Energy Research & Social Science 109 (2024) 103426

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Original research article

Inclusivity in urban energy transitions: A methodological approach for mapping gendered energy vulnerability

Nayely B. Capetillo-Ordaz [a,b], Fernando Martín-Consuegra [a], Carmen Alonso [a], Jon Terés-Zubiaga [b,*], Sesil Koutra [c]

[a] Institute of Construction Sciences Eduardo Torroja (IETcc), Spanish National Research Council (CSIC), Serrano Galvache 4, 28033 Madrid, Spain

[b] 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

[c] Faculty of Architecture and Urban Planning, University of Mons, Rue d'Havre 88, 7000 Mons, Belgium

ARTICLE INFO

Keywords:
Energy poverty
Energy vulnerability
Gender-responsive indicators
Mapping
GIS
Open data
Spatial analysis
Women

ABSTRACT

Energy poverty has become a notable concern within the European Union (EU), with adverse implications for the well-being and social inclusion of susceptible populations, particularly women. Despite an increasing focus on gender perspectives in the context of the energy transition in recent years, the assessment of the geographical distribution of energy vulnerability remains *gender-blind*.

This paper introduces a simplified method for mapping gendered energy-vulnerable areas through a gender-responsive index. The proposed method enlightens the potential use of open-access data for evaluating energy vulnerability from a gender perspective. Additionally, the methodology cross-references previous energy poverty assessments to identify matching cases of gendered energy vulnerability, resulting in the Gendered Energy Vulnerability Index (GEVI). The GEVI enables the classification of areas based on their risk of experiencing gendered energy vulnerability.

To illustrate the method, it is applied to the evaluation of a case study of Madrid, Spain. Findings estimate that 42 neighborhoods, representing 32 % of the total in the city, might be at risk of facing gendered energy vulnerability, with a pronounced impact on elderly women, single-parent households led by women, and women engaged in part-time employment or elementary occupations. The study also identifies specific spatial patterns and correlations within the city.

1. Introduction

Access to dependable and appropriate energy services is critical for maintaining a good standard of living [1]. However, according to the European Parliamentary Research Service [2], in 2020, an estimated 36 million Europeans faced challenges securing the energy required to satisfy their basic needs. This phenomenon, known as energy poverty, has far-reaching consequences on health, social integration, financial difficulties, and overall reduced quality of life [3].

Energy poverty, driven by limited economic resources, high energy expenses, and inefficient housing, is influenced by a combination of factors, such as climate change, economic crises, energy transition policies, housing and labor market shifts, and spatial disparities [4]. Even though rural areas may, in several cases, present a higher prevalence of energy poverty due to the energy performance of the building stock [5], these spatial disparities are more prevalent in urban settings, influenced by fluctuations in income levels, service distribution, demographics, migration trends, and built environments [6].

A related term introduced in recent studies is *energy vulnerability,* defined as *"the propensity of an individual to become incapable of securing a*

Abbreviations: CNIG, Spanish National Centre for Geographic Information; CSIC, Spanish National Research Council; CSV, Comma-separated values; DN, Deprived Neighborhoods; EP, Energy poverty; EPI, Energy Poverty Index; EV, Energy vulnerability; FP, Fuel poverty; GIS, Geographic Information Systems; GEVI, Gendered Energy Vulnerability Index; GGI, Gender Gap Index; GVA, Gender-Vulnerable Areas; IE, Institute of Statistics of the Community of Madrid; IETcc, Eduardo Torroja Institute for Construction Sciences; IMPE, Multidimensional Index of Fuel Poverty; INE, Statistics National Institute; MITMA, Ministry of Transport, Mobility and Urban Agenda; SDG, Sustainable Development Goals; SHP, Shapefile; UHI, Urban Heat Island; UK, United Kingdom; VN, Vulnerable Neighborhoods.

* Corresponding author.
E-mail address: jon.teres@ehu.eus (J. Terés-Zubiaga).

https://doi.org/10.1016/j.erss.2024.103426
Received 25 October 2023; Received in revised form 2 January 2024; Accepted 14 January 2024
Available online 28 January 2024

materially and socially needed level of energy service in the home" [7]. Energy vulnerability acknowledges factors within households contributing to individuals' inability to secure their required energy needs, including specific demographics, such as ethnicity, age, and gender [8]; household composition, including lone-parent or socially isolated families [9]; and socio-economic factors, such as unemployment, part-time employment, limited education, or full-time students [10].

While tackling the multifaceted issue of community marginalization requires action on different drivers and causes, addressing energy poverty may play a role in preventing the exclusion of vulnerable communities in the context of the energy transition, as underscored by the United Nations Sustainable Development Goal (SDG) 7 [11] and the dedication of the European Union to achieving climate neutrality by 2050 [12]. Several measures have been developed in recent years along these lines, such as the Fit for 55 package [13], and the Clean energy for all Europeans package [14]. Specifically in Spain, the Constitutional Act 15/2018 called for national strategies against energy poverty, resulting in the establishment of the "National Strategy Against Energy Poverty 2019-2024" [15] and the "2020 Update of the Long-Term Strategy for Energy Renovation in the Building Sector in Spain" [5], among other national strategies.

Moreover, this heightened awareness has extended to scientific publications, evident in the increasing number of studies related to "*energy poverty*", "*fuel poverty*",[1] and *"energy vulnerability"* over the past two decades, as indicated by Scopus search results [18]. This growing trend reached 2010 publications by the end of 2022, as illustrated in Fig. 1. Additionally, this surge in awareness has prompted researchers to turn to multidimensional indices and Geographic Information Systems (GIS) for estimating and visualizing the distribution of energy-vulnerable areas at different scales [19,20], as a measure to contribute to the alleviation and informed understanding of energy vulnerability.

1.1. Gender-blindness in energy vulnerability

Gender, a socially constructed concept [21], has been widely studied in various fields, such as urban planning [22], mobility [23], and climate change [24]. In the context of energy transition, gender plays a pivotal factor in determining energy consumption patterns [25], since gender roles can significantly influence household energy management [26], with women frequently bearing this responsibility [27] and often serving as primary users, though their energy use may be predominantly allocated to household chores rather than personal needs or comfort [28,29].

Moreover, household dynamics, schedules, and caretaking chores may also become factors for aggravating gendered energy vulnerability [28,29]. For instance, women, on average, spend more time at home alone during the daytime [27] and, particularly in vulnerable groups, they may abstain from using heating systems to prevail in its usage while other family members are at home, aiming to increase savings [26]. Despite these efforts, women may encounter obstacles, including restricted access to energy-efficient appliances or modern energy services, attributable to such factors as knowledge gaps, lower incomes due to the gender pay gap, or unpaid caregiving responsibilities [30].

In light of the increasing interest in energy vulnerability in Europe, *gender-blindness,* defined as "*the inability to recognize distinct gender roles, needs, and responsibilities of women and men*" [31], unintentionally persists in the context of the energy transition [27], with a notable disparity in approaches that integrate the gender perspective [8]. For example, Fig. 2 illustrates a limited number of studies addressing gendered energy vulnerability in Scopus research compared to Fig. 1. Furthermore, these studies primarily focus on conceptualizing the phenomenon [21,30], examining energy policies [27,32], and exploring lived experiences [33,34], leaving a gap in the estimation and characterization of the theoretical number of households facing gendered energy vulnerability [8]. This gap arises mainly since data related to energy consumption are typically aggregated at the household level [8], presuming an equal allocation of resources and treating households as homogeneous entities [27,35]. Moreover, such data are often unavailable at the region or city level or inaccessible through open databases.

Consequently, there is a need for research that seeks to identify the spatial aspects of gendered energy vulnerability [8] and its potential unequal distribution [26] for women and men, leveraging open-access data to facilitate easy updates and extrapolation to different contexts [17]. Such a proposal holds the potential to bring value to policy and practice by identifying and categorizing gendered energy-vulnerable areas, enabling decision-makers to prioritize regions that demand thorough analysis and, subsequently, necessitate more targeted interventions within the energy sector [8,33].

1.2. Aim of the study

This study aims to develop a method for assessing and visualizing gendered energy-vulnerable areas, for both women and men, using currently available demographic and socio-economic disaggregated data. To achieve this, the secondary objectives include: *i)* identifying and deriving gender-responsive indicators from the literature review; *ii)* determining the overall energy vulnerability distribution, as well as its distribution across women and men; and *iii)* establishing a Gendered Energy Vulnerability Index (GEVI) to classify areas based on their risk of experiencing gendered energy vulnerability.

The originality of the research lies in several aspects. Firstly, it primarily leverages disaggregated geographic data from open-access sources, allowing for easy monitoring, regular updates, and replicability in various contexts due to the consistent updating of public databases. Secondly, it adopts a mixed-method approach, combining statistical and spatial analyses. This combination not only facilitates the identification and better understanding of gender-vulnerable clusters, but also enables the exploration of potential disparities among vulnerable groups without presuming gender differences. Thirdly, the study is conducted at the neighborhood scale, chosen for its optimal balance between spatial detail and statistical accuracy in spatial analysis. This scale is preferred over district-level mapping, considering the potential impact of significant variations in district sizes on statistical accuracy during local research. Lastly, the study further incorporates the energy poverty dimension derived from previous assessments, strengthening the reliability of the results in quantifying gendered energy vulnerability.

Thus, the paper unfolds as follows. After the introduction and presentation of motivations, Section 2 offers a concise literature review encompassing definitions, driving factors, and gender perspectives regarding energy vulnerability. Section 3 presents the proposed methodology designed to visualize and evaluate gender-specific energy vulnerability. Moving to Section 4, the paper implements the developed methodology in a case study set in Madrid, Spain, to illustrate its capabilities and constraints. Section 5 presents the obtained results and engages in discussions, while the paper draws its conclusions in Section 6.

2. State-of-the-art

It should be noted that there is no global definition for the concept of *energy poverty*, nor is there one single indicator for quantifying it, while indicators and methodologies proposed in the literature to identify it are assorted. By way of example, Castaño-Rosa et al. carried out a comprehensive review of the current concepts and indicators of energy poverty, which can be considered an example of the diversity of understanding of this concept across Europe [4].

[1] The Spanish term *pobreza energética* includes both *energy poverty* and *fuel poverty* concepts, despite their differences, as emphasized by Martín-Consuegra et al. [16] and Terés-Zubiaga et al. [17].

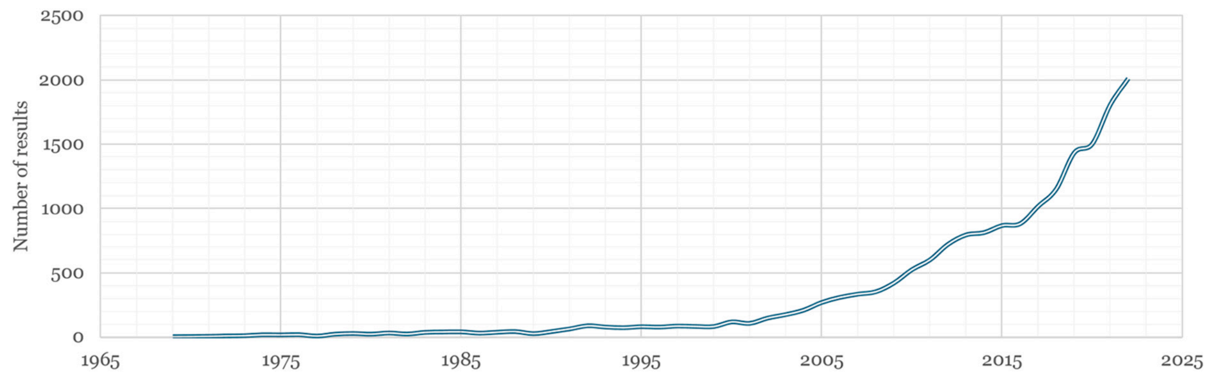

Fig. 1. Number of publications in Scopus by year from 1969 to 2022 (n = 17,704) matching keywords "*energy poverty*" or "*fuel poverty*" or "*energy vulnerability*" (source: authors' elaboration based on [18]).

