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Research paper

Geographical inequalities in energy poverty in a Mediterranean city: Using small-area Bayesian spatial models

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A B S T R A C T

Energy poverty (EP) is becoming an increasingly important problem in the urban contexts of southern Europe. In Barcelona, EP indicators are higher than those of the European Union and are strongly associated with poor health status and high use of health services and medication, becoming a major public health problem. EP is unevenly distributed in the population of Barcelona, according to axes of social stratification. However, its geographic distribution at the small-area level remains unknown because it cannot be directly estimated with the available information sources and commonly used methods. Therefore, the aim of this study was to analyze geographical inequalities in EP in Barcelona by estimating reliable small-area EP indicators and a composite indicator (index). We used a novel method that allowed us to obtain 6 EP indicators for the 73 Barcelona neighborhoods and an EP index from a principal component analysis of these indicators. We found major geographical inequalities in the distribution of EP in Barcelona. Many neighborhoods had significantly higher EP than the city average, and these areas made up 3 well-defined spatial clusters. Therefore, the estimated small-area indicators and index allowed identification of the most affected neighborhoods. These results indicate the need to prioritize these areas for local interventions to alleviate EP, and could also be used for policy making.

1. Introduction

Energy poverty (EP) is defined as the inability of a household to secure a socially and materially required level of energy services in the home (Bouzarovski, 2013). EP is currently a social problem in Europe and recent publications have shown that the most affected countries are those in southern and eastern European Union (EU) (Bouzarovski and Tirado Herrero, 2017; Recalde et al., 2019). For example, in 2016, 9.0% of the EU population was unable to keep their home adequately warm during the cold months, while in Spain this percentage increased to 13.4% (Oliveras et al., 2021b). Several studies have shown that EP is strongly associated with worse health and wellbeing, making it a major public health problem (Bosch et al., 2019; Marí-Dell'Olmo et al., 2017; Marmot Review Team, 2011; Oliveras et al., 2020; Thomson et al., 2017b).

The distribution of EP in the population is uneven, following the classical lines of social stratification. The phenomenon particularly affects people with a more disadvantaged social class, those born in low- and middle-income countries and women aged 65 years and older (Carrere et al., 2020; Oliveras et al., 2020). Geographical inequalities in EP at the small-area level have also been found in various contexts. Some of the best studied regions are England (Baker et al., 2003; DECC, 2009; Fahmy et al., 2011a; Fahmy and Gordon, 2007; HM Government, 2013; Robinson et al., 2018; Sun and Sundell, 2011), Scotland (Morrison and Shortt, 2008) and Portugal (Gouveia et al., 2019), with all showing marked geographical inequalities. Some studies have found such inequalities within cities such as Oberhausen (Germany) (März,

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2018), London (United Kingdom) and Madrid (Spain) (Martín-Consuegra et al., 2019; Sanchez-Guevara et al., 2019). Other studies have found marked geographical inequalities in EP at the medium- to large-area level, such as districts, in cities such as Valencia and Barcelona (Ajuntament de Barcelona, 2018a; Gómez-Navarro et al., 2021; Tirado Herrero, 2018). However, the geographical inequalities found within cities may be oversimplified by the size of these areas, leading to the danger of falling into the modifiable areal unit problem (MAUP) which could lead, for example, to misinterpretations by policymakers and local authorities (Openshaw, 2016). Unfortunately, in these cities, EP distribution at the smaller area level such as neighborhoods or census tracts is still unexplored.

Most EP analyses are undertaken at the country level or even on a larger scale such as the EU level. However, estimates of EP at the small-area level are a versatile and powerful tool that could be used for the following (Baker et al., 2003; Morrison and Shortt, 2008; Wilson et al., 2012): (1) identifying the most affected areas and prioritizing them in the fight against EP (developing evidence-based local public policies prioritizing the most affected areas, including effective targeting of EP programs or developing local affordable warmth and cold strategies); (2) identifying more contextual causes of EP, such as deficiencies in the housing stock or in the distribution network; (3) raising social and political awareness of EP as an issue of concern and providing civil society with tools for advocacy (maps are a very powerful tool for this purpose) and (4) advancing research, e.g. exploring the relationship between EP and health inequalities and other health and deprivation indicators.

EP is also becoming an increasingly important problem in the urban contexts of southern Europe. A clear example is the city of Barcelona (Spain), where several EP indicators show values above those of the EU and EP has become an explicit priority for the city council (Tirado Herrero, 2018). For instance, in 2016, 9.4% of the population in Barcelona could not afford to keep their homes adequately warm and 13.9% were in arrears in utility bills in the last 12 months. In this city, EP is also a major public health problem. There is a proven strong association between EP and worse health status, as well as with a higher use of health services and medication, which substantially impacts health and health services at the population level (Carrere et al., 2020; Oliveras et al., 2021a, 2020). However, the maximum level of spatial disaggregation at which the EP situation is known in detail are the 10 districts of the city, mainly because surveys are usually representative at this level at most. In contrast, there are important city-level strategies focusing on a smaller level than the district, specifically on the neighborhood level. This is the case, for example, of the Barcelona Neighborhoods Plan, which aims to reduce social inequalities in different neighborhoods of the city with actions on education, employment, public space and urban ecology, among other areas (Ajuntament de Barcelona, 2016a). In addition, it is known that people living in EP are more vulnerable to climate change due to their reduced ability to adapt (Jessel et al., 2019). For example, living in poorly insulated houses with no means of cooling does not protect people from high daytime and nighttime temperatures and heat waves. Consequently, among the objectives of the Barcelona City Council Climate Plan for 2030 is the elimination of EP with actions designed to improve knowledge of the phenomenon and its impact on health and to reinforce interventions that are already under way (Ajuntament de Barcelona, 2018a). Moreover, the Public Health Agency of Barcelona is working on the design of a system to monitor over time and space the effects of climate change on health including, among many other indicators, EP and its effects on health (Marí-Dell'Olmo et al., 2019a; Mercuriali et al., 2021). Therefore, there is a clear need for a tool able to detect the small areas with the highest levels of EP.

The aim of this study was to analyze geographical inequalities in EP in Barcelona by estimating reliable EP indicators and a composite indicator (index) at the neighborhood level. To the best of our knowledge, this is the first study to analyze EP in this small sub-division of the city, making inequalities on this scale visible for the first time. Furthermore, we employ a novel methodology that permits obtaining reliable EP indicators at small-area level, while taking into account both the potential dependence between EP indicators and the spatial dependence of the values of each of the EP indicators (between adjacent neighborhoods). The EP indicators and index estimates can be finally represented graphically in the form of maps, thus allowing, among other things, the study of its geographical patterns, and the detection of neighborhoods with significantly greater or lower EP. In addition, the EP indicators used in this study are among those recommended by the EU Energy Poverty Observatory to study and monitor EP. Finally, we make available the code used to perform the statistical analyses in order to facilitate the replicability of the study in other settings.

