructure of the Basque Country (Eusko Jaurlaritza / Gobierno Vasco (Basque Government) 2022), and building-related information was collected from the Cadastre of Bizkaia (Diputacion Foral de Bizkaia - Bizkaiko Foru Aldundia 2022). The cadastre of Bizkaia provides
Table 1
Summary of dimensions, indicators and data used.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Indicator</th>
<th>Level of detail provided by the data source</th>
<th>Data used</th>
<th>Source</th>
<th>Ref. year</th>
</tr>
</thead>
<tbody>
<tr>
<td>General data</td>
<td>-</td>
<td>Cartography of the census section limits of municip.</td>
<td>INE (INE-Spanish National Statistics Institute 2022 Jun 7)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Deprived neighbourhoods</td>
<td>-</td>
<td>Building use Number of dwellings per building</td>
<td>Cadastre of Bizkaia (Biputación Foral de Bizkaia - Bizkaiko Foru Aldundia 2022 Jun 7)</td>
<td>2022</td>
<td></td>
</tr>
<tr>
<td>Inefficient Buildings</td>
<td>% of buildings constructed before 1979</td>
<td>Building construction year</td>
<td>Cadastre of Bizkaia (Biputación Foral de Bizkaia - Bizkaiko Foru Aldundia 2022 Jun 7)</td>
<td>2022</td>
<td></td>
</tr>
<tr>
<td>Inadequate thermal</td>
<td>% of dwellings with no heating system</td>
<td>Census section</td>
<td>EUSTAT (EUSTAT - Statistical Office of the Basque Country 2022 Jun 3)</td>
<td>2020</td>
<td></td>
</tr>
<tr>
<td>Energy expenses</td>
<td>% of dwellings with PE cons. higher than 2M</td>
<td>Building/dwelling (some of them)</td>
<td>Primary energy consumption</td>
<td>Basque Government (Department of Economic Development, Sustainability, and Environment (Basque Government) 2016)</td>
<td>2022</td>
</tr>
<tr>
<td>Incomes</td>
<td>% of household with incomes lower than 60M</td>
<td>Census section</td>
<td>INE (INE-Spanish National Statistics Institute 2022 May 20)</td>
<td>2019</td>
<td></td>
</tr>
<tr>
<td>Vulnerable people</td>
<td>% of people older than 65 or younger than 5</td>
<td>Census section</td>
<td>INE (INE-Spanish National Statistics Institute 2022 May 20)</td>
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</table>

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<td>2021</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Summary of dimensions, indicators and data used.

Finally, as far as inadequate thermal facilities are concerned, information related to this issue is provided by various databases, such as the Cadastre of Bizkaia, EUSTAT or the INE, with slight differences amongst them. In the case of EUSTAT, this information is provided by “the Statistics of Municipal Dwellings” (EUSTAT - Statistical Office of the Basque Country 2022), which present annual information on the main characteristics of the Basque Country’s housing stock, the equipment present in the houses and the building where they are located, amongst other aspects. In this regard, the percentage of dwellings with heating systems by census tract is provided. The last update of this item dates from January, 2020. The INE offers similar information through the Population and Housing Censuses (INE-Spanish National Statistics Institute 2022). In this case, information is also provided by census tract and is desegregated by type of heating system used, the most recent data being from 2011. Finally, the Cadastre of Bizkaia (Diputación Foral de Bizkaia - Bizkaiko Foru Aldundia 2022) provides information at a building level. It is the most detailed data source in terms of scale, the information provided about the availability of heating facilities refers to the moment when the building was included in the cadastre. Thus, an important number of buildings that have installed a heating system later appear as having “no heating system”, thus constituting an oversized and non-representative value (see Fig. 6).

After analysing in detail the values provided by these three public data sources, and based on the reliability of the data and its timeliness, data provided by EUSTAT was taken as input to analyse the percentage of dwellings with no heating system in this study.