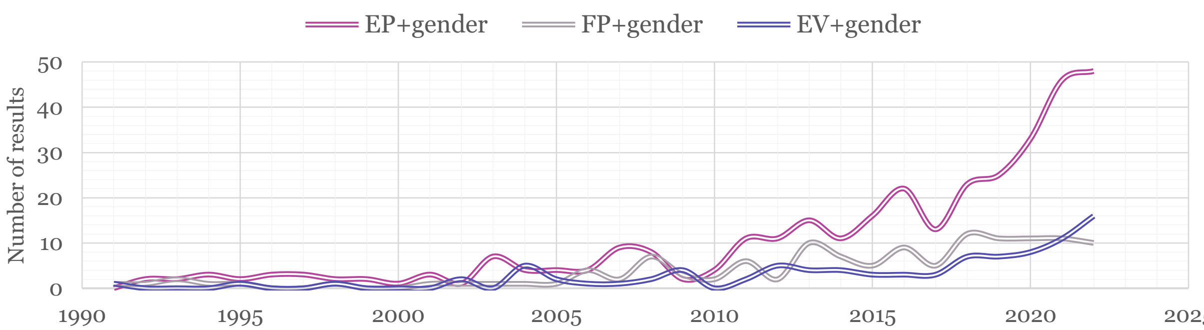

Fig. 2. Number of publications in Scopus by year from 1990 to 2022 (source: authors' elaboration based on [18]).

Other recent works outside of Europe can also be found in this regard, such as the research piece carried out by Guevara et al., who presented an extensive systematic literature review of energy poverty and related terms since the 1970s up to the year 2020, focusing on theoretical and methodological contributions [36]. Additionally, the work developed by Chang and Delina in [37] is relevant for exploring the dichotomy in the understanding of energy poverty between Asia and the rest of the world, especially in the Global North, through a detailed review of energy poverty studies in Asia, using bibliometric analysis to identify emerging discussions and researchers.

Turning back to the European Union, the European Commission [38] describes energy poverty as "*a household's lack of access to essential energy services that underpin a decent standard of living and health, including adequate warmth, cooling, lighting, and energy to power appliances, in the relevant national context, existing social policy and other relevant policies.*" This concept was first presented in the United Kingdom (UK) under the term *fuel poverty,* during the 1973 oil crisis, when low-income households struggled to afford enough heat indoors [39]. Subsequently, the UK government operationalized *fuel poverty* as spending over 10 % of income on fuel to ensure adequate warmth [40], based on the definition given by Boardman [41] in 1991.

In understanding the causes of energy poverty, key factors include limited economic resources, high-energy expenses, and energy-inefficient housing [38]. Pye and Dobbins [42] note that the interaction of these factors defines areas where energy poverty indicators can be measured. For instance, the low energy efficiency of a building may be linked to its heating system, leading to higher energy bills for the household [16]. Moreover, low-income households, especially renters, may be less inclined to invest in energy efficiency upgrades [43]. In this line, low-income plays a critical role in driving energy poverty [44], which can be caused by multiple factors, such as low salaries, job instability, minimal social welfare, large households, or severe illnesses [45–47]. These challenges are notably observed in Southern European countries due to their high rates of unemployment and in-work poverty [48]. In 2022, Greece and Spain reported some of the highest percentages of people at risk of poverty or social exclusion in Europe [49].

However, a vast body of literature, such as Stojilovska [50] or Feenstra and Clancy [51], has emphasized the adverse repercussions of confining energy poverty to just the aforementioned drivers. Recognizing energy poverty as a systemic issue [52], it becomes evident that such factors as lived experience [9], climate change [53], spatial variations [19], and territorial disparities [45] increase the risk of experiencing it.

Notably, the role of gender in the context of energy vulnerability has been highlighted by some researchers, such as Petrova and Simcock, who noted that women and men encounter energy poverty differently, both in terms of "*household practices of responding to and resisting energy poverty*", as well as "*the emotional labor of living in and responding to the lack of adequate energy services in the home*" [54]. The European Parliament [55] also recognizes that "*women and women-led households appear to be disproportionately affected by energy poverty due to structural inequalities in income distribution, socioeconomic status and the gender care gap.*"

Traditionally, energy poverty measurement relies on techno-economic metrics, mainly related to the *affordability* of energy [56], using either *objective* or *subjective* indicators [57]. Frequently used *objective* indicators include the 10 % indicator [41], the Low Income High Cost [58], and the Minimum Income Standard [59,60]. In European studies, *subjective* indicators are gaining preference as they capture broader aspects of energy poverty, including social inclusion, material deprivation, and the perceived impacts of living in energy poverty [61,62]. The Survey on Income and Living Conditions [63] is commonly used, incorporating such indicators as the inability to keep the home adequately warm, arrears on utility bills, and population living in a dwelling with a leaking roof, damp walls, floors, or foundation.

However, these indicators face limitations due to the lack of disaggregated data on energy poverty across different groups [55]. As highlighted by The Gender Dimension and Impact of the Fit for 55 Package report [64], this limitation leads to a failure to "*identify unequal power relations at all levels in society*" adversely affecting the ability of such groups to react to measures and policy interventions. Moreover, the lack of disaggregated data makes it difficult to discern the nature of energy poverty and develop appropriate interventions, "*both in terms of what is addressed and its mechanisms of delivery*." [64].

2.1. Energy vulnerability from a socio-spatial perspective

Vulnerability is defined as the level of susceptibility to pressures and challenges that are not adequately countered, ultimately leading to a general deterioration in overall well-being [65]. Social vulnerability pertains to the susceptibility of individuals or communities to adverse impacts influenced by demographics, socio-economic status, and access to resources [43,66]. It varies across fields, for instance, in the context of health, vulnerable populations encompass individuals with compromised immune systems, such as the elderly, and those lacking access to medical care, making them more susceptible to the detrimental effects of low temperatures [67]. Similarly, vulnerable populations in urban planning may be located in coastal areas or slums, leaving them subject to such climate change effects as flooding, and urban heat island effects [68]. Social vulnerability is further compounded by numerous factors, including inadequate infrastructure, limited resources, and social marginalization [68].

Socio-spatial vulnerability refers to the susceptibility of various geographic areas, such as regions, cities, neighborhoods, or urban environments, to risks stemming from a range of dynamics, events, and impacts. These risks can be either sudden shocks or gradual changes driven by various factors such as political, environmental, or economic influences [69]. This concept considers the complex interplay of location, time, individual, social, and environmental factors, and serves as a valuable tool for creating a geographical representation of the extent to which external events can potentially lead to declines in overall well-being [70].

When intersected with energy vulnerability, socio-spatial energy vulnerability recognizes the temporal unpredictability of energy poverty, as households experience income fluctuations and variations in energy service quality, influenced by demographic, socio-economic, and technical factors [71]. Moreover, it highlights the unequal geographical distribution of energy resources and the disproportionate impacts faced by marginalized groups [22]. This perspective acknowledges the intricate interplay between social factors and spatial dynamics that shape vulnerability, including income levels, housing conditions, geographic location, and social inequalities [43]. These different levels are schematically depicted in Fig. 3.

Quantitative spatial analyses can complement qualitative assessments by addressing potential biases influencing perceptions of vulnerability, as it sheds light on the intricate interplay between individuals, their needs, the built environment, socio-economic aspects, and climate conditions by geographically pinpointing the prevalence and manifestations of energy vulnerability [72].

2.1.1. Energy vulnerability factors

Factors associated with energy vulnerability encompass sociodemographic characteristics, such as social aid recipients and renters; health-related vulnerabilities, including the elderly, those severely ill, children, and pregnant women; household composition, such as single parents and large families; energy literacy; and cultural factors [73]. Additionally, energy vulnerability tends to affect individuals with low-incomes, particularly such vulnerable groups as disabled individuals and migrants, as well as those engaged in part-time employment and individuals with limited educational attainment [10].

Living in energy vulnerability can have substantial repercussions on health and overall well-being [74]. For instance, vulnerable groups, especially those with chronic and severe conditions such as cardiovascular diseases, pulmonary restrictions, and asthma, are at a higher risk of excess winter mortality [75], attributed to low thermal efficiency dwellings [76]. Counterintuitively, Southern European countries face higher climatological issues that contribute to energy vulnerability, despite their warmer climates [7]. For instance, a study [77] showed that between 2002 and 2011, Malta, Portugal, and Spain had significantly higher rates of excess winter mortality compared to other Member States. Furthermore, energy vulnerability is also linked to increasing summer mortality rates due to climate change [78]. Rising temperatures lead to an increased demand for cooling systems [52,79]. Sánchez-Guevara et al. [80] explained in their study, conducted in Madrid and

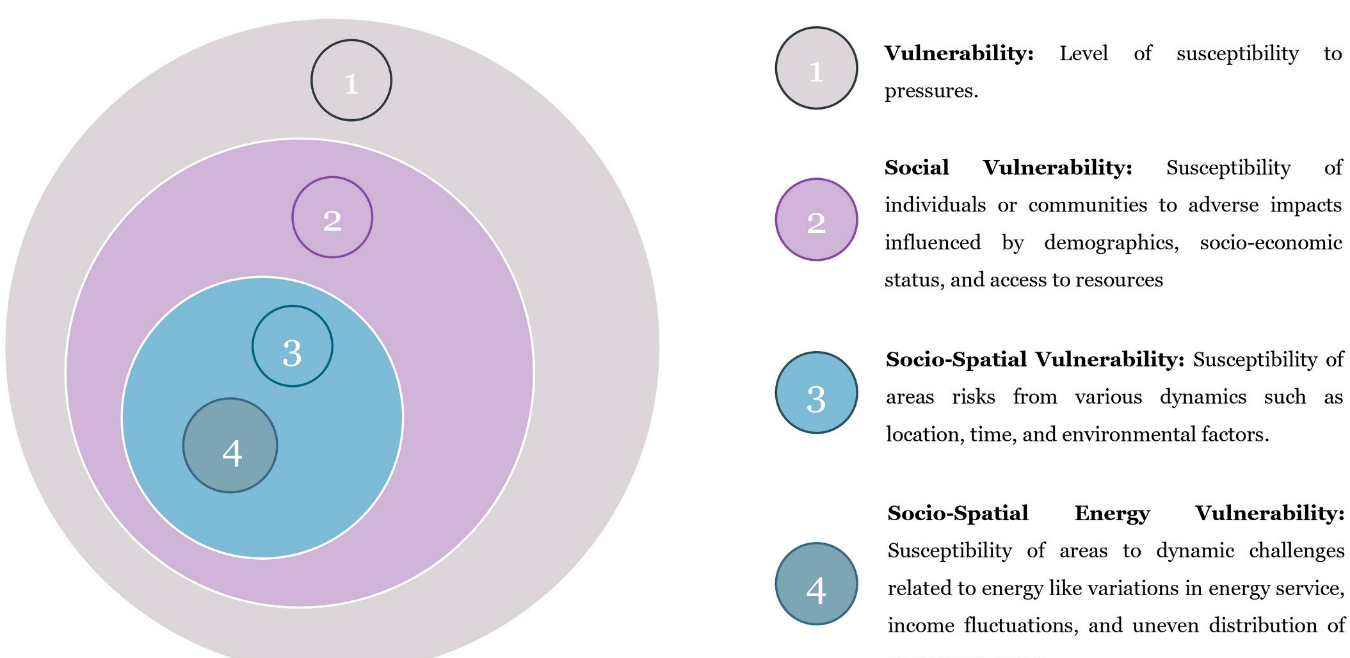

Fig. 3. Relationships between the different levels of (energy) vulnerability from a socio-spatial perspective (authors' elaboration).

London, that low indoor temperatures at night and high outdoor temperatures during the day can result in greater levels of heat stress, especially during heatwaves. This poses a significant challenge for low-income households, particularly for the elderly, pensioners, caregivers, or people with disabilities, as they face a dual challenge during hot weather [80,81].

Energy vulnerability also impacts mental health, as individuals facing financial concerns often experience elevated levels of anxiety and other stress-related issues [82]. Moreover, a lack of adequate energy services in the household can result in marginalization, strained relationships with landlords and energy providers, discrimination, and stigma [9].

2.2. Gender perspectives on energy vulnerability

As highlighted by UN Women and UNIDO [83] and The 2030 Agenda for Sustainable Development [11], achieving gender equality is crucial for progress across all goals and targets, as well as for ensuring that all communities and social groups benefit from a just, sustainable, and inclusive energy transition.