The paper is organized as follows. Section 2 specifies the methods used in this study: the design, the sources of information, the study population, the variables studied, and the novel statistical approach that we propose. Section 3 illustrates the results of the study, including the estimated values of the EP indicators and of the index obtained for each of the Barcelona neighborhoods, as well as their geographic distribution. Section 4 incorporates the discussion of our main results, where we state the main findings of our research, interpret the results and we comment the main limitations and strengths of the study. Finally, the EP policy implications derived from the study, possible future work and the conclusions of the study are given in Section 5.

2. Methods

2.1. Design, information source, units of analysis and study population

We performed a cross-sectional study using EP indicators and sociodemographic variables at the individual level and sociodemographic variables at the neighborhood level. Individual-level variables were obtained from the 2016 Barcelona Health Survey (BHS). This survey was conducted by interviewing 3519 individuals. The sample was representative of the city and the 10 districts of Barcelona (median population 164,881 people) (Bartoll et al., 2018). The aggregated values of sociodemographic variables for each of the 73 neighborhoods of Barcelona (median population 20,369 people) was drawn from the 2016 municipal register (Barcelona city council) and from the 2011 Housing and Population Census (National Statistics Institute). The study population consisted of non-institutionalized individuals aged 15 years or older who resided and were included in the Barcelona municipal register of inhabitants in 2016. To aid understanding of this article, a map is provided with the geographical location of the neighborhoods, their identification number and their full name (Fig. A.1).

2.2. Study variables and data analysis

The EP index and small-area estimates of the EP indicators comprising the index were obtained by using a novel method. To promote the reproducibility of the research conducted, the statistical methods and the R scripts used for data analysis are documented in detail in an RMarkdown document (Appendix B). In summary, the method was based on the following 5 steps:

Step 1: Variables of the BHS that allowed detection of a situation of EP in households were identified, henceforth termed *EP indicators*. These indicators were: (1) households that could not afford to keep the home at an adequate temperature during the cold months (Temp_cold); (2) households that could not afford to keep the home at an adequate temperature during the hot months (Temp_hot); (3) households in arrears in utility bills in the last 12 months (Arrears); (4) dwellings with leaks, dampness in walls, floors, ceilings or foundations, and/or rot in floors, window frames or doors (Conditions); (5) dwellings without means of heating or with central heating or room-heating appliances, but not used when necessary (Heating); and (6) dwellings without an air conditioner or with an air conditioner, but not used when necessary (Air_cond). Other EP indicators related to energy expenditure and household income were excluded due to the large number of missing data, 33.7% and 48.9%, respectively. Thus, a total of 6 indicators were included (Table 1). Of note, all indicators are recommended and monitored by the EU Energy Poverty Observatory, 2 of which are primary indicators and the remaining 4 are secondary indicators (EU Energy Poverty Observatory, 2021).

Step 2: Using the conceptual framework of the determinants of health inequalities related to EP previously developed by our group (Marí-Dell'Olmo et al., 2017), we identified those sociodemographic variables included in the BHS that could be related to EP (indicators selected in step 1) and which, in turn, were available at the neighborhood level from population-based records (not based on a sample). A total of 7 variables were obtained (Table 1).

Step 3: To make estimates at the small-area level (neighborhood) of each of the EP indicators, we used the M-model, a multivariate model for estimation in small areas (Botella-Rocamora et al., 2015; Corpas-Burgos et al., 2019). This allowed, on the one hand, analysis of all EP indicators in the same model, taking into account their possible dependence and, on the other hand, to take into account the possible spatial dependence of data between adjacent neighborhoods by means of the Leroux distribution (Leroux et al., 2000).

In summary, a Bayesian hierarchical model was estimated where the dependent variables were the 6 EP indicators (obtained in step 1). As covariates of the model, all variables obtained in step 2 were explored. Covariate effects were included into the small area estimates as introduced in Vergara-Hernández et al. (2021). Not all of the covariates mentioned were included in the final model, as we did not find a relationship with EP indicators for all of them. To select the covariates for the final multivariate model, we used the following criteria: (1) each of the covariates had to be significantly associated with at least 2 dependent variables and, (2) a lower value of the deviance information criterion (DIC) of multivariate models. The covariates of the final model were age group, educational level, country of birth, housing tenure and employment status (Table 1). A random effects matrix combining the spatial and multivariate dependence of the EP indicators was included in the model. Cases with missing values in any of the covariates were excluded in the estimation of the final model and therefore this model included a sample of 3378 individuals instead of 3519 (4% loss).

All models were fitted using a full Bayesian approach. Posterior distributions were obtained using Markov Chain-based Monte Carlo methods via WinBUGS and R (Lunn et al., 2012; R Core Team, 2021).

Step 4: The above-mentioned model allowed us to estimate the relationship between the demographic covariates and the EP indicators, as well as the spatial effects that could not be explained by the covariates. Once these components had been estimated, the exhaustive demographic information for each neighborhood was used, together with the estimated spatial effects, to calculate the indicators in each neighborhood, taking into account all the available demographic and spatial information.

Step 5: Once the estimates of the EP indicators were obtained at the small-area level (smaller than originally planned in the BHS), to obtain the EP composite indicator or index (at the neighborhood level), a principal component analysis (PCA) was performed on the posterior mean of the proportions (of the 6 EP indicators) obtained in step 4. In particular, the logit of the posterior mean of these indicators was used to normalize their values. Finally, the index was constructed from the first component of the PCA that explained 91% of the variance. The indicator with the highest weight was inadequate temperature in cold months, while the indicator with the lowest weight was that related to the presence of leaks and dampness (Table 1).

As a result of the entire process described above, using posterior means, point estimates of the proportions of each of the 6 EP indicators and the EP index were obtained for the 73 neighborhoods. Henceforth, we will refer to these 6 indicators as "small-area indicators" (SAI). Moreover, to quantify the statistical evidence of these parameters in each neighborhood, we estimated the probability of each EP SAI and the index to be higher than the overall value for the city. This means that for all EP estimates (the 6 SAIs and the index) and for each neighborhood, we calculated a probability of excess in comparison to the city average. These excess probabilities were categorized with the following cut points: [0, 0.025), [0.025, 0.05), [0.05, 0.95), [0.95, 0.975), and [0.975, 1].