In short, the different input data used in this case study, as well as the database where they are obtained from, is summarised in Table 1. This information is introduced and analysed by using QGIS. The results obtained are presented in the following section.

4. Results and discussion

The main outcomes regarding the case study described in the previous section are presented in this part. Firstly, general results are presented by dimension, i.e., the buildings’ energy inefficiency (Section 4.1), energy expenses (Section 4.2) and socioeconomic indicators (Section 4.3); and secondly, global vulnerability index-related results are presented in Section 4.4.

4.1. Building features related indicators

As presented in Section 2.2, this dimension is defined based on 3 different indicators: building age, the amount of EPCs rated as G and the amount of dwellings with no heating system. In the evaluated region, according to the cadastre of Bizkaia, 25.94% of the buildings were constructed or renovated after 1979 and almost half of the EPCs (42.68%) are rated as G. Concerning the availability of heating systems in dwellings, the average percentage of dwellings with no heating system reaches 20.25%.

Based on these values, the thresholds for identifying census sections at risk are defined, in such a way that, according to the “inefficient buildings” indicator (European Commission 2019), all census sections in the first quartile in terms of building age (2.1), with more than 95.5% of buildings constructed before 1979, and with a percentage of EPCs rating with a “G” higher than 64.02% (2.2), were identified as vulnerable areas. Meanwhile, similarly, those census sections with more than 30.38% of dwellings with no heating system are considered as vulnerable areas when attending to the indicator related to inadequate energy systems (European Commission 2019). The census sections identified for...
this dimension are depicted in the maps presented in Fig. 7.

Considering these indicators, the global indices for the “Building features” dimension (see Fig. 3) are depicted in Fig. 8. 205 census sections (out of 703) were identified as vulnerable attending to this criterion, affecting a population of 218,383 people, and of these, 18 census sections were identified as “level II”, affecting 17,156 people. Focusing on the geographical distribution, it can be observed that all census sections identified as “level II” are located in the municipality of Bilbao (six census sections) and in those municipalities located on the left bank of the river (namely, eight census sections in Barakaldo, three in Sestao and one in Portugalete). A similar pattern can be observed when the overall analysis is carried out considering both vulnerability levels I and II, especially when the non-urban areas (the less dense areas, and in the map, the census sections with the highest surfaces) are omitted in the analysis.

4.2. Energy expenses

For its part, some general energy expenses-related insights can also be highlighted. The median of the PE consumption values in Greater Bilbao, calculated based on the EPCs as described in section 2.4, is 217.9 kWh/(m²·year). Taking this value as a reference, the average percentage value per census section of dwellings with a PE consumption value higher than 435.8 kWh/m²·year (i.e., 2M) is 0.74%. Hence, 143 census sections presented more than 1.11% (i.e., 1.5 times the average value) of the dwellings with a calculated PE consumption value higher than 2M, affecting 169,099 people.

As presented in Fig. 9, when the geographical distribution is analysed, a similar pattern to that shown in the “building features” indicator can be observed. In this case, a significant number of vulnerable areas correspond to the municipality of Bilbao and municipalities located on the left bank as well, especially when the analysis is focused on the densest areas. Three census sections present values higher than 10%, namely Santurtzi (San Juan District, 20.19%), Barakaldo (Cruces District, 18.65%) and Bilbao (Santutxu District, 10.35%).

4.3. Socio-economic indicators

As far as the socio-economic indicators are concerned, the percentage of households with incomes lower than 60% of the median and the percentage of people older than 65 and/or younger than 5 are the two indicators taken into consideration.

At the regional level, the average percentage value of people with incomes lower than 60% of the median is 15.34% (in 2019). Based on this value, 91 census sections present values higher than 23.01% (1.5 times the average value), with values ranging between 23.1% and 57.7%. As depicted in Fig. 10 (left), the majority of the census sections identified are once again located in Bilbao (delimited by a dotted green line in the map) or in municipalities located on the left bank: 63 in Bilbao, 9 in Barakaldo and 8 in Sestao.