In Europe, dedicated initiatives are focused on advancing gender equality within the energy industry. For instance, the Clean energy for all Europeans package [14] prioritizes the involvement and leadership of women in the sector, while the European Institute for Gender Equality [84] supports gender equality integration in research and data collection. Simultaneously, SDG 5 [11] reinforces the importance of ending discrimination, promoting economic empowerment, and ensuring equal access to resources and opportunities for women and girls. Additionally, within academia, an expanding body of studies on gender perspectives in energy vulnerability is arising, examining areas such as policy-making [27], geographical distribution [8,26], and lived experiences [33,54].

In the national context, Spain has emerged as a leader in equality policies. The establishment of the first Ministry of Equality in 2008 [85] marked a significant step, becoming a crucial pillar in the development of social rights and the fight against discrimination. Another milestone for gender equality policy was the approval of Organic Law 3/2007, the Equality Law, which formalizes the institutionalization of gender mainstreaming by requiring *"public administrations to mainstream gender in the adoption, implementation, and budgeting of all policies"* [85]. Furthermore, Spain has been at the forefront of studies addressing the feminization of energy poverty, as evident in various research works [8,33,80,86–88].

Historically, discussions surrounding energy often omitted the gender dimension, operating under the assumption of equal access to resources, consumption patterns, and impacts on women, men, and households [27,30]. However, as emphasized by Feenstra [27], energy vulnerability exhibits a strong gender face exacerbated by different factors, which are encompassed in three interconnected dimensions. Firstly, the economic dimension reveals an overrepresentation of households headed by women with limited incomes, whether due to being single parents or their longer life expectancy compared to men, resulting in a significant portion living alone during their retirement years [27].

Secondly, in terms of the biological and physiological dimensions, age emerges as a key factor affecting vulnerability to heat and cold stress, especially for older and pregnant women [27]. Furthermore, women exhibit a higher sensitivity to temperature fluctuations compared to men [27]. Lastly, the socio-cultural dimension refers to the intricacies of energy requirements and consumption behaviors of women, which not only vary from men, but also manifest diversity among women. Additionally, such factors as civil and employment status are notable influencers of their energy consumption patterns [27].

Adopting a gender perspective in the context of energy vulnerability provides valuable insights into how gender influences access and affordability of energy resources, which further allows for an assessment of whether the energy transition equally benefits all genders and facilitates the identification of gender disparities [27,89].

Furthermore, gender cannot be understood in isolation, but is intricately intertwined with other social dimensions, such as ethnic background, health, and age [21,51]. The theory of *intersectionality* (originally conceptualized by Crenshaw [90]) offers a framework to explore how these social divisions intersect and contribute to disparities, enabling a more nuanced understanding of complex issues [91,92]. The interconnections between gender and energy vulnerability manifest in diverse forms of inequalities across different contexts and periods, and vary in their configuration and intensity [26,93], for instance, lone-parent households led by women, experiencing low-income, belonging to an ethnic minority group, and being in an older age bracket, face compounded vulnerabilities in accessing energy resources, surpassing the limitations faced by those under a single vulnerability group [94].

According to Robinson [26], women predominantly shoulder unpaid caregiving and domestic roles, which are often undervalued and underrepresented in policies [93]. This fact creates challenges, as lower-income women struggle to balance these responsibilities with earning a living, limiting their financial resources for energy expenses [41]. Simultaneously, gender segmentation in the labor market leads to women's exclusion from economic opportunities, resulting in part-time or precarious employment, lower wages, and financial instability, especially for lone-parents, who are predominantly women [26,95].

Additionally, inadequate social protection, particularly in older age, further contributes to women's energy vulnerability, with disparities in pensions and financial support linked to employment [96,97]. To cope with these challenges, women employ various strategies, such as reducing energy consumption and prioritizing their families' well-being over their own [98,99]; however, these personal coping mechanisms are often overlooked and not adequately captured by quantitative data [8,27].

In short, energy vulnerability is a pressing issue that affects numerous communities in Europe. While there is growing recognition of the phenomenon as a multidimensional problem, current research often falls short in providing a thorough exploration of its gender-related dimensions. Many studies primarily concentrate on overarching indicators, neglecting the aforementioned difficulties [26,51] encountered by individuals of different genders in diverse demographic and socio-economic groups. This knowledge gap, derived from the lack of analysis on how energy vulnerability affects individuals of different genders in different groups, highlights the need for a gendered nuanced analysis that incorporates gender-specific factors into its metrics, thereby informing gender inequalities and variations in its geographical distribution.

3. A methodological approach for engendering energy vulnerability

The proposed methodology consists of four stages. The initial stage, detailed in Section 3.2, centers on the derivation of gender-responsive indicators. Subsequently, the second stage, outlined in Section 3.3, focuses on preliminary assessments of energy vulnerability distribution. In the third stage, as described in Section 3.4, Gender-Vulnerable Areas (GVA) are identified, highlighting areas where women and men face intersectional vulnerabilities. Finally, the fourth stage, covered in Section 3.5, establishes the Gendered Energy Vulnerability Index (GEVI). The methodology workflow is summarized in Fig. 4.

3.1. Scale and unit of analysis

The method is conducted at the administrative-neighborhood scale, as it provides an optimal balance between spatial detail and statistical accuracy for spatial analysis, being able to combine available data and provide information to address actions at the neighborhood scale. This scale is preferred over district-level mapping, since the significant variation in district sizes can potentially affect statistical accuracy when

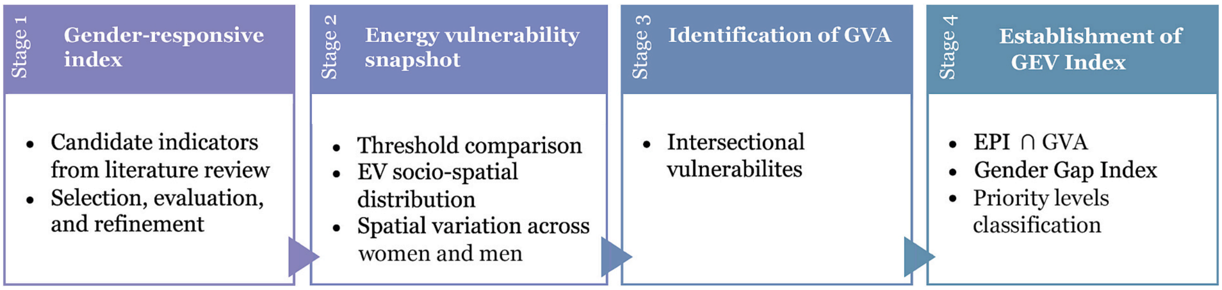

Fig. 4. Stages of the proposed methodology.

researching locally [100].

Additionally, the *individual* is set as the primary unit to ensure the accuracy and effectiveness of the study. As mentioned by Millar and Glendinning [35] and Robinson [26], using the *dwelling* as a unit oversees certain vulnerabilities by wrongly assuming equal resource allocation among family members. However, for the lone-parent indicator, as well as per the Vulnerable Neighborhoods [101] and the Deprived Neighborhoods [16] (Section 5.4), the *household* or *dwelling* is considered as the measurement unit. Moreover, to ensure the replicability of the method across different regions, the proposed index must be sourced from open datasets. Demographic and socio-economic variables are typically available through municipality databases and surveys conducted by national statistics agencies.

3.2. Stage 1: gender-responsive index

In the pursuit of developing a gender-responsive index to assess gendered energy vulnerability, seven representative indicators, classified into demographic and socio-economic dimensions, are selected from the literature review (Section 2). These chosen gender-responsive indicators have consistently been highlighted as important in assessing energy vulnerability across different contexts and meet the following criteria: availability with gender disaggregation for both women and men, suitability for individual-level assessment, reliance on open data sources, and accessibility at the chosen scale.

However, as clarified by Robinson [26], it should not be assumed that all individuals identified through this methodology will experience energy vulnerability. This is because the proposed gender-responsive index does not consider factors that could alleviate vulnerability, such as practical interventions or policy measures, and assigns equal weight to each indicator, without delving into the varying lived experiences and limitations associated with each indicator.

The gender-responsive index, as summarized in Table 1, comprises the elderly indicator, representing individuals over 75 years old who may face challenges related to limited income, health issues, and inadequate access to energy resources [102]. The ethnicity indicator acknowledges that individuals from migrant or refugee backgrounds may encounter additional vulnerabilities due to language barriers, limited social networks, precarious jobs, inability to access social benefits, and potential discrimination [66]. The disability indicator recognizes the unique challenges faced by individuals with any degree of disability or chronic illness, such as increased energy needs, limited mobility, and higher healthcare expenses [3].

The lone-parent indicator comprises individuals who are raising children on their own, and who may be facing financial constraints, lack of social support, and increased responsibilities [8,76]. Unemployed individuals are highlighted as vulnerable due to their current economic status, which leads to financial constraints [103]. Individuals with part-time employment face lower income levels and reduced access to employment benefits [66]. Finally, elementary occupations encompass individuals enrolled in low-remunerated jobs, which may provide limited opportunities for advancement, lower wages, and precarious working conditions [66].

Table 1
Summary of the gender-responsive index.

Dimension		Gender-responsive indicator	Parameter	Reference (s)
Demographic	1	Elderly	Woman/man; over 75 years	[102]
	2	Ethnicity	Woman/man; foreign nationality	[66]
	3	Disability	Woman/man; with day-to-day limited activity	[3]
	4	Lone-parent	Woman/man; lone-parent; dependent children	[8,76]
Socio-economic	5	Unemployment	Woman/man; 16–64 years; unemployed	[103]
	6	Part-time employment	Woman/man; 16–64 years; part-time employed	[66]
	7	Elementary occupation	Woman/man; 16–64 years; elementary occupation	[66]
Energy poverty	8	Energy Poverty Index (EPI)	Leverage on previous works; customized for different regions	[17]

Additionally, to incorporate the energy poverty dimension, the procedure draws on established methodologies that have adeptly assessed energy poverty through composite indices, such as dwelling stock's energy performance, households' energy consumption, average monthly income, and inadequate thermal facilities. Examples of such methodologies are found in such works as Horta et al. [104], Terés-Zubiaga et al. [17], and Fabbri and Gaspari [105]. In the context of this paper, this dimension is denoted as the Energy Poverty Index (EPI) and can be customized for different regions.

3.3. Stage 2: energy vulnerability snapshot (pre- and post-gender disaggregation)

In the second stage, two preliminary assessments are conducted to explore the socio-spatial distribution of energy vulnerability, one before gender disaggregation, and another across women and men. The objective is to investigate whether new patterns in the distribution of energy vulnerability emerge when indicators are derived from the total population and when a gender perspective (i.e., broken down by women and men) is incorporated into the metrics. This approach draws upon methodologies developed by Martín-Consuegra et al. [16] and Terés-Zubiaga et al. [17].

Initially, spatial demographic data are gathered from the most recent population survey or census conducted in the study area. Subsequently, these data are computed by establishing the ratio of individuals under each gender-responsive indicator to the total population of the area. For instance, the count of individuals aged 75 or more in each area is divided by the total population of that respective area. The resulting value is then compared to some proposed relative thresholds, with the aim of identifying the most vulnerable areas. The predetermined thresholds are set at 1.5 times (150 %), 1.75 times (175 %), twice (200 %), and more than twice (>200 %) the city average. This means that, if the average value of the whole region for a given indicator is 10 %, the first threshold will be defined at 15 % (1.5 times the average value), the second threshold will be 17.5 % (1.75 times the average), and the third one would be overpassed by those neighborhoods with a value higher than 20 % (two times the average). These reference values have been previously used in works such as [16,17].

Finally, GIS software, specifically QGIS,[2] is used to map the geographic distribution of the gender-responsive indicators. These maps not only help in identifying energy-vulnerable areas, but also utilize color coding based on the aforementioned thresholds to visually represent varying levels of energy vulnerability risk within the study area. This approach aids in recognizing clusters of vulnerability and can serve as a valuable resource for informing targeted interventions [16].