3. Results

Table 2 shows the distribution of each SAI and of the EP index in the Barcelona neighborhoods, as well as their correlation matrix. There was wide variability in the EP SAIs by neighborhood. For example, the SAI of inadequate temperature in cold months had a median of 8.39%, the 25th and 75th percentile values were 6.62% and 13.28%, respectively, and their values ranged from 2.10% to 35.38%. Therefore, all the dwellings in neighborhoods above the 3rd quartile showed this problem, at least twice as often as those below the 1st quartile. The EP SAIs were highly correlated with each other, with the SAIs referring to inadequate temperatures in the cold and hot months and the availability of air conditioning being the most closely correlated, with correlations greater than 0.95. In contrast, the presence of conditions such as leaks or dampness showed the lowest correlations with the remaining SAIs. This is possibly the reason why this SAI showed the lowest weight, and therefore the lowest contribution, to the EP index (Table 1).

The rows in Table 3 show the 73 Barcelona neighborhoods, ordered from highest to lowest value of the EP index, while the columns show the 6 SAIs and the EP index. Each cell shows the SAI percentages and the index values with their 95% credible intervals (95%CI). The cells are colored according to the categories of the probability of EP excess with respect to the overall city specified above. Thus, red cells indicate a high probability of the EP SAIs and of the index being higher than that for the rest of the city and green cells a low probability. Fifteen neighborhoods were notable for their high values of the EP index and a significant excess of EP in 3 or more EP SAIs. Thus, for example, the neighborhood with the highest EP according to the index obtained (3.50) was Ciutat Meridiana. Examination of the different SAIs of this neighborhood showed that 31.41% of households could not afford to keep their homes at an adequate temperature during the cold months and that 35.95% could not do so during the warm months, 41.25% of households had at least one delay in utility bills in the last 12 months, 21.88% reported leaks, dampness in walls, floors, ceilings or foundations, and/or rot in floors, window frames or doors, 32.29% had no means of heating the home or did not

Table 1
Characteristics of each of the 6 energy poverty indicators (step 1 of the method) and the 7 sociodemographic variables related to energy poverty available in the Barcelona Health Survey and at the neighborhood level in population-based registries (step 2 of the method). Barcelona, 2016.

Name	Description	Data source	Year	Overall value for the city (%)	Number of missing values	Weight in the 1st principal component analysis dimension
Energy poverty indicators						
Temp_cold	Identifies households that cannot afford to maintain the dwelling at an adequate temperature during the cold months.	Barcelona Health Survey	2016	9.36	39	0.47
Temp_hot	Identifies households that cannot afford to maintain the dwelling at an adequate temperature during the hot months.	Barcelona Health Survey	2016	11.41	43	0.45
Arrears	Identifies households that have one or more arrears in utility bills in the last 12 months	Barcelona Health Survey	2016	13.90	738	0.45
Conditions	Identifies dwellings with leaks, dampness in walls, floors, ceilings or foundations, and/or rot in floors, window frames or doors	Barcelona Health Survey	2016	9.66	0	0.25
Heating	Identifies dwellings without means of heating or with central heating or room-heating appliances, but not used when necessary	Barcelona Health Survey	2016	9.96	20	0.40
Air_cond	Identifies dwellings without an air conditioner or with an air conditioner, but not used when necessary	Barcelona Health Survey	2016	51.43	23	0.39
Sociodemographic variables related to energy poverty available in the Barcelona Health Survey and at the neighborhood level in population-based registries						
Sex	Describes sex classified into female and male	Barcelona Health Survey Municipal Register	2016 2016		0 –	
Age group[a]	Describes age according to the groups: 0–19, 20–39, 40–59, 60–79,>79 years	Barcelona Health Survey Municipal Register	2016 2016		0 –	
Education level[a]	Describes education level grouped into 4 categories: no education, primary education, secondary education and higher education	Barcelona Health Survey Municipal Register	2016 2016		44 –	
Country of birth[a]	Describes country of birth classified into high-income and low-and middle-income countries according to the 2018 World Bank classification[b]	Barcelona Health Survey Municipal Register	2016 2016		9 –	
Housing tenure[a]	Describes the tenancy regime distinguishing between paid property and others (including property paying mortgage, rent at market price, social and other situations)	Barcelona Health Survey Census	2016 2011		66 –	
Employment status[a]	Describes employment status classified into unemployment and other	Barcelona Health Survey Municipal Register	2016 2016		43 –	
Households composition	Describes household composition classified into single-parent households and other	Barcelona Health Survey Municipal Register	2016 2016		0 –	

[a]Covariates included in the final statistical model.
[b]The World Bank World Bank Country and Lending Groups – World Bank Data Help Desk Available online: https://datahelpdesk.worldbank.org/knowledgebase/articles/906519 (accessed on Jul 25, 2021).

Table 2
Summaries and Spearman correlations between the 6 energy poverty small-area indicators and index. Barcelona, 2016.

Energy poverty indicators and index	Minimum	P25	P50	P75	Maximum	Correlation matrix						
						Temp_cold	Temp_hot	Arrears	Conditions	Heating	Air_cond	Index
Temp_cold	2.10	6.62	8.39	13.28	35.38	1.00	0.99	0.87	0.77	0.89	0.96	0.98
Temp_hot	3.12	8.50	10.75	16.49	42.72	0.99	1.00	0.84	0.78	0.84	0.95	0.97
Arrears	3.24	11.00	14.50	19.94	41.25	0.87	0.84	1.00	0.56	0.87	0.82	0.91
Conditions	4.85	7.57	9.13	11.31	22.29	0.77	0.78	0.56	1.00	0.75	0.88	0.79
Heating	2.58	7.19	9.10	11.54	32.29	0.89	0.84	0.87	0.75	1.00	0.93	0.94
Air_cond	25.60	45.21	52.29	60.88	83.19	0.96	0.95	0.82	0.88	0.93	1.00	0.98
Index	−3.33	−0.68	−0.12	0.81	3.50	0.98	0.97	0.91	0.79	0.94	0.98	1.00

P: Percentile.

use heating when necessary, and 83.19% had no air conditioning or did not use it when necessary. These values are higher than the respective average percentages for the city (9.36%; 11.41%; 13.90%; 9.66%; 9.96% and 51.43%) with a probability greater than