Regarding the second indicator, the regional average value of people older than 65 reaches 24.73%, whereas 3.33% is the average value of people younger than 5. In this case, the geographical pattern is not so defined, as presented in Fig. 10 (right).

Considering these two indicators, all in all, the global index for the socio-economic dimension is calculated as described in section 2.7.3, where those different areas can be distinguished (see Fig. 11): in orange (L1 of vulnerability), those census sections that present a percentage value higher than 150% of households with income below the 60M (5th indicator); and, in red (L2 of vulnerability), those census sections that meet the 5th indicator and present, in addition, a percentage of vulnerable population higher than 150% of the average value of the evaluated
region (6th indicator). Thus, 10 census sections are identified as L2 (in red), located in Bilbao (7 of them, in three districts: Otxarkoaga, Santurtxu and Bilbao la Vieja –see Fig. 11, right), Santurtzi, Barakaldo and Erandio, and the other 81 are identified as L1 (in orange).

4.4. Global vulnerability index in Greater Bilbao

The global vulnerability index in Greater Bilbao, based on the previously presented partial indicators and categories, is depicted in Fig. 12, while the main figures are summarised in Table 2.

In all, 93,000 people (almost 11% of Greater Bilbao’s population) and almost 49,500 dwellings, present a certain degree of energy vulnerability. As previously pointed out, practically all the vulnerable areas are located in the municipality of Bilbao or in municipalities located on the left bank of the river (79 out of the 89 census sections identified), and the ratio is even higher when focusing on the highest vulnerability levels (moderate, severe and critical). In such a case, only 1 of the 28 census sections detected is not located in Bilbao or in a municipality on the left bank.

In short, following the criteria defined in section 2.7.4, 14 census sections present the highest level of vulnerability (in red), 5 of those 14 being critical. These census sections can be gathered into 9 areas, two in a “critical level of vulnerability”, and seven considered to be in a “severe level of vulnerability”. This means that 14,342 people (1.68% of the region’s population) and 7120 dwellings might be in the highest level of vulnerability, and of these, 4669 people live in areas identified as having a critical level of vulnerability.

Some general trends can be identified when the indicators obtained in vulnerable areas are analysed. In Fig. 13, the main indicators corresponding to the census sections identified as having critical or severe levels of vulnerability are plotted in two radar charts, where each indicator is represented in relation to the maximum value identified in the region evaluated. It can be seen that, in the case of those areas with a severe level of vulnerability (left), there is a general trend where those indicators related to the building features (I2A: Building age; I2B: Energy label and I3: Buildings with no heating system) play an important role in determining the level of vulnerability. In fact, with the exception of Bilbao-Santutxu and Erandio-Alzaga, the rest of the areas range between 89% and 100% of the maximum value of indicator I2A, between 71% and 89% in I2B and between 52% and 70% in I3. As far as indicator I4 (energy expenses) is concerned, the results are significantly conditioned by the value from the San Juan District (Santurtzi), the maximum of the region, reaching 20.19% of dwellings with a calculated PE consumption value higher than 2M. However, it should be noted that, with the exception of Barakaldo-Beurko, the remaining identified areas present values significantly higher than the average value of the region (0.74%), ranging from 2.25% (Barakaldo-Zuatzu) to the already mentioned 20.19% in Santurtzi-San Juan.