3.4. Stage 3: gender-vulnerable areas

In this stage, the aim is to illustrate the intersectionality of factors and their spatial distribution for women and men; specifically, to identify where two or more gender-responsive indicators intersect within the same area. Using the ratio values computed in the previous stage for women and men, areas exceeding the 150 % threshold under each indicator are assigned a score of 1. Finally, adding up the scores independently for women and men in each area establishes the Gender-Vulnerable Areas (GVA). The GVA serve multiple purposes. They provide information about the number of intersectional vulnerabilities present within the same area, along with potential correlations with the regional context. For instance, the coexistence of individuals from ethnic minorities, aged 75 or above, and lone-parent households—all concentrated in the east side of the region where salaries are lower compared to regional pay levels. Additionally, it facilitates comparisons to determine if energy vulnerability is equally distributed across both genders, identifying whether there is a higher number of GVA for women compared to men, or vice versa. Moreover, it allows the identification of which gender-responsive indicators are more prevalent in the region.

3.5. Stage 4: Gendered Energy Vulnerability Index

The final stage of the methodology focuses on characterizing and prioritizing areas where women may be facing gendered energy vulnerability, ultimately leading to the development of the Gendered Energy Vulnerability Index (GEVI). This process helps guide policymakers and practitioners to allocate more attention to these identified areas.

It starts by considering the city-level distribution of energy poverty, denoted as the Energy Poverty Index (EPI) as stated in Section 3.2, from previous works, which can be customized for other regions. Subsequently, the EPI is overlaid with the previously identified Gender-Vulnerable Areas (GVA) through GIS techniques, revealing where energy poverty and gender vulnerabilities intersect.

After identifying these areas, an evaluation is conducted to determine whether the gendered vulnerability is more pronounced for women or men. This evaluation utilizes the Gender Gap Index (GGI) from the Global Gender Gap Report 2022 [106], calculated by subtracting the GVA score for men from the GVA score for women in each area. A positive GGI denotes a higher vulnerability for women and a negative value implies a higher vulnerability for men, while a result of zero suggests an equal level of vulnerability for women and men.

Finally, the GGI is integrated with the EPI to establish the Gendered Energy Vulnerability Index (GEVI). The GEVI classifies areas where the women may be at risk of experiencing gendered energy vulnerability, determined by the presence of intersectional vulnerabilities within the same area. This index categorizes areas into four priority levels: *Mild priority*, *Moderate priority*, *Severe priority*, and *Critical priority*. The latter, also referred to as *hot spots,* indicates the highest level of susceptibility to gendered energy vulnerability, suggesting that a thorough analysis from researchers and policy makers should be conducted in these areas.

4. Case study: Madrid, Spain

The developed tool is showcased in a case study using Madrid as the focal point, illustrating its capabilities and constraints. Madrid is chosen, firstly within the national context, due to Spain's evolution in gender equality. There has been significant social change and an increasing consideration of gender equality as a political priority, leading to the development and consolidation of well-established policies devoted to promoting gender parity over the last three decades, both at national and regional governmental levels [86,107]. Additionally, in this national context, Madrid is also emerging as a key European research hub for energy poverty, given its diverse neighborhoods, mixed building stock, and varied population. The city's extreme weather conditions contribute to higher energy costs for vulnerable households. Furthermore, as the capital of Spain, Madrid exhibits disparities in wealth distribution, employment opportunities, and overall higher prices, including energy costs and housing expenses.

It should be noted that previous studies have been carried out in this city. In this regard, this study introduces a novel methodology, complementing existing approaches on the feminization of energy poverty in Madrid, such as qualitative characterization [33], summer energy poverty analysis [81], and the income and energy expenditure approach [8]. Key differentiating factors are described in Fig. 5.

Madrid, the capital of Spain, is a major urban area in Europe with a diverse population of 3,286,662 residents, according to the Continuous Register Statistics [108], in 2022, contributing to a population density of 5438.79 inhabitants per km^2. The city covers an area of 604.3 km^2 and is administratively divided into 21 districts, further subdivided into 131 neighborhoods (Fig. 6). The demographic profile of Madrid, in 2022, includes a significant elderly population, with women representing a majority among those aged 75 and above [109], and a substantial foreign-born population, mainly Americans (52.8 %), Europeans (28.0 %), and Asians (12.6 %) [109].

Regarding household composition, in 2022, single-person households are prevalent in Madrid, particularly among the elderly, with a notable gender imbalance in favor of women [109]. Lone-parent households are less common, but also exhibit a gender disparity, with 83.1 % being headed by women [109]. Socioeconomically, the employment rate in Madrid is slightly higher than the national average, with women having a slight advantage in employment; however, 19.1 % of the workforce is engaged in part-time contracts, with 70.2 % of them being women [109].

4.1. Previous studies on energy poverty in Madrid

In Spain, extensive regional studies have been conducted to examine energy poverty and its quantification, driven by the diverse climates of the country resulting from its topography and geographical position, particularly between the northern and southern regions [79,114]. One notable study is the Atlas of Urban Vulnerability by the Ministry of Transport, Mobility and Urban Agenda (MITMA) [115], which analyzed urban deprivation in Spanish cities with over 50,000 inhabitants at the neighborhood level, using three indicators, education level, unemployment, and residential vulnerability, based on census data. Specifically, some parameters included in the residential vulnerability indicator are dwellings smaller than 30 m^2, deteriorated or inefficient dwellings, and

[2] QGIS is a no-cost, open-source Geographic Information System (GIS) that enables users to create, map, conduct spatial analysis, and manage geographic data.

Differentiating factors	How does this method differ?
Scale of Analysis	Focus on the administrative-neighborhood level, ensuring increased spatial analysis accuracy and addressing potential district-size variations.
Inclusion of Marginalized Groups	Includes other marginalized groups that have not been accounted for in prior assessments of energy vulnerability.
Integration of Energy Poverty Dimension	Incorporates the energy poverty dimension from previous works, enhancing the reliability of results when quantifying gendered energy vulnerability.
Data Utilization	Utilizes disaggregated geographic data from open-access sources, allowing for easy monitoring and replicability in various contexts due to the consistent updating of public databases.

Fig. 5. Key differentiating factors of the proposed methodology (source: authors' elaboration).

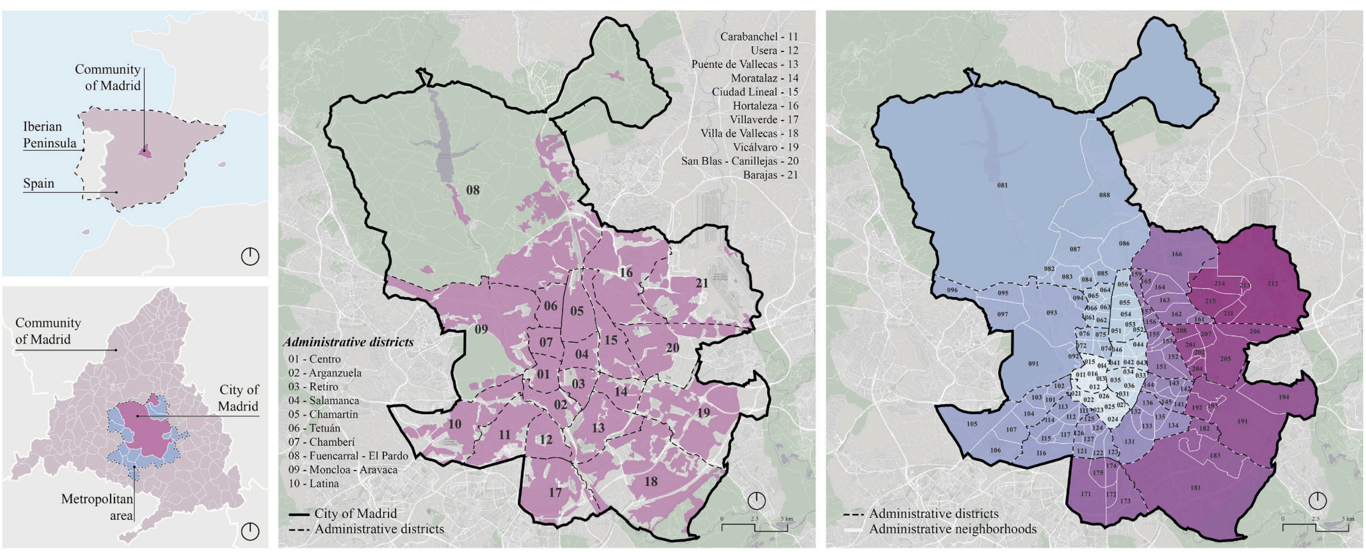

Fig. 6. Location and administrative division of Madrid (source: authors' elaboration based on [110–113]).

dwellings built before 1951. Its latest edition in 2011 [101], identified 918 Vulnerable Neighborhoods (VN) across Spain, with 91 located in Madrid [116].

Madrid has emerged as a significant research hub for energy poverty, with numerous studies exploring energy needs, vulnerable neighborhoods, energy-inefficient dwellings, gender perspectives, and summer energy poverty. For instance, the Technical Report on Energy Poverty in Madrid, conducted by Sanz Fernández et al. [117], highlighted that 23.4 % of households in the city were at risk of energy poverty in 2016. Additionally, a study by Sánchez-Guevara et al. [8] in 2020 revealed that 28.0 % of households with women as the breadwinners were at risk of energy poverty, as well as 40 % of single-parent homes led by women, and 38 % of single-households composed of women over the age of 65. Regarding summer energy poverty, the research of Sánchez-Guevara et al. [80] analyzed the connection between the Urban Heat Island (UHI) effect, housing energy efficiency, overheating risk, and social vulnerability. The findings indicated that 44 % of residential areas exhibit low thermal performance, thereby increasing the vulnerability to energy poverty caused by cooling demands during the summer season in the city.

Another noteworthy study, conducted by Martín-Consuegra et al. [16] is the development of a Multidimensional Index of Fuel Poverty (IMPE), which incorporated data from the Atlas of Urban Vulnerability and previous research on energy efficiency to assess energy poverty and its spatial distribution at the census section level in Madrid. The IMPE classification system categorized Deprived Neighborhoods (DN) at risk of energy poverty based on overlapping indicators, including energy inefficiency, low-income, high energy costs, lack of heating, and the presence of elderly residents. The results revealed that, out of the 91 analyzed zones, 54 DN exhibited varying degrees of energy deprivation. Specifically, 16 neighborhoods were classified as being at severe risk, while 25 were at critical risk of energy poverty.

4.2. Applied methodology and data sources

The application process is illustrated in Fig. 7, starting with stage 1 (S1), where open-access data for each gender-responsive indicator are collected, both aggregated and disaggregated by women and men. Moving to stage 2 (S2), each gender-responsive indicator is mapped without disaggregation to observe the overall distribution of socio-spatial vulnerability. This is followed by gender-disaggregated results, meaning each gender-responsive indicator is mapped separately for women and men. In stage 3 (S3), the intersectionality of factors and their spatial distribution for women and men are illustrated, denoted as

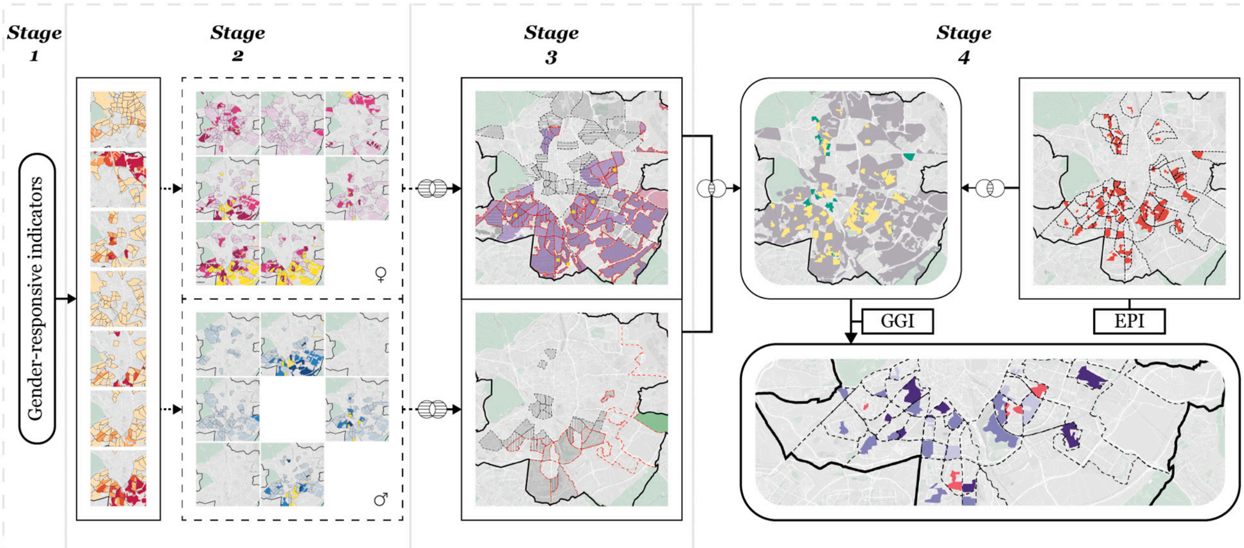

Fig. 7. Applied methodology flowchart.