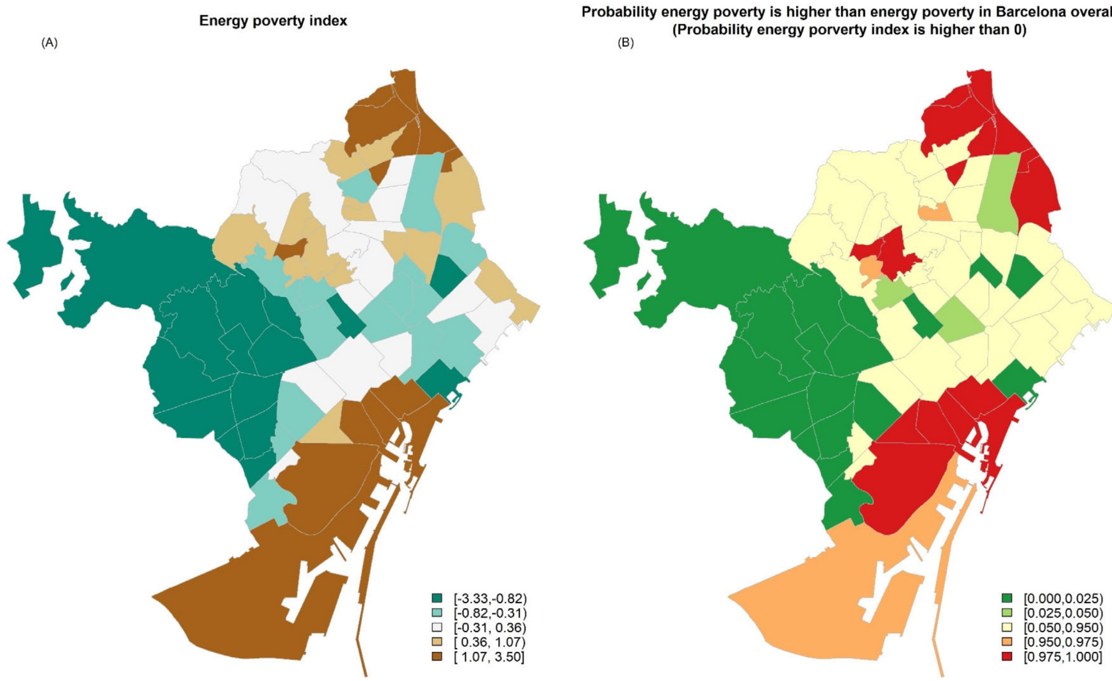


Fig. 1. Geographical distribution of the energy poverty index at the neighborhoods level (A) and probability of the index being higher than the overall value for the city (B). Barcelona, 2016.

0.95. Finally, 20 of the 73 neighborhoods had a significantly higher EP index (probability greater than 0.95) than the average value for the city.

Fig. 1 shows the spatial distribution of the EP index and its probability of being higher, for each neighborhood, than for the city overall. The geographical pattern of the EP index was uneven, with the northernmost neighborhoods, some in the north-west, those in the historic city center (around the port area) and those in the south-east showing the highest values of the EP index (Fig. 1A). In addition, there were 3 spatial clusters of neighborhoods with significantly higher EP indexes (probability greater than 0.95) than the average value for the city (Fig. 1B).

However, examination of the different geographical patterns of the EP SAIs (see Appendix B) revealed some differences with respect to the index. The 2 EP SAIs related to inadequate household temperatures in the cold and warm months followed a similar geographical pattern to each other and to the EP index (Figures S1.A, S1.B, S2.A and S2.B). However, the EP SAI referring to the warm months showed fewer significant percentages (than the EP SAI considering the cold months) in 2 neighborhoods close to the coast (El Gòtic and Barceloneta). The SAI referring to late payment of energy bills showed a significant cluster of high percentages in the historic center and followed a more spatially heterogeneous pattern, with numerous neighborhoods with high percentages in the north and northwest (figures S3.A and S3.B). The SAI of dwellings with physical deficiencies (figures S4.A and S4.B) showed significantly higher values than the city in the historic city center, with 2 neighborhoods in the north of the city (Ciutat Meridiana and Baró de Viver) standing out. In these areas, there was also a high percentage of dwellings without heating or which, even if heating was available, did not use it when necessary (figures S5.A and S5.B), e.g., 32.29% in Ciutat Meridiana, 25.68% in La Barceloneta and 23.66% in El Raval (Table 3). Finally, in the city, 51.43% of dwellings reported not having air conditioning or having it but not using it when necessary and, according to our study, this percentage increased in the city center and southeast, and in various northern neighborhoods, especially those located in the north and northeast (Figures S6.A and S6.B). In some of these neighborhoods, this SAI could even reach values above 75%, as is the case of Ciutat Meridiana (83.19%), Baró de Viver (81.83%), Vallbona (76.19%) and El Raval (76.00%).

4. Discussion

4.1. Main findings

This study identified substantial geographical inequalities in the distribution of EP in the city of Barcelona. The highest EP levels were found in the northernmost neighborhoods, some in the north-west, those in the historic city center and those in the south-east. Within these areas, there were 3 well-defined spatial clusters of neighborhoods with a significant excess of EP compared with the city as a whole.

4.2. Interpretation of results

EP is a complex, multidimensional and dynamic construct that affects different people depending on the combination of multiple social and economic determinants (Bouzarovski and Petrova, 2015; Marí-Dell'Olmo et al., 2017). Important intermediate determinants are low household income, low energy efficiency of housing and high energy prices (Hills, 2011). These intermediate determinants are in turn the result of structural determinants related to the labor, housing and energy markets and their policies (Recalde et al., 2019). All these complexities make measuring

Table 3
Energy poverty index and small-area indicators with their 95% credible intervals (95%CI) and their probability of being higher than the overall value for the city, for each of the 73 neighborhoods. Barcelona, 2016.