In contrast, none of the areas with a severe level of vulnerability present high indices when socio-economic indicators are considered (I5: household incomes; and I6: population age). In fact, none of them exceed the threshold associated with the percentage of population older than 65 (37.1%, as presented in section 4.3), ranging between 11.14% and 25.48% in those areas with severe levels of vulnerability, and between 13.95% and 23.82% when the focus is on those areas with a critical level of vulnerability (right). In the case of I5, it should be noted that, as happened with I4, the results presented in the chart are conditioned by the maximum value of 57.7% of people with incomes lower than 60% of the median. However, it should be noted that this indicator ranges between 17.5% and 38.6% in those areas with a severe level of vulnerability (all over the average of the census sections values, 15.34%). In any case, indicator I5 stands out in those areas with a critical vulnerability level, which is coherent with the fact that those areas present an overlap with the areas identified by the atlas of deprived...
neighbourhoods, presented in section 2.1. Additionally, when other socioeconomic indicators are considered, such as unemployment rates (which, to some extent, is indirectly considered, since it has a direct effect on household incomes), a link between them and energy vulnerability can be observed. In fact, such municipalities as Sestao or Sanurtzi present the highest unemployment rates of the region (15.65% and 13.95% respectively, against 8.15% in Getxo, for instance). This link has also been pointed by other authors (e.g., (Dagoumas, 2014)).

Furthermore, some general data about the areas identified with severe or critical vulnerability risk are collected in Appendix B. Even though it is difficult to draw an inference concerning the relationship between building age or urban morphology and the vulnerability level, there are some common features in the majority of the areas identified. All of them, with the exception of Santutxu in Bilbao, are urban developments constructed in the second industrialisation (1950s and 60s): Sestao-Txabarri in 1947-1950, Barakaldo-Beurko in 1958, and Bilbao-
Masustegi, Santurtzi-San Juan, Bilbao-Otxarkoaga, or Bilbao-Errekakalde in the 60s. As far as the typology is concerned, several trends can also be observed. Even if the identified areas are heterogeneous in terms of occupation, all of them present apartment sizes significantly smaller than the average in the region (84.83 m²), giving as a result an average value of area per inhabitant significantly lower than the region’s average (average area per occupant in the region evaluated is 42.60 m²/inhab.). Additionally, the majority of the cases correspond to multi-storey buildings, with more than 4 floors and, in some cases, with accessibility barriers (even though different actions to reduce these barriers have been taken in recent years). Bilbao-Santutxu (a new urban development from the 2000s), together with Bilbao-Masustegi (single-family buildings, which started as a shantytown on the outskirts of the urban area of Bilbao, in many cases self-constructed by inhabitants in the 1950s), also make a difference in this aspect. It can also be observed that, in the region evaluated, results do not show a clear trend when urban density in relation to the buildings’ access to sunlight is considered; nevertheless, in some cases, identified areas present high densities with important limitations to access to sunlight in some apartments (Bilbao – Zorroza, Barakaldo – Rontegi, Barakaldo – Beurko, Barakaldo – Zuatzu, Bilbao – Rekalde, Santurtzi – San Juan or Sestao – Txabarri) while others

<table>
<thead>
<tr>
<th>Table 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summary of the global energy vulnerability levels identified.</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Number of census sections</td>
</tr>
<tr>
<td>Total population (%)</td>
</tr>
<tr>
<td>Total dwellings (%)</td>
</tr>
<tr>
<td>Total buildings (%)</td>
</tr>
</tbody>
</table>

Fig. 11. Socio-economic indicator: region (left) and the municipality of Bilbao in detail (right).

Fig. 12. Global energy vulnerability results: region (left) and the municipality of Bilbao in detail (right).
do not share this characteristic (Bilbao – Otxarkoaga, Bilbao – Santutxu, Bilbao – Masustegi or Erandio – Altzaga).