Gender-Vulnerable Areas (GVA). Finally, in stage 4 (S4), the resulting GVA intersects with the Energy Poverty Index (EPI) and the Gender Gap Index (GGI), yielding the Gendered Energy Vulnerability Index (GEVI) and final classification of neighborhoods based on their risk of facing gendered energy vulnerability.

For the case study, input data were collected from various open-access databases in their latest available editions. Cartographic data were gathered from three sources: The vector file of the districts for the year 2022 was obtained from the Institute of Statistics of the Community of Madrid (IE) [110]. In the absence of a vector file for the neighborhoods, delimited text data from 2022 were gathered from the Madrid City Council [111], and manually integrated with the 2022 vector file of the census sections obtained from the Spanish National Statistics Institute (INE) [112] and then intersected with the residential land use from CORINE 2018 [113] using QGIS.

The total population of the city was gathered from the latest available 2022 Continuous Register Statistics published by the INE [108]. Demographic and socio-economic variables from 2022 were collected from the Madrid City Council Data Bank [109]. For the energy poverty dimension, data were sourced from two studies: the Vulnerable Neighborhoods from the Catalogs of Vulnerable Neighborhoods of Spain 2011 by the Atlas of Urban Vulnerability [101] and the Deprived Neighborhoods from the Multidimensional Index of Fuel Poverty 2020 by Martín-Consuegra et al. [16].

An overview of the datasets used in this section is summarized in Table 2. It is important to emphasize that, although the data in this section pertains to Madrid, the methodology is designed to be applicable in various contexts, and hence, adjustments to the data should be made accordingly when replicating the proposed index in different settings.

5. Results and discussion

Section 5.1 examines socio-spatial vulnerability, followed by the gender-disaggregated results in section 5.2. In section 5.3, Gender-Vulnerable Areas (GVA) are identified. Finally, the results of the Gendered Energy Vulnerability Index (GEVI) are presented in section 5.4.

Table 2
Data sources for case study in Madrid.

Dimension	Parameter	Data source	Dataset	Ref. year	File type
Cartography	Districts	Institute of Statistics of the Community of Madrid	Regional Center for Cartographic Information [110]	2022	SHP
	Neighborhoods	Madrid City Council	Municipal neighborhoods of Madrid [111]	2022	CSV
	Census sections	INE	Digital cartography of census sections [112]	2022	SHP
	Residential land use	CNIG	CORINE Land Cover [113]	2018	SHP
Demographic	Total population	INE	Continuous Register Statistics [108]	2022	CSV
	Age	Madrid City Council Data Bank	Population by age group and sex [109]	2022	CSV
	Ethnicity/nationality	Madrid City Council Data Bank	Population by Nationality, Place of Birth and Sex [109]	2022	CSV
	Disability/chronic illness	Madrid City Council Data Bank	Characteristics of Registered Unemployment [109]	2022	CSV
	Lone-parent	Madrid City Council Data Bank	Households classified by their Size and Composition [109]	2022	CSV
Socio-economic	Part-time employment	Madrid City Council Data Bank	Affiliates residing in the city of Madrid who work in the Community of Madrid [109]	2022	CSV
	Elementary occupation	Madrid City Council Data Bank	Affiliates residing in the city of Madrid who work in the Community of Madrid [109]	2022	CSV
	Unemployment	Madrid City Council Data Bank	Affiliates residing in the city of Madrid who work in the Community of Madrid [109]	2022	CSV
Energy poverty	Vulnerable Neighborhoods	Atlas of Urban Vulnerability	Catalogs of Vulnerable Neighborhoods. Databases and geographic information layers [118]	2011	SHP
	Deprived Neighborhoods	CSIC; IETcc	Multidimensional Index of Fuel Poverty Dataset [119]	2020	SHP

5.1. Mapping energy vulnerability without gender disaggregation

Stage 2 of the methodology is applied to pinpoint energy-vulnerable neighborhoods in Madrid, considering as a reference the aforementioned thresholds presented in section 3.3. The resulting maps without disaggregating the data by gender are depicted in Fig. 8(7). As an illustrative example, focusing on the elementary occupation indicator (Fig. 8), the average value, accounting for both women and men, for the city of Madrid is 6.6 %. In the map, it is evident that most neighborhoods in the central and northern parts of Madrid are either at or, in most cases, below the average, meaning the percentage of people with an elementary occupation in these neighborhoods is lower than the city's average. In contrast, the southern part of the city shows the opposite effect, with eight neighborhoods in the light-orange range between 1.5 and 1.75 times the average (i.e., 0.10 % and 0.11 %), seven neighborhoods in the dark-orange range between 1.75 and 2 times the average (i.e., between 0.11 % and 0.13 %), and 12 neighborhoods in red with above 2 times the average (0.13 %), reaching maximum values in the neighborhoods of San Cristóbal and Entrevías (with 0.19 % and 0.17 %, respectively).

Thus, when relying solely on current available aggregated data and overlooking gender perspectives in assessing energy vulnerability, it is evident that certain neighborhoods exhibit heightened concentrations of individuals, namely non-European foreign-born residents, with different abilities, lone-parent status, or employed in elementary occupations, reaching values exceeding twice the average of the city of Madrid. Conversely, the results indicate that aging individuals, as well as those unemployed or in part-time jobs, are not prevalent across the city, with most neighborhoods aligning with the city's average value.

Furthermore, it is worth noting that socio-economic aspects, identified as key contributors to energy vulnerability, are mainly associated

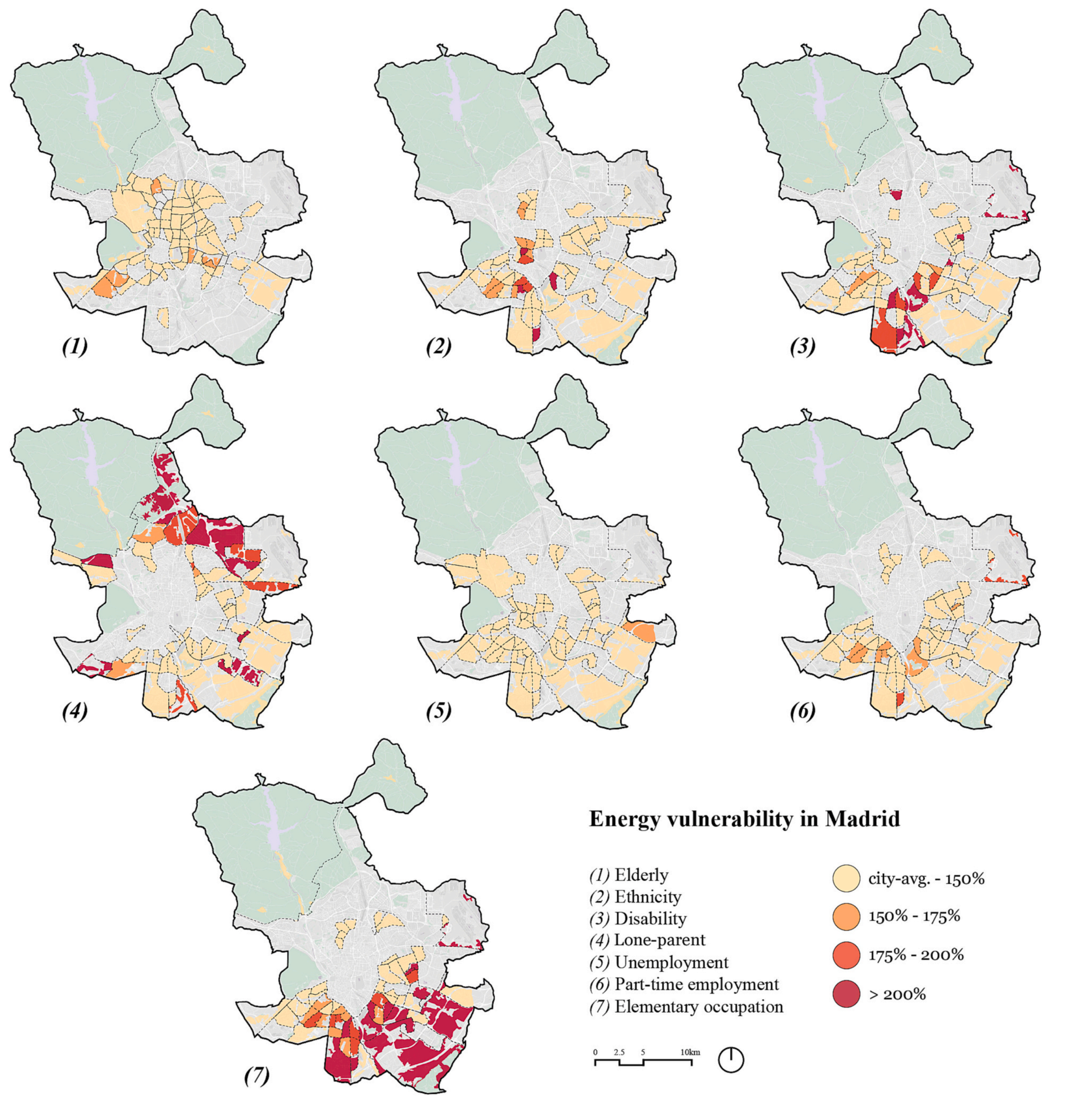

Fig. 8. Visualization of energy vulnerability in Madrid: (1) Elderly; (2) Ethnicity; (3) Disability; (4) Lone-parent; (5) Unemployment; (6) Part-time employment; (7) Elementary occupation (source: authors' elaboration based on [108–113]).

with the peripheries of the city, mainly in the southern districts. In contrast, only ethnicity is prevalent in the historic center of the city, while the indicator of aging progressively extends from the central areas towards the peripheries.

5.2. The spatial variation of energy vulnerability across genders

When disaggregating the data by gender, with assessments for women on the right and for men on the left, contrasting results emerge compared to Section 5.1, as shown in Table 3 and Fig. 9.

To illustrate, focusing on the elderly indicator shown in Fig. 9.1, a notable overrepresentation of women aged 75 years or older becomes evident when compared to the distribution of elderly men. In the case of women, the city-average value is set at 0.11 %, and a total of 26 neighborhoods surpass the 150 % threshold. Among these, 18 neighborhoods fall within the 150 % to 175 % segment (i.e., 0.16 % and 0.19 %), seven neighborhoods range between the 175 % and 200 % thresholds (i.e., between 0.19 % and 0.22 %), and one neighborhood exhibits values exceeding twice the average (0.23 %). Notably, these neighborhoods cluster into three distinct regions in the north, southwest, and southeast of the city, with maximum values observed in Vinateros. In contrast, all neighborhoods align closely with the city's average value for elderly men (i.e., 0.11 %) without surpassing the 150 % threshold (i.e., 0.16 %).

In the broader context, Fig. 10 compares the total number of identified neighborhoods exceeding the 150 % threshold, from section 5.1 and section 5.2. On the left side of the figure, only a few neighborhoods are identified for most indicators, particularly for the elderly, unemployment, and part-time employment indicators. However, the right side reveals new insights. Firstly, indicators previously overlooked now expose gendered energy vulnerability. Notably, part-time employment stands out with the highest overrepresentation of women in neighborhoods. Secondly, there is a significant increase in the number of neighborhoods surpassing the 175 % and 200 % thresholds for disability and elementary occupations (see Fig. 9). This emphasizes the fact that adopting a gender perspective in assessing energy vulnerability not only reveals factors worsening energy vulnerability for women, but also draws attention to vulnerabilities experienced by other marginalized groups. Lastly, a clear gender disparity in energy vulnerability becomes evident, with women being disproportionately represented in most of the gender-responsive indicators, especially in the elderly, lone-parent, part-time employment, and elementary occupation categories.