Neighborhood		Energy poverty indicators						Energy poverty index
ID number	Name	Temp_cold	Temp_hot	Arrears	Conditions	Heating	Air_cond	
55	Ciutat Meridiana	31.41 (20.13, 46.02)	35.95 (23.54, 51.48)	41.25 (23.79, 59.40)	21.88 (10.67, 35.90)	32.29 (18.79, 48.23)	83.19 (74.19, 90.39)	3.50 (2.60, 4.44)
58	Baró de Viver	35.38 (19.39, 56.83)	42.72 (23.38, 64.90)	32.00 (12.93, 57.99)	22.29 (9.74, 41.50)	25.19 (12.01, 44.74)	81.83 (69.86, 91.54)	3.33 (1.92, 4.85)
56	Vallbona	26.66 (14.33, 43.89)	32.48 (17.96, 53.32)	33.90 (15.55, 57.56)	17.73 (7.70, 33.77)	18.96 (8.81, 33.28)	76.19 (63.05, 87.28)	2.62 (1.23, 4.07)
1	el Raval	19.44 (15.64, 24.06)	21.61 (17.41, 26.80)	22.72 (16.97, 28.69)	16.75 (12.17, 21.35)	23.66 (18.14, 29.13)	76.00 (71.40, 80.96)	2.08 (1.73, 2.43)
54	Torre Baró	19.62 (10.36, 34.27)	23.36 (12.79, 39.03)	28.78 (13.05, 50.95)	14.05 (6.62, 25.92)	17.64 (8.30, 31.07)	69.99 (56.51, 81.99)	1.88 (0.60, 3.30)
57	la Trinitat Vella	20.06 (12.95, 29.03)	24.49 (16.15, 36.12)	23.61 (12.36, 36.80)	13.61 (8.00, 21.46)	14.41 (7.78, 22.29)	68.73 (58.84, 77.67)	1.71 (0.84, 2.51)
3	la Barceloneta	13.54 (8.84, 18.94)	14.90 (9.19, 21.53)	24.62 (16.49, 34.07)	16.82 (10.88, 23.80)	25.68 (18.10, 34.26)	72.46 (65.43, 79.18)	1.67 (1.09, 2.22)
2	el Barri Gòtic	14.28 (9.50, 20.13)	16.55 (10.84, 23.28)	24.24 (15.05, 35.65)	16.62 (10.46, 24.66)	22.08 (14.81, 31.39)	71.90 (63.93, 79.42)	1.65 (0.96, 2.30)
4	Sant Pere, Santa Caterina i la Ribera	13.41 (9.32, 17.87)	15.52 (10.74, 20.82)	21.21 (14.10, 29.92)	17.55 (12.16, 24.60)	20.95 (15.10, 27.34)	72.19 (65.61, 78.75)	1.51 (0.97, 2.01)
12	la Marina del Prat Vermell	18.90 (8.83, 32.71)	22.79 (10.85, 39.53)	19.13 (6.96, 36.41)	14.61 (6.84, 27.11)	14.26 (6.11, 26.96)	68.31 (51.64, 81.89)	1.45 (0.00, 2.78)
53	la Trinitat Nova	17.14 (11.67, 24.38)	20.59 (14.02, 29.24)	23.50 (13.47, 35.12)	12.64 (7.76, 19.38)	13.79 (7.55, 20.77)	66.38 (56.91, 75.47)	1.43 (0.62, 2.18)
38	la Teixonera	16.39 (10.75, 23.23)	20.72 (14.14, 28.94)	23.31 (13.92, 34.23)	10.61 (5.66, 15.95)	12.88 (7.69, 19.79)	63.98 (54.40, 72.42)	1.29 (0.60, 1.95)
51	Verdun	14.14 (9.32, 20.45)	16.49 (10.90, 23.18)	23.18 (14.46, 33.67)	10.93 (6.57, 16.68)	14.68 (9.00, 21.59)	63.50 (54.58, 72.41)	1.14 (0.38, 1.87)
11	el Poble Sec	14.85 (11.01, 19.85)	17.39 (12.84, 23.17)	15.80 (9.33, 23.21)	13.65 (9.26, 18.73)	13.80 (9.15, 19.55)	65.68 (59.52, 72.23)	1.07 (0.51, 1.60)
37	el Carmel	15.43 (11.03, 20.69)	19.57 (14.38, 26.18)	19.82 (13.09, 27.87)	10.72 (6.83, 15.51)	11.20 (7.00, 16.36)	62.61 (55.32, 69.80)	1.06 (0.51, 1.61)
47	Can Peguera	14.12 (5.70, 26.06)	18.75 (7.76, 33.59)	19.94 (6.89, 39.63)	15.01 (6.78, 29.04)	11.41 (4.30, 21.47)	64.08 (46.47, 78.94)	1.01 (-0.68, 2.49)
59	el Bon Pastor	13.28 (8.14, 20.32)	16.87 (10.52, 25.95)	18.24 (8.59, 31.04)	12.17 (6.79, 19.73)	13.34 (7.14, 22.07)	62.39 (52.54, 72.92)	0.92 (0.04, 1.82)
29	el Coll	11.91 (6.95, 18.08)	16.51 (9.77, 25.39)	19.09 (10.10, 31.18)	14.84 (8.02, 24.22)	11.51 (5.60, 19.43)	64.38 (53.96, 74.99)	0.90 (-0.05, 1.76)
10	Sant Antoni	13.28 (9.23, 18.58)	16.85 (11.63, 23.69)	18.08 (11.00, 27.21)	10.63 (6.23, 15.66)	11.54 (6.79, 17.39)	60.79 (53.00, 68.49)	0.81 (0.18, 1.46)
42	la Clota	13.16 (5.71, 25.64)	17.19 (8.04, 33.14)	21.42 (8.09, 43.22)	11.32 (4.45, 21.65)	10.64 (4.20, 21.39)	59.99 (42.39, 75.78)	0.79 (-0.75, 2.47)
46	el Turó de la Peira	11.96 (7.36, 16.71)	15.14 (9.41, 21.85)	22.04 (13.26, 33.29)	9.82 (5.63, 15.59)	10.93 (5.97, 16.96)	59.77 (50.98, 68.56)	0.73 (-0.01, 1.38)
49	Canyelles	11.89 (7.32, 17.84)	14.48 (8.98, 21.82)	20.29 (11.00, 31.65)	9.29 (5.25, 15.81)	11.64 (6.47, 18.49)	58.97 (48.97, 69.28)	0.66 (-0.18, 1.51)
39	Sant Genís dels Agudells	13.47 (8.15, 20.94)	17.57 (10.53, 27.57)	14.26 (6.78, 23.67)	11.13 (6.21, 17.50)	9.82 (4.86, 16.85)	60.88 (50.66, 71.26)	0.62 (-0.32, 1.51)
61	la Sagrera	10.96 (7.66, 14.92)	13.52 (9.54, 18.59)	17.06 (10.10, 25.14)	8.65 (5.21, 12.86)	12.72 (8.42, 18.40)	56.72 (49.00, 64.05)	0.49 (-0.12, 1.10)
70	el Besòs i el Maresme	10.43 (6.27, 15.64)	11.39 (6.57, 16.58)	15.50 (8.80, 25.89)	10.23 (5.73, 15.37)	14.50 (8.42, 22.45)	59.81 (50.88, 69.08)	0.46 (-0.27, 1.12)
41	la Vall d'Hebron	10.82 (5.86, 17.86)	14.18 (8.06, 23.07)	22.52 (11.56, 37.94)	7.58 (3.52, 12.90)	9.10 (4.40, 15.68)	54.35 (41.00, 66.49)	0.38 (-0.60, 1.42)
34	Can Baró	11.20 (6.48, 17.53)	15.01 (8.87, 23.77)	16.12 (8.01, 28.61)	10.24 (5.78, 17.58)	8.61 (3.95, 14.57)	56.83 (45.51, 68.42)	0.36 (-0.60, 1.32)
62	el Congrés i els Indians	11.08 (6.82, 17.06)	13.90 (8.52, 21.55)	13.69 (5.48, 24.38)	10.11 (5.65, 16.35)	11.34 (6.63, 18.19)	57.60 (46.61, 67.78)	0.36 (-0.54, 1.21)