Finally, some general considerations can be observed regarding the policy implications. A clear relationship between energy vulnerability and buildings’ features is observed, especially when the age of the building stock and the potential for improving its energy performance is considered. In this sense, the energy renovation of buildings may have a positive impact on the reduction in energy vulnerability, thus linking energy poverty mitigation and climate policies in the EU. However, as some authors point out, focusing only on strategies based on retrofitting buildings’ envelopes overlooks the multidimensionality of energy poverty situations, and it should also involve actions aimed at implementing renewable energy installations (Desvallées, 2022) and strategies to facilitate access to and affordability of the energy resources required to meet the household’s basic needs, such as flexibility or energy communities (even though some authors note the necessity of carefully evaluating this sort of innovative solutions (Bouzarovski et al., 2021)). However, as results obtained in this case study show, public policies should address energy vulnerability in a comprehensive way, considering all its causes all together. In this sense, the socioeconomic dimension also plays a key role (including behavioural issues), in such a way that it should also be targeted in public policies. This fact is in line with previous studies, such as Streimikiene et al. (2020).

5. Conclusions and future works

This work has focused on proposing a simple method to identify energy vulnerable areas based on information available in public databases, periodically updated with the aim of enabling the monitoring of the evolution of energy vulnerability for a period of time at regional level, and that can be easily applicable to different regions and contexts. The proposed method takes into consideration three dimensions for evaluating this vulnerability: the focus is put on building features and energy expenses, and they are complemented with two socio-economic indicators.

The method has been applied to evaluating the energy vulnerability of a region, namely Greater Bilbao, located in the north of the Iberian Peninsula. The public data used are periodically updated (monthly in some cases, yearly in others), so that the evolution of vulnerability levels could also be evaluated, and the effect of potential measures implemented analysed. The application of the methodology to the case-study has allowed identifying different levels of vulnerability in more than 10% of the census sections evaluated, where 11% of Greater Bilbao’s population lives, and of these, 14 census sections are identified with severe or critical levels of vulnerability. A geographical pattern is clearly identified, the majority of the areas being located in the municipality of Bilbao or in municipalities located on the left bank.

Concerning the indicators used, the information related to the building age is easily accessible through Spain’s cadastres, and it is used by several studies to determine, through archetypes with different levels of complexity, the energy performance of the building stock. In this case, the proposal is to complement buildings’ age with the information provided by EPCs. As can be seen, EPCs have an important potential as a source for determining the building stock’s energy features, and they appear as a key data source for evaluating energy vulnerability and fuel poverty at a regional level. They are mandatory, the databases should be public and accessible, and include not only aggregated information about PE consumption or carbon dioxide emissions, but also be disaggregated by energy use and include information about energy systems. However, some issues still need to be addressed in this regard. In the case of Spain, the implementation, control and register of EPCs is managed by each autonomous region, in such a way that there are 17 registers of EPCs, with different levels of accessibility and detail of data provided. Similarly, control procedures differ depending on the autonomous region, and this may influence the reliability of the values presented in EPCs, and therefore varying depending on the region where the analysis is carried out. Additionally, some incoherencies can also be found in EPCs (e.g., a building or apartment with more than one EPC,
Table 3
Indicators and other general data about the areas identified with severe or critical vulnerability risk (source of pictures: bing maps).

<table>
<thead>
<tr>
<th>Area</th>
<th>Vulnerability level</th>
<th>Census section(s)</th>
<th>Total population</th>
<th>Number of buildings</th>
<th>Number of dwellings</th>
<th>Occupants per dwelling</th>
<th>Average area of dwellings</th>
<th>area/occupant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bilbao - Otarteaga</td>
<td>Critical</td>
<td>4802000009, 480200001, 480200003</td>
<td>2756</td>
<td>91</td>
<td>1316</td>
<td>2.10</td>
<td>63.57 m²</td>
<td>30.24 m²/person</td>
</tr>
<tr>
<td>Bilbao - Zorrotza</td>
<td>Critical</td>
<td>4802000006</td>
<td>936</td>
<td>49</td>
<td>468</td>
<td>2.09</td>
<td>62.50 m²</td>
<td>29.59 m²/person</td>
</tr>
<tr>
<td>Barakaldo - Rontagi</td>
<td>Critical</td>
<td>4802000003</td>
<td>827</td>
<td>33</td>
<td>459</td>
<td>2.02</td>
<td>67.68 m²</td>
<td>33.30 m²/person</td>
</tr>
</tbody>
</table>