5.3. Identifying gender-vulnerable areas

The results of applying stage 3 of the methodology (section 3.4) are summarized in Table 4 and illustrated in Fig. 11. A total of 86 Gender-Vulnerable Areas (GVA) were identified for women, encompassing 65.6 % of the neighborhoods in Madrid. Fig. 11.1 illustrates a geographical division line, with the majority of GVA concentrated in the southeastern part of the city. Among these, 39 GVA exhibited a single gender-responsive indicator, while 20 GVA intersected with two indicators, and another 20 contained three indicators within the same neighborhood. Additionally, six GVA, denoted as *hot spots*, exhibited the overlapping of four out of seven gender-responsive indicators, namely Vista Alegre (114), San Diego (132), Fontarrón (145), San Cristóbal (172), Butarque (173), and Hellín (202).

In contrast, for men, 36 GVA were identified (Fig. 11.2), about 36.43 % less than those identified for women. Among these, 24 GVA exhibited one gender-responsive indicator, 10 GVA showed two indicators, and two GVA, namely San Diego and San Cristóbal, exhibited overlaps of three indicators. Notably, none of the GVA for men showed four or more gender-responsive indicators in this study. These findings underscore the varying levels of gendered vulnerability across neighborhoods in Madrid, with women generally facing higher levels of intersectional vulnerability.

Upon deeper analysis of the identified *hot spots*, Table 5 presents the city-wide average percentages of women under each indicator and contrasts them with the specific percentages observed in Vista Alegre (114), San Diego (132), Fontarrón (145), San Cristóbal (172), Butarque (173), and Hellín (202). Two significant correlations are evident. Firstly, highlighted in purple, there is a correlation between the indicators of ethnicity, disability, part-time employment, and elementary occupation present in Vista Alegre (114), San Diego (132), and San Cristóbal (172), all situated in the southern part of the city. The other, highlighted in yellow, indicates a correlation between elderly, disability, part-time employment, and elementary occupation in the neighborhoods of Fontarrón (145) and Hellín (202). These correlations can be explained by the fact that part-time employment is primarily undertaken by women [120,121]. It is closely associated with the need for flexible work schedules for domestic work and caregiving responsibilities [120], with women often assuming this role, tending to elderly family members or individuals with special needs [122].

Moreover, part-time employment is prevalent in such elementary occupations as retail, helpers, cleaners, hospitality, and personal services [121,123], where women from ethnic minority backgrounds are often employed [124,125]. These sectors typically offer lower wages and limited career prospects [126], contributing to women's inability to meet their energy expenses and other essential needs [51].

Elderly women and women with disabilities often have elevated energy needs due to medical conditions [82], resulting in additional energy expenses that may strain their limited income, heightening energy vulnerability. Additionally, part-time employment and elementary occupations, more prevalent among elderly women [127], may not provide adequate access to benefits such as healthcare coverage, leaving them reliant on social security benefits or pensions, which may not sufficiently address their energy-related needs. In the case of Madrid, their energy expenditures exceed their pension income by >30 % per

Table 3
Summarized results of the assessment of the distribution of energy vulnerability across genders.

Gender-responsive indicator	Identified neighborhoods								
	City avg-150 %		150 %–175 %		175 %–200 %		>200 %		Highest vulnerability
	Women	Men	Women	Men	Women	Men	Women	Men	
Elderly	66	23	18	0	7	0	1	0	W: Vinateros
Ethnicity	39	39	11	9	2	2	3	5	W: Sol M: Pradolongo
Disability	32	34	6	6	5	3	10	7	W:Aeropuerto M: Entrevías
Lone-parent	17	0	6	0	2	0	1	0	W: El Goloso
Unemployment	73	53	1	1	0	0	0	0	W: El Cañaveral M: El Cañaveral
Part-time employment	25	1	17	0	15	0	18	0	W: San Cristóbal
Elementary occupation	17	30	10	7	10	5	21	4	W: San Cristóbal M: San Cristóbal

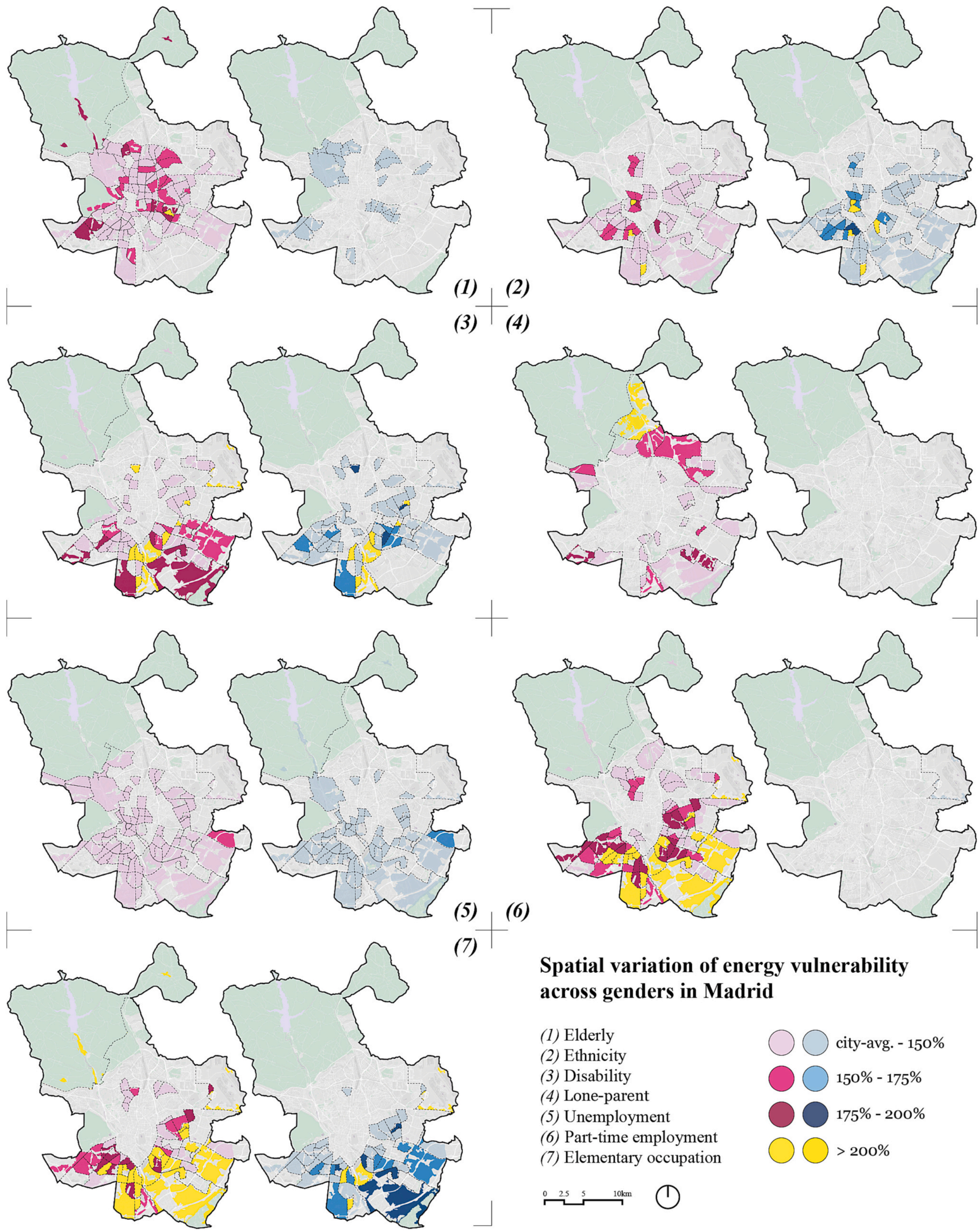

Fig. 9. The spatial variation of energy vulnerability across genders in Madrid: (1) Elderly; (2) Ethnicity; (3) Disability; (4) Lone-parent; (5) Unemployment; (6) Part-time employment; (7) Elementary occupation (source: authors' elaboration based on [108–113]).

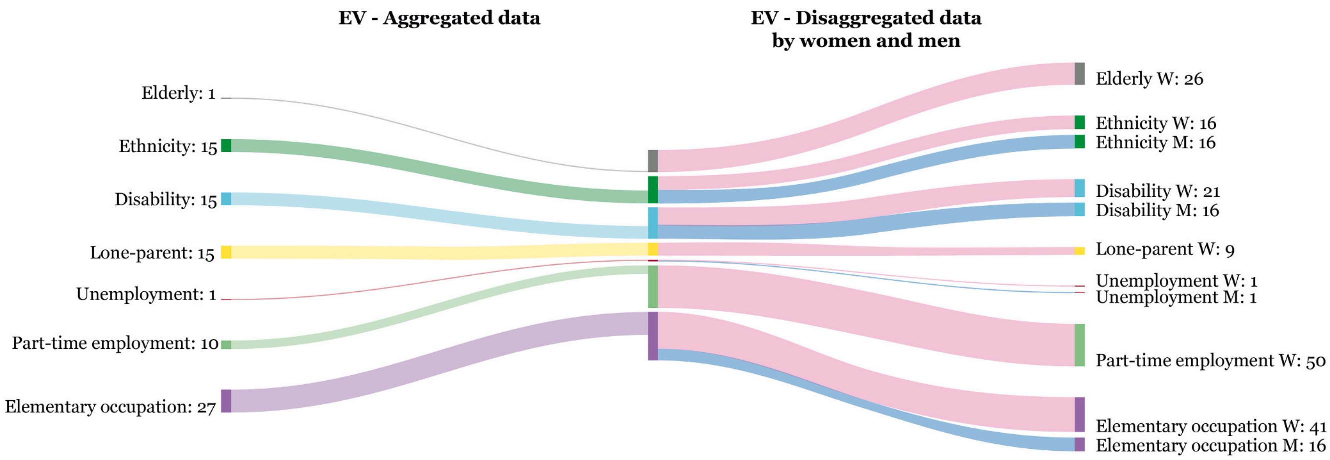

Fig. 10. Comparison of number of neighborhoods identified with EV: (1) aggregated data, left; (2) gender-disaggregated data, right (source: authors' elaboration based on [108–113]).

Table 4
Summary of the resulting Gender-Vulnerable Areas.

Gender	Total GVA	Number of neighborhoods with overlapping gender-responsive indicators			
		One indicator	Two indicators	Three indicators	Four or more indicators
Women	86	39	20	21	6
Men	36	24	10	2	0

year [109], compounding the challenges faced by elderly women in meeting their energy requirements.