50	les Roquetes	10.66 (6.39, 15.85)	13.03 (8.07, 19.09)	18.66 (10.95, 29.09)	9.20 (5.10, 14.96)	9.92 (5.29, 15.84)	55.12 (45.11, 64.44)	0.36 (-0.48, 1.12)
40	Montbau	10.92 (5.36, 18.84)	13.93 (6.42, 24.30)	16.49 (6.23, 31.29)	9.39 (4.17, 17.08)	9.79 (4.06, 18.66)	57.28 (41.66, 71.39)	0.31 (-1.05, 1.58)
43	Horta	9.70 (6.51, 13.53)	12.52 (8.79, 17.32)	21.71 (14.69, 30.62)	7.31 (4.50, 10.65)	9.04 (5.70, 13.39)	52.28 (44.12, 59.90)	0.25 (-0.34, 0.82)
52	la Prosperitat	9.21 (5.89, 13.04)	11.11 (7.24, 15.98)	14.88 (8.57, 22.19)	9.36 (6.10, 13.91)	9.64 (5.95, 14.41)	54.24 (45.81, 62.27)	0.07 (-0.61, 0.72)
5	el Fort Pienc	8.32 (5.16, 12.75)	10.08 (6.04, 15.21)	16.12 (9.02, 25.00)	8.09 (4.12, 12.44)	11.46 (7.09, 17.64)	54.04 (44.60, 62.84)	0.03 (-0.68, 0.76)
14	la Font de la Guatlla	9.41 (5.05, 15.44)	12.19 (6.71, 19.89)	14.02 (6.36, 26.72)	8.90 (4.61, 15.25)	8.42 (3.84, 14.90)	52.05 (39.31, 64.28)	-0.06 (-1.16, 1.00)
69	Diagonal Mar i el Front Marítim del Poblenou	7.64 (3.70, 13.22)	9.77 (4.96, 17.11)	16.91 (7.50, 30.90)	9.13 (3.90, 16.11)	11.06 (5.31, 19.83)	52.29 (39.03, 64.42)	-0.06 (-1.21, 1.05)
8	l'Antiga Esquerra de l'Eixample	8.69 (5.66, 12.42)	11.90 (7.36, 17.74)	11.00 (5.55, 17.93)	10.93 (6.59, 16.46)	8.86 (5.11, 13.89)	55.47 (46.60, 64.56)	-0.07 (-0.84, 0.65)
36	la Font d'en Fargues	8.57 (4.69, 14.19)	11.49 (6.35, 18.40)	14.21 (6.77, 23.78)	9.15 (4.66, 15.39)	8.58 (4.28, 14.95)	51.36 (39.68, 64.09)	-0.12 (-1.13, 0.89)
33	el Baix Guinardó	8.07 (5.30, 11.40)	10.44 (6.68, 15.44)	14.38 (8.74, 21.75)	8.52 (5.00, 12.60)	8.87 (5.39, 13.62)	53.18 (45.63, 61.61)	-0.13 (-0.82, 0.53)
44	Vilapicina i la Torre Llobeta	8.39 (5.64, 11.71)	10.64 (7.16, 14.58)	16.29 (10.37, 23.81)	7.23 (4.54, 10.43)	7.95 (5.30, 11.57)	49.24 (41.94, 56.77)	-0.18 (-0.76, 0.39)
7	la Dreta de l'Eixample	6.90 (4.29, 9.77)	9.27 (6.15, 13.01)	11.89 (7.05, 18.36)	11.40 (7.89, 16.14)	9.61 (6.29, 13.60)	55.09 (47.42, 62.80)	-0.21 (-0.95, 0.41)
45	Porta	8.62 (5.53, 12.51)	10.90 (7.00, 15.78)	14.30 (8.26, 22.41)	7.57 (4.15, 11.81)	7.73 (4.23, 12.00)	50.12 (41.36, 58.31)	-0.23 (-0.90, 0.48)
71	Provençals del Poblenou	7.30 (4.27, 11.34)	8.94 (5.11, 13.69)	14.56 (8.20, 22.34)	7.60 (4.20, 11.50)	10.27 (5.98, 15.82)	49.72 (40.45, 59.04)	-0.28 (-1.11, 0.49)
35	el Guinardó	7.57 (5.46, 10.18)	9.80 (6.73, 13.08)	13.19 (8.37, 18.84)	8.20 (5.31, 11.11)	8.21 (5.31, 11.60)	50.55 (43.95, 57.29)	-0.31 (-0.83, 0.23)
73	la Verneda i la Pau	7.45 (4.06, 11.42)	8.76 (5.08, 13.69)	13.19 (7.27, 21.18)	7.58 (4.25, 12.11)	10.23 (5.92, 15.46)	51.26 (42.17, 61.09)	-0.32 (-1.15, 0.43)
31	la Vila de Gràcia	7.37 (5.03, 10.19)	10.34 (7.25, 14.17)	9.13 (5.43, 13.52)	13.02 (9.46, 17.96)	7.19 (4.49, 10.17)	53.73 (47.60, 60.00)	-0.36 (-0.89, 0.14)
64	el Camp de l'Arpa del Clot	6.86 (4.05, 10.69)	8.47 (4.52, 13.10)	23.62 (14.14, 34.34)	4.85 (2.30, 8.54)	7.92 (4.07, 12.77)	43.21 (34.39, 51.64)	-0.42 (-1.14, 0.22)
60	Sant Andreu	7.60 (5.46, 10.26)	10.14 (7.34, 13.77)	14.50 (9.62, 20.68)	6.79 (4.42, 9.47)	6.87 (4.35, 9.78)	46.45 (40.23, 52.43)	-0.43 (-0.91, 0.02)
28	Vallcarca i els Penitents	7.76 (4.63, 11.41)	10.75 (6.64, 15.69)	9.93 (5.08, 16.54)	9.88 (6.22, 15.05)	6.71 (3.75, 10.57)	51.95 (43.50, 60.58)	-0.43 (-1.17, 0.30)
6	la Sagrada Família	6.89 (4.71, 9.59)	8.81 (5.92, 12.23)	14.50 (9.30, 21.05)	6.79 (4.03, 9.73)	7.78 (4.82, 11.27)	47.61 (40.56, 54.58)	-0.48 (-1.04, 0.07)
15	Hostafrancs	7.57 (4.36, 11.67)	9.50 (5.57, 14.91)	12.53 (5.84, 21.52)	7.61 (3.99, 12.38)	7.56 (3.98, 12.70)	47.56 (37.12, 57.24)	-0.50 (-1.45, 0.35)
68	el Poblenou	6.34 (3.64, 9.96)	8.05 (4.45, 12.86)	12.55 (6.71, 20.84)	8.88 (5.17, 14.09)	9.17 (5.20, 14.58)	48.71 (39.03, 57.53)	-0.52 (-1.30, 0.30)
48	la Guineueta	6.85 (3.87, 10.12)	8.66 (4.86, 12.81)	13.78 (7.07, 22.12)	7.26 (4.21, 11.31)	7.82 (4.21, 11.90)	47.08 (36.84, 55.90)	-0.54 (-1.43, 0.21)
65	el Clot	6.49 (3.74, 9.61)	8.11 (4.81, 12.01)	16.87 (10.05, 25.90)	5.70 (2.95, 9.15)	8.40 (4.86, 13.09)	44.75 (35.41, 53.84)	-0.55 (-1.29, 0.16)
66	el Parc i la Llacuna del Poblenou	5.79 (3.35, 8.86)	7.07 (3.96, 10.39)	11.40 (5.62, 18.88)	8.51 (4.81, 13.07)	9.54 (5.60, 14.78)	48.56 (39.44, 58.33)	-0.67 (-1.52, 0.13)
9	la Nova Esquerra de l'Eixample	7.36 (4.85, 10.67)	9.86 (6.38, 14.16)	12.03 (6.89, 18.96)	6.74 (4.02, 10.01)	5.86 (3.25, 8.99)	44.54 (36.45, 51.79)	-0.68 (-1.36, -0.01)
30	la Salut	6.58 (3.97, 9.98)	9.54 (5.90, 14.06)	10.26 (5.05, 16.63)	8.16 (4.60, 12.61)	5.85 (3.21, 9.14)	47.28 (38.31, 56.09)	-0.75 (-1.53, 0.03)
13	la Marina de Port	6.85 (4.03, 10.39)	8.51 (5.12, 12.76)	10.95 (5.30, 17.72)	5.89 (3.12, 9.29)	7.12 (4.14, 11.44)	43.63 (35.37, 51.42)	-0.82 (-1.52, -0.15)