(continued on next page)
Table 3 (continued)

Barakaldo - Beurko

Vulnerability level: Severe
Census section(s): 4800104003
Total population: 752 inhab.
Number of buildings: 41
Number of dwellings: 374
Occupants per dwelling: 2.01
Average area of dwellings: 65.82 m²
area/occupant: 32.74 m²/person

Barakaldo - Zuatzu

Vulnerability level: Severe
Census section(s): 4803506007
Total population: 1,396 inhab.
Number of buildings: 48
Number of dwellings: 513
Occupants per dwelling: 2.24
Average area of dwellings: 73.08 m²
area/occupant: 32.62 m²/person

Bilbao - Errekale

Vulnerability level: Severe
Census section(s): 4802507034, 4802007037
Total population: 1,851 inhab.
Number of buildings: 92
Number of dwellings: 822
Occupants per dwelling: 2.35
Average area of dwellings: 59.93 m²
area/occupant: 26.64 m²/person

(continued on next page)
Table 3 (continued)

Bilbao - Masustegi

Vulnerability level: Severe
Census section(s): 48020080212
Total population: 1506 inhab.
Number of buildings: 304
Number of Dwellings: 856
Occupants per dwelling: 1.76
Average area of dwellings: 59.64 m²
area/occupant: 33.89 m²/person

Bilbao - Santutxu

Vulnerability level: Severe
Census section(s): 48020040215
Total population: 1058 inhab.
Number of buildings: 30
Number of Dwellings: 563
Occupants per dwelling: 1.88
Average area of dwellings: 73.37 m²
area/occupant: 39.63 m²/person

Erando - Altzaga

Vulnerability level: Severe
Census section(s): 48020030305
Total population: 973 inhab.
Number of buildings: 29
Number of Dwellings: 472
Occupants per dwelling: 2.09
Average area of dwellings: 73.68 m²
area/occupant: 25.48 m²/person

(continued on next page)
presenting the most recent rating lower than the previous EPC). In any case, the amount of information collected in certificates and the calculation procedure applied, as well as the amount of certificates available currently (which is continuously increasing) make EPCs a tool with a great potential for determining the energy performance of buildings, and therefore, for use as a significant indicator to evaluate energy vulnerability on a regional scale. In fact, in some Spanish regions, EPC databases already provide more detailed information, regarding the energy demand by use or the energy systems existing in the building. In this sense, the improvement of the data provided by EPCs (both in terms of level of detail and of accuracy and reliability) would be an ally to overcoming some of the limitations of the proposed method. Further analysis of the implementation of EPCs (in the case of Spain, also mandatory for existing buildings since 10 years ago) is recommended in this regard.

Finally, socio-economic indicators complement the information for determining the vulnerability level, and help to categorise and prioritise the most vulnerable areas. Even though the analysis presented in this paper is mainly focused on the energy performance of buildings, fuel poverty is also intrinsically linked to socio-economic issues. The detailed analysis of socio-economic issues is beyond the scope of this study, and, as presented in the first section, vulnerability maps are being developed by different public administrations (two examples are the aforementioned Atlas of Deprived Neighbourhoods in Spain, or the analysis of Vulnerable Areas in the Basque Country, where a set of several indicators are evaluated in detail). In this case, this dimension is proposed for consideration by including two single indicators, while exploring the possibilities of integrating the outcomes of these analyses into energy vulnerability studies is also identified as future work.

**Declaration of Competing Interest**

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

**Data Availability**

Supplementary data related to this article can be found online at https://data.mendeley.com/datasets/3hy8mmvnn , and open-source online data repository hosted at Mendeley Data Multidimensional procedure for mapping and monitoring urban energy vulnerability at regional level using public data: proposal and implementation into a case study in Spain - ASSOCIATE DATA (Original data) (Mendeley Data)

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Appendix

Table 3

References