Concerning lone-parent women, it is worth noting that this indicator is exhibited in only one neighborhood, among the hot spots, and overlaps with disability, part-time employment, and elementary occupation. Lone-parent families led by women are generally more vulnerable to energy poverty due to the unique challenges they encounter [8,103]. As the sole providers for their households and dependents, these women must manage all aspects of their families' well-being, including meeting their energy needs [8,27,128]. Limited employment options and income can potentially contribute to their financial strain, and the juggling of work and caregiving responsibilities hinders their ability to secure

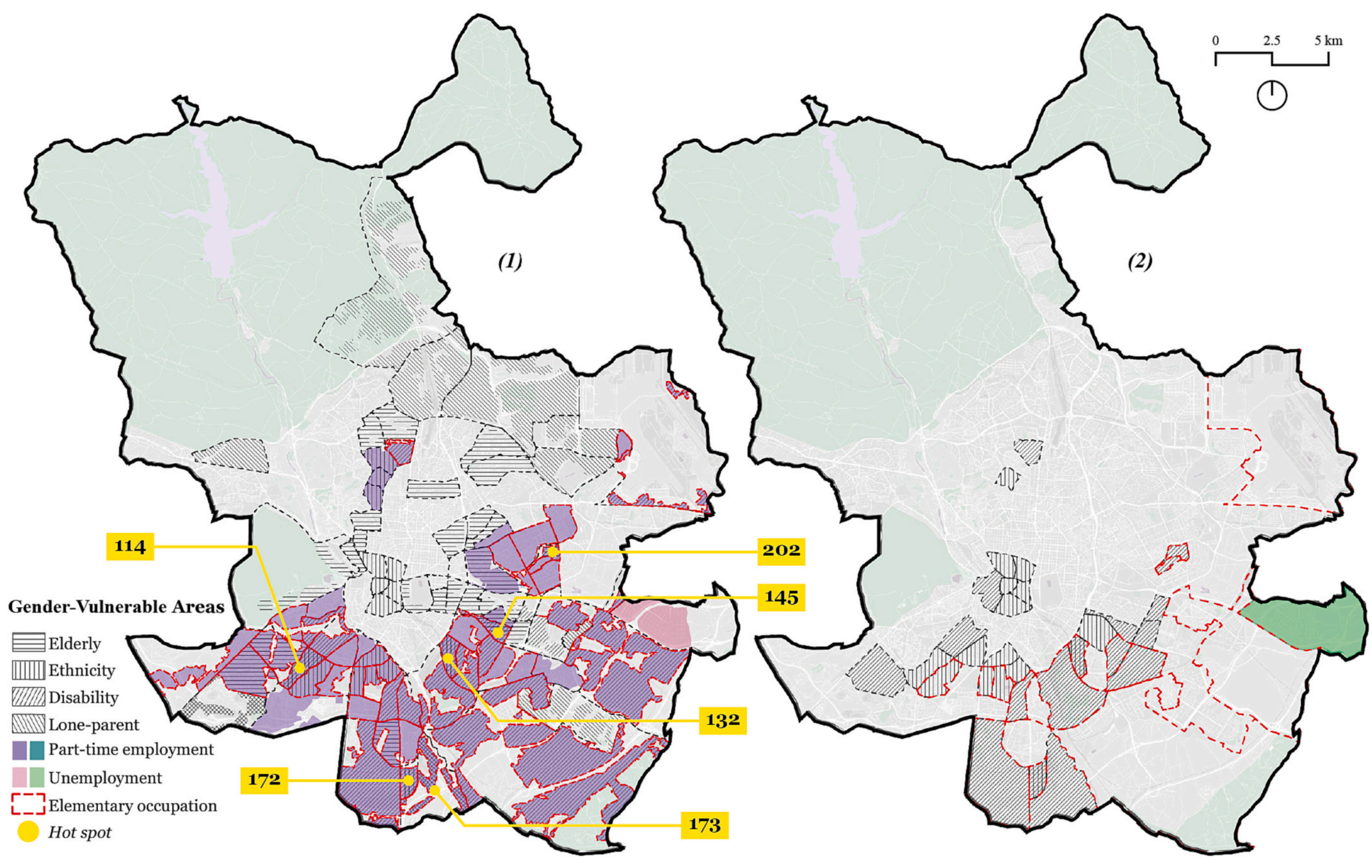

Fig. 11. Distribution of Gender-Vulnerable Areas in Madrid: (1) women, left; (2) men, right (source: authors' elaboration based on [108–113]).

Table 5
Summary of results of identified hot spots.

N. Code	Elderly		Ethnicity		Disability		Lone-parent		Part-time employment		Elementary occupation		Unemployment	
	City-avg.	*% of women*	*City-avg.*	*% of women*	*City-avg.*	*% of women*	*City-avg.*	*% of women*	*City-avg.*	*% of women*	*City-avg.*	*% of women*	*City-avg.*	*% of women*
114				23.9%		0.3%				15.8%		4.9%		
132				30.9%		0.4%				17.6%		6.6%		
145	7.1%	19.4%	8.4%		0.1%	0.3%	2.0%		13.4%	13.%	3.9%	4.1%	20.1%	
172				33.6%		0.6%				18.1%		7.6%		
173						0.4%		4.1%		13.9%		5.0%		
202		17.3%				0.7%				14.7%		5.8%		

stable, well-paying jobs [33]. This results in insufficient resources to adequately cover their energy expenses.

To summarize, while areas with inequality indicators exist throughout the city, the intersection in low-income areas causes a critical situation.

5.4. The geography of gendered energy vulnerability

As indicated in stage 4 (Section 3.5) the proposed method intersects with previous assessments of energy poverty. In this case study, the energy poverty dimension in Madrid leverages data from two studies: the Atlas of Vulnerability [101], which identifies 39 Vulnerable Neighborhoods (VN) in the city based on the residential vulnerability indicator assessing deficiencies in residential buildings (Fig. 12.1), and data from the Multidimensional Index of Fuel Poverty (IMPE) [16], which categorizes 52 Deprived Neighborhoods (DN) in Madrid based on low-income, high energy expenses, and lack of heating system (Fig. 12.2). By combining the results of both studies, a total of 80 cases, highlighted in red, are identified as instances of energy poverty in Madrid (Fig. 12.3). The intersection of these cases with the 87 GVA (Section 5.3) led to the identification of 48 neighborhoods highlighted in yellow in Fig. 12.4. In these neighborhoods, individuals are likely to face simultaneous challenges related to energy poverty and gender-specific vulnerabilities.

In further analysis, five neighborhoods, namely Embajadores, Cortés, Sol, Palomeras Sureste, and Amposta, with GGI values equal to zero are discarded, as they do not exhibit significant differences in vulnerability between men and women (refer to section 3.5). Additionally, one neighborhood, Palacio, expressing a negative value, is also excluded. After the refinement process, it is found that 42 neighborhoods exhibit gendered energy vulnerability for women. Among these, 11 are classified as *Mild priority*, 17 as *Moderate priority*, 10 as *Severe priority*, and four as *Critical priority*. This indicates that approximately 32.1 % of the neighborhoods in the city are at risk of experiencing gendered energy vulnerability. Remarkably, these neighborhoods account for nearly 50 % of the previously identified GVA and almost 90 % of the overall assessment of energy poverty in Madrid.

Table 6 compiles the number of neighborhoods where each gender-responsive indicator is present in each GEVI priority level, shedding light on the indicators that appear more frequently. For instance, the elderly indicator is present in four out of the 11 neighborhoods classified as *Mild priority*. Furthermore, indicators that are most prevalent in each category are highlighted in yellow, while the second most identified ones are in purple. Thus, it can be seen that the elderly indicator is prevalent in both *Mild* and *Critical* levels, while part-time employment and elementary occupations consistently repeat across all levels.

Additionally, as it can be seen in Fig. 13, the spatial distribution of gendered energy vulnerability for women forms two clusters: one small cluster in the northwest and the northeast, and a larger cluster in the south of the city.

Cluster 1 in the northwest consists of the neighborhoods Bellas Vistas, Valdeacederas, and Berruguete, which exhibit a higher

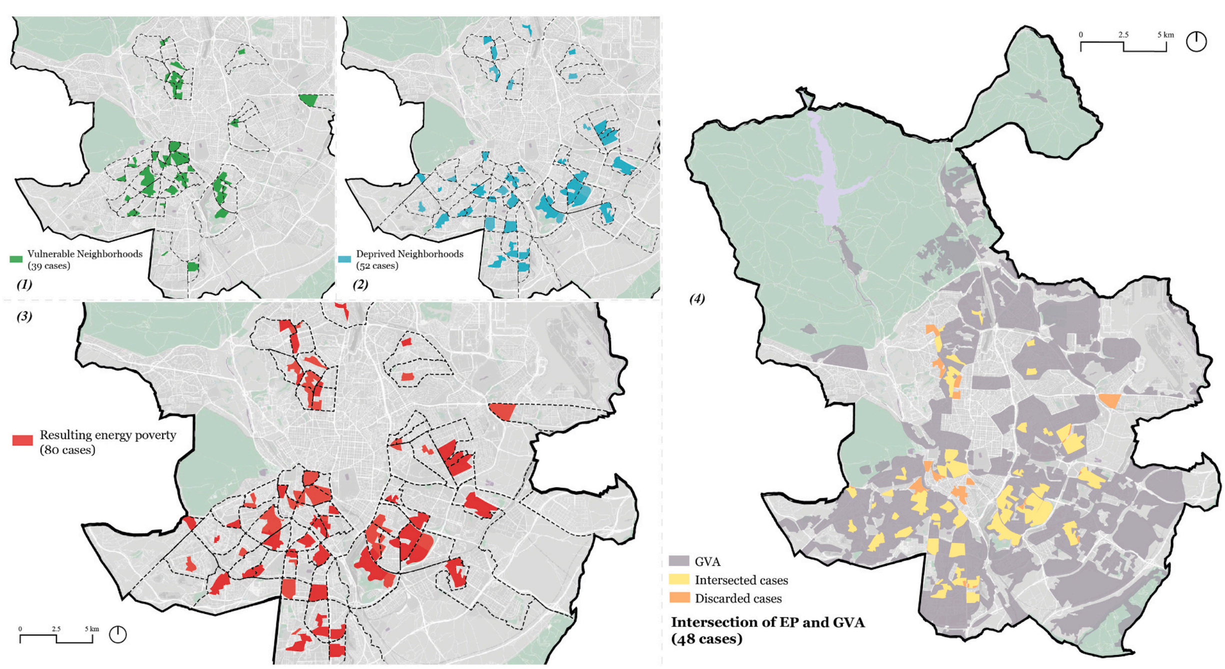

Fig. 12. (1) Vulnerable Neighborhoods; (2) Deprived Neighborhoods; (3) Resulting instances of energy poverty; (4) Intersection of GVA and EP in Madrid (source: authors' elaboration adapted from [118,119]).

Table 6
Summary of the results of the Gendered Energy Vulnerability Index (GEVI).

Gender-responsive indicator	GEVI priority levels			
	Mild (11 neighborhoods)	*Moderate (17 neighborhoods)*	*Severe (10 neighborhoods)*	*Critical (4 neighborhoods)*
Elderly	4/11	3/17	0/10	3/4
Ethnicity	1/11	6/17	3/10	0/4
Disability	2/11	4/17	4/10	2/4
Lone-parent	1/11	0/17	0/10	0/4
Part-time employment	6/11	16/17	10/10	4/4
Unemployment	0/11	0/17	0/10	0/4
Elementary occupation	4/11	12/17	9/10	4/4

representation of ethnic foreign-born and part-time employed women. These developments belong to the expansion stage of the city prior to urbanized developments after the Civil War. They are spontaneous peripheral subdivision developments that have now been incorporated into the city. They are currently undergoing gentrification due to their proximity to the city center. According to the Technical Report on Energy Poverty in Madrid [117], these neighborhoods have incomes below the municipal average. Furthermore, in the Tetuán district where these