(continued on next page)

Table 3 (*continued*).

63	Navas	6.62 (4.08, 10.05)	8.50 (5.04, 12.85)	10.95 (5.47, 18.24)	6.10 (3.46, 9.45)	7.27 (4.13, 12.02)	43.04 (35.02, 51.80)	-0.82 (-1.62, -0.07)
18	Sants	6.98 (4.64, 9.97)	9.33 (5.95, 13.28)	9.19 (4.90, 14.86)	7.83 (4.94, 11.30)	5.61 (3.16, 8.67)	45.21 (37.46, 53.03)	-0.84 (-1.48, -0.15)
32	el Camp d'en Grassot i Gràcia Nova	5.70 (3.54, 7.85)	7.86 (5.11, 11.23)	8.43 (4.75, 13.08)	8.91 (5.89, 12.64)	6.77 (4.08, 10.02)	48.22 (41.63, 55.20)	-0.90 (-1.52, -0.29)
16	la Bordeta	6.32 (3.46, 10.06)	8.05 (4.29, 13.03)	8.79 (3.85, 16.53)	7.72 (4.28, 12.93)	6.47 (3.26, 11.30)	44.18 (34.14, 55.33)	-0.98 (-1.96, -0.04)
17	Sants - Badal	6.45 (3.74, 10.04)	8.07 (4.57, 12.54)	9.27 (4.32, 16.20)	6.34 (3.22, 10.26)	6.32 (3.39, 10.33)	42.99 (33.80, 53.03)	-1.02 (-1.88, -0.17)
72	Sant Martí de Provençals	4.79 (2.48, 7.77)	5.71 (2.84, 9.36)	12.59 (6.22, 20.98)	5.08 (2.37, 8.18)	7.67 (3.96, 12.94)	39.95 (29.81, 49.20)	-1.21 (-2.15, -0.37)
67	la Vila Olímpica del Poblenou	3.89 (1.60, 6.91)	5.09 (2.10, 9.59)	11.81 (4.77, 22.75)	7.48 (3.25, 13.43)	7.82 (3.50, 14.46)	41.06 (27.51, 53.15)	-1.31 (-2.59, -0.17)
22	Vallvidrera, el Tibidabo i les Planes	5.11 (2.06, 9.70)	7.39 (2.93, 13.90)	5.77 (1.79, 12.78)	11.31 (5.60, 21.72)	5.58 (2.15, 11.26)	44.58 (30.82, 60.59)	-1.36 (-2.78, -0.06)
27	el Putxet i el Farró	4.51 (2.30, 7.60)	6.41 (3.36, 10.65)	4.60 (1.77, 8.68)	11.08 (6.71, 17.33)	5.63 (2.89, 9.69)	44.76 (35.21, 53.57)	-1.53 (-2.42, -0.67)
25	Sant Gervasi - la Bonanova	3.69 (1.97, 6.00)	5.40 (3.18, 8.58)	4.43 (1.93, 7.82)	8.05 (4.85, 12.08)	4.19 (2.11, 6.91)	37.36 (30.00, 46.22)	-2.04 (-2.90, -1.26)
19	les Corts	3.63 (2.26, 5.39)	5.02 (3.23, 7.27)	4.47 (2.31, 7.22)	5.33 (3.45, 7.32)	3.89 (2.40, 5.89)	32.78 (27.89, 37.89)	-2.27 (-2.87, -1.76)
26	Sant Gervasi - Galvany	2.96 (1.68, 4.52)	4.23 (2.41, 6.38)	3.96 (1.99, 6.69)	8.04 (5.21, 11.71)	4.48 (2.50, 6.95)	36.44 (30.04, 42.96)	-2.29 (-2.98, -1.65)
23	Sarrià	3.13 (1.46, 5.45)	4.62 (2.29, 8.00)	3.86 (1.31, 7.78)	6.43 (3.35, 10.60)	3.56 (1.60, 6.54)	32.39 (23.13, 42.21)	-2.51 (-3.54, -1.58)
20	la Maternitat i Sant Ramon	3.21 (1.66, 5.16)	4.16 (2.07, 6.81)	4.21 (1.75, 7.92)	4.91 (2.47, 8.07)	3.92 (1.93, 6.54)	31.34 (24.29, 39.16)	-2.54 (-3.41, -1.80)
24	les Tres Torres	2.58 (1.14, 4.72)	3.81 (1.67, 6.71)	3.73 (1.17, 7.47)	5.73 (2.85, 9.72)	3.40 (1.54, 6.49)	29.93 (19.82, 40.44)	-2.84 (-4.03, -1.76)
21	Pedralbes	2.10 (0.84, 3.69)	3.12 (1.31, 5.70)	3.24 (1.06, 6.90)	4.99 (2.61, 8.61)	2.58 (1.13, 4.86)	25.60 (17.37, 34.52)	-3.33 (-4.46, -2.32)
*	Overall Barcelona city	9.36	11.41	13.90	9.66	9.96	51.43	0

Probability of being higher than the overall value for Barcelona city (*)

(dark green)	[0, 0.025)
(light green)	[0.025, 0.05)
(pale yellow)	[0.05, 0.95)
(orange)	[0.95, 0.975)
(red)	[0.975, 1]

EP a difficult task that requires methods that take into account the multiple characteristics of EP and allow its optimal quantification. In recent years, various proposals have been made to try to measure EP more comprehensively through composite indicators (or indices). These range from simple combinations of EP indicators to more complex methods, vary in the geographical level of analysis, and have been proposed for different contexts (e.g. high- and low-income countries) (Siksnelyte-butkiene et al., 2021). The index presented in this study is based on 6 underlying indicators, which are also estimated at the neighborhood level, a more detailed disaggregation level than that used at the sampling stage.

In Barcelona, most of the key intermediate determinants of EP show a geographical pattern in the city. Additionally, these geographical patterns may differ across these determinants. For example, the household disposable income per capita index calculated for each neighborhood shows large contrasts between the north and west of the city (Ajuntament de Barcelona, 2017). Regarding proxy indicators of the energy efficiency of dwellings, such as the age of buildings, there are notable geographical differences that reflect the historical process of urbanization of the city. Thus, the city center has a high percentage of old buildings (pre-1940), while in other areas most of the housing stock was built in the decades of greatest growth of the city, because the city had to absorb a large wave of migration (between 1961 and 1980), and finally, in the eastern part of the city, there have been large urban development operations in the last 30 years (Ajuntament de Barcelona, 2021, 2016b; Donat et al., 2015). The state of preservation of buildings is also unevenly distributed across the city. The highest percentages of buildings considered to be in a dilapidated or poor state of repair are found in the city center and in neighborhoods with greater socioeconomic deprivation, where the percentage can exceed 10% (Ajuntament de Barcelona, 2021, 2016b). Therefore, the uneven spatial distribution observed in this study in the EP SAIs and index was similar to that expected and is consistent with the different patterns of some of its determinants in the city (Robinson et al., 2018).

EP SAIs related to inadequate home temperatures in the cold and warm months follow a very similar geographical pattern, probably due to poor building isolation. In addition, neighborhoods with higher values for these SAIs tend to be those where there are older, hastily constructed buildings with low construction standards (Ajuntament de Barcelona, 2016b; Donat et al., 2015). On the other hand, the less significant percentages of the SAI of inadequate temperatures in the warm months in 2 neighborhoods close to the coast could be due to the effect of sea breezes on daytime temperatures in these neighborhoods (Yamamoto and Ishikawa, 2020).

In turn, the SAI referring to arrears in utility bills showed a similar geographical pattern to that of the income of its inhabitants. Except for some neighborhoods on the north-eastern border of the city, such as La Verneda i la Pau and El Besos i el Maresme, which have very low incomes (Ajuntament de Barcelona, 2017), their values for this EP SAI were not significantly higher than the Barcelona average. In contrast, the income level of Barri Gòtic (located in the city center) is medium-high, but the percentage of households with late payment of bills is 24.24% (1.73 times higher than that of the city as a whole). This could be because the disposable household income per capita indicator calculated by the City Council may be affected by an ecological fallacy. According to the National Institute of Statistics (Instituto Nacional de Estadística, 2020), many areas of this neighborhood have a much lower average income level (per person) than that of the rest of the city, while in other areas there has been a major gentrification where many residents of the neighborhood have been replaced by inhabitants from northern Europe, with higher purchasing power (Ajuntament de Barcelona, 2017; Sánchez-Ledesma et al., 2020). This artifact could modify the average income level of the neighborhood but have little influence on the percentage of people with difficulties in paying bills.

With regard to the spatial distribution of the SAI that identified dwellings with physical deficiencies, such as the presence of leaks or damp, the highest values were concentrated in neighborhoods with older buildings and poor construction quality, such as those in the historic city center. In addition, the Ciutat Meridiana neighborhood stands out, where 94.85% of dwellings were built hastily between 1961 and 1980 and many of them show construction deficiencies, and Baró de Viver, with 14.95% of dwellings in a poor state of repair (Ajuntament de Barcelona, 2021).

An important finding was the continued existence of neighborhoods in the city with a high percentage of the population that did not have heating or did not use heating when necessary. This factor is relevant because, although Barcelona enjoys a temperate climate, cold temperatures currently have a greater impact on mortality in the city than warm temperatures, and it is estimated that in the period 1992–2015 they were responsible for more than 5% of mortality in Barcelona (Marí-Dell'Olmo et al., 2019b).

Barcelona also has periods of the year with high or extremely high temperatures. In the last 34 years, there have been 8 heat waves and, due to climate change, it is estimated that this frequency will increase significantly, with between 1 and 4 a year by the end of the century (Ajuntament de Barcelona, 2018a). Moreover, these high temperatures and heat waves in Barcelona pose a demonstrated risk and have a major impact on people's health (Borrell et al., 2006; Ingole et al., 2020; Marí-Dell'Olmo et al., 2019b). However, a high percentage of the households in the city report not having air conditioning or not using it when necessary. In this study, this percentage rose to more than 75% in some of the low and very low-income neighborhoods.

4.3. Limitations and strengths

Obtaining reliable EP estimates at the small-area level is by no means a trivial task, since most information sources (usually surveys) used to obtain EP indicators are not usually representative at this geographical disaggregation. Several approaches to estimating EP at the small-area level have been used (Baker et al., 2003; Castaño-Rosa et al., 2019; Centre for Sustainable Energy, 2001; DECC, 2009; Fahmy et al., 2011b; Gouveia et al., 2019; HM Government, 2013; März, 2018; Morrison and Shortt, 2008; Robinson et al., 2018; Sanchez-Guevara et al., 2019; Simoes et al., 2016; Wilson et al., 2012), ranging from simple procedures such as looking for reliable proxy indicators of EP available at the small-area level, to employing procedures with several steps (including several information sources with different scales and statistical methods).

The main strength of this study is that, for the first time in Barcelona, it obtained reliable estimates of EP at the neighborhood level, identifying significant geographical differences that could be highly useful for local EP policies. To obtain these estimates, we designed a sophisticated new method, employing statistical models that draw on the information provided by all the EP indicators used, taking into account the information available in adjacent neighborhoods, which is a key aspect in small-area estimation models. Moreover, our multivariate approach considers the EP indicators as potentially dependent. This assumption preserves the potential relationship, in contrast to models assuming independence, which is the cornerstone for the subsequent PCA used to construct the EP index. However, as a drawback, less accurate estimates of EP SAIs may occur