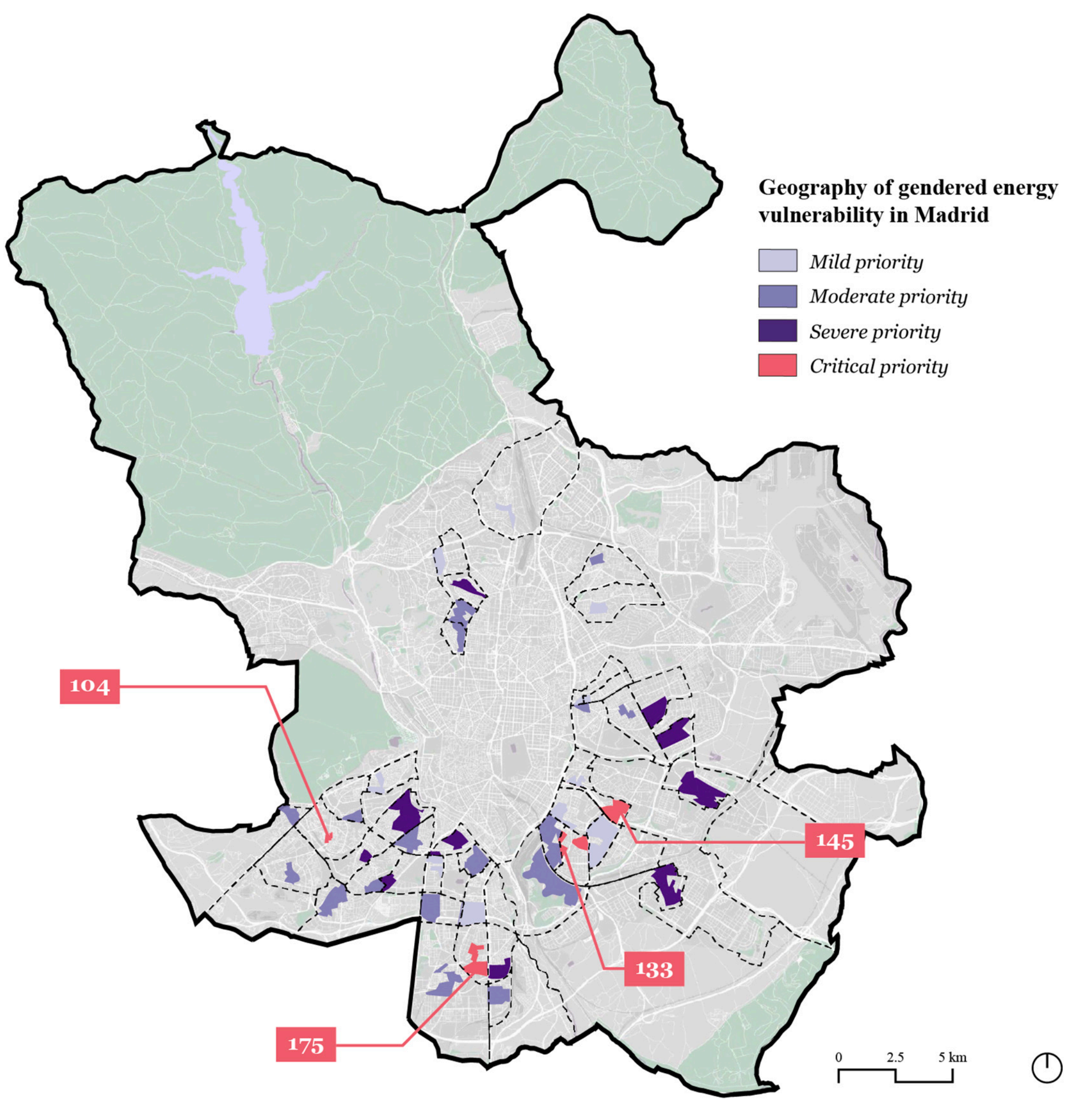

Fig. 13. The geography of gendered energy vulnerability in Madrid (source: authors' elaboration).

neighborhoods are located, 69.81 % of the dwellings were built before 1980, with values higher than the mean for inefficient buildings [117]. Additionally, Barrio del Pilar and Valverde, as well as Canillas and Pinar del Rey, share characteristics such as a higher representation of elderly women and lone-parent households led by women. Despite having older building stock, these neighborhoods have income levels above the city average [111].

Cluster 2 exhibits the highest distribution of gendered energy vulnerability for women in Madrid, comprising 27 % of the city's neighborhoods. Within this cluster, 10 neighborhoods are classified as *Severe priority*, while four are categorized as *hot spots,* namely Aluche (104), Palomeras Bajas (133), Fontarrón (145), and Ciudad de los Ángeles (175). These are areas on the first periphery of the city, which show advanced deterioration processes and are in urgent need of urban renewal. Some of these neighborhoods are isolated and have been identified as priority areas for action in successive municipal plans. Despite efforts, the problems of deprivation in these neighborhoods remain persistent.

Aluche (104) and Ciudad de los Ángeles (175), located in the southwest, exhibit similar patterns of gendered energy vulnerability. These neighborhoods have a higher representation of elderly women, part-time employment, and women working in elementary occupations. Furthermore, in terms of energy poverty, both neighborhoods are characterized by low-income levels (lower than 20 % of the city's income) [117], and a considerable number of dwellings lacking adequate heating system installations, with >15 % of the dwellings relying on electrical heaters, leading to increased energy expenses for the residents [117]. The only distinction between the two lies in the residential vulnerability indicator, with Aluche, located in the Latina district, having >80 % of its building stock constructed before 1980 [117].

Moving to the southeast, the neighborhood of Palomeras Bajas (133), in the Puente de Vallecas district, exhibits a higher representation of women with limited day-to-day activity, part-time employment, and working in elementary occupations. In terms of energy poverty, despite >40 % of its building stock being constructed after 1980 [117], indicating a relatively newer district, Palomeras Bajas faces significant challenges. It shows high values of building deprivation, energy inefficiency, and UHI. Moreover, this district is characterized by having the lowest income levels in the city [117].

The Fontarrón (145) neighborhood in the Moratalaz district is characterized by the highest risk of gendered energy vulnerability, with most gender-responsive indicators present in the area. In terms of gender vulnerability, the neighborhood has above-average values for women aged 75 or more, accounting for 1800 individuals, which represents 19.4 % of the female population in the neighborhood. Additionally, there is a notable prevalence of women with disabilities or chronic illnesses, with 28 women accounting for 0.3 % of the female population in the neighborhood. Part-time employment among women is also significant, with 13.2 % of women in the neighborhood working in part-time jobs, totaling 1288 individuals, which is 175 % above the city's threshold for this indicator. Furthermore, women working in the elementary sector represent 4.1 % of all women in the neighborhood, totaling 377 individuals. In terms of energy poverty, the Fontarrón neighborhood exhibits all the indicators. Firstly, 66.9 % of the buildings in the neighborhood were constructed between 1961 and 1980, which is the highest percentage for this period in the city [117]. Additionally, the neighborhood shows high values for the UHI effect [117], which can represent a significant concern, especially considering that almost 80 % of the buildings in the neighborhood do not have cooling systems [117]. Moreover, the neighborhood has below-average income levels compared to the city, which further contributes to its energy poverty risk.

6. Conclusions

This paper has presented a methodology for assessing and visualizing gendered energy vulnerability, with a case study conducted in Madrid using GIS techniques. The study revealed disparities in energy vulnerability between women and men in most gender-responsive indicators, such as elderly women, single-parent households led by women, part-time employed women, and those in elementary occupations. It identified 86 Gender-Vulnerable Areas (GVA) for women, 36.43 % more than those identified for men. Additionally, the neighborhoods Vista Alegre, San Diego, Fontarrón, San Cristóbal, Butarque, and Hellín, exhibited the highest number of overlapping indicators within each area.

Given the lack of specific disaggregated data for analyzing gendered energy vulnerability, the resulting GVA were cross-referenced with two studies, the Atlas of Vulnerability [101,116] and the IMPE [16]. When applying the Gendered Energy Vulnerability Index (GEVI), 42 neighborhoods were identified in Madrid, constituting 32.1 % of the city's total, where women may be facing gendered energy vulnerability. As far as spatial distribution is concerned, although it is a generalized problem and vulnerability-related indicators can be found throughout the city, the problem of inequality becomes critical in combination with poverty, neighborhood degradation and social exclusion, particularly affecting peripheral areas in the southern part of the city. Additionally, Aluche, Palomeras Bajas, Fontarrón, and Ciudad de los Ángeles emerged as *Critical priority.* Within these neighborhoods, an estimated 2655 elderly women, 15,785 foreign-born women, 322 women with limited daily activity, 304 single-parent households led by women, 12,909 women in part-time employment, and 4561 women in elementary occupations may be experiencing critical levels of gendered energy vulnerability. These findings reinforced the role of demographic factors in exacerbating gendered energy vulnerability.

Notably, the economic dimension and social gender norms emerged as key factors, with low-income being a common thread across all indicators. Gendered disparities in income, employment, activity distribution, affordability of modern energy, and resource allocation all contribute to increased energy needs and expenses, thereby perpetuating gendered energy vulnerability among women.

The proposed method facilitates the identification and categorization of gendered energy-vulnerable areas, providing value to decision-makers in prioritizing regions that require in-depth analysis and subsequent targeted interventions within the energy sector. Moreover, the simplicity of the method enhances its potential for replicability in similar studies, leveraging open-access data that can be easily customized. In that sense, the spatial distribution of these indicators makes it possible to address renovation strategies at neighborhood level including the gender perspective, which is essential for successful operations, and where a good diagnosis plays a key role in the effective implementation of social policies.

Regarding limitations, one of the main limitations identified is the level of aggregation of the data. The methodological proposal is shown to be effective when aiming to have an overall view on an urban scale of the spatial distribution and to detect the areas with greater exposure using open data. However, for a greater level of detail of a given area, it may be interesting to complement the study analysis with additional information and qualitative evaluations, for example, through targeted surveys. Additionally, adjustments and refinements may be necessary based on data availability, socio-cultural context, and research objectives. Further validation (e.g., a complementary study with verification on the ground via interviews and surveys) and adaptation would strengthen its reliability, facilitating its widespread use in addressing gendered energy vulnerability in other scales and regions.

CRediT authorship contribution statement

Nayely B. Capetillo-Ordaz: Data curation, Funding acquisition, Investigation, Software, Writing – original draft, Writing – review & editing. **Fernando Martín-Consuegra:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Carmen Alonso:** Conceptualization, Methodology, Supervision, Writing – review &

editing. **Jon Terés-Zubiaga:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing. **Sesil Koutra:** Conceptualization, Supervision, Writing – review & editing.

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 pertaining to this study is accessible through Mendeley Data, an open-source online data repository, at: https://data.mendeley.com/datasets/vmt2wktp3j (Capetillo-Ordaz, Nayely B.; Martín-Consuegra, Fernando; Alonso Ruiz-Rivas, Carmen; Terés-Zubiaga, Jon; Koutra, Sesil (2023), "Inclusivity in Urban Energy Transitions: A methodological approach for mapping gendered energy vulnerability and assessing the city of Madrid - ASSOCIATED RESEARCH DATA", Mendeley Data, doi: 10.17632/vmt2wktp3j.1).

Acknowledgments

The project leading to these results has received funding from "La Caixa" Foundation under the project code LCF/PR/SR20/52550013. Additionally, the author, Nayely B. Capetillo-Ordaz, who conducted this research as part of the SMACCs Erasmus Mundus Master program, acknowledges the funding received from the European Commission.

Open Access funding provided by the University of the Basque Country.

Appendix A. Applied methodology

Table 7
Summary of the parameters for each indicator.

Gender-responsive indicator	Statistical measures			Threshold		
	Min	*Max*	*Mean*	*150%*	*175%*	*200%*
1 Elderly	0.0072	0.1922	0.1105	0.1658	0.1934	0.2210
2 Ethnicity	0.0397	0.3662	0.1574	0.2361	0.2754	0.3148
3 Disability	0.0000	0.0057	0.0019	0.0029	0.0033	0.0038
4 Lone-parent	0.0116	0.0777	0.0240	0.0361	0.0421	0.0481
5 Unemployment	0.2410	0.6066	0.3802	0.5702	0.6653	0.7603
6 Part-time employment	0.0822	0.3517	0.1911	0.2867	0.3345	0.3823
7 Elementary occupation	0.0058	0.1911	0.0667	0.1000	0.1167	0.1333

Table 8
Summary of the parameters for each indicator by gender.

Gender-responsive indicator	Gender	Statistical measure			Threshold		
		Min	*Max*	*Mean*	*150%*	*175%*	*200%*
1 Elderly	Women	0.0093	0.2260	0.1105	0.1658	0.1934	0.2210
	Men	0.0051	0.1602				
2 Ethnicity	Women	0.0424	0.3444	0.1574	0.2361	0.2754	0.3148
	Men	0.0368	0.3926				
3 Disability	Women	0.0000	0.0075	0.0019	0.0029	0.0033	0.0038
	Men	0.0000	0.0063				
4 Lone-parent	Women	0.0091	0.0578	0.0240	0.0361	0.0421	0.0481
	Men	0.0011	0.0199				
5 Unemployment	Women	0.2639	0.6267	0.3802	0.5702	0.6653	0.7603
	Men	0.2157	0.5865				
6 Part-time employment	Women	0.1019	0.5280	0.1911	0.2867	0.3345	0.3823
	Men	0.0511	0.2175				
7 Elementary occupation	Women	0.0061	0.2225	0.0667	0.1000	0.1167	0.1333
	Men	0.0045	0.1603				

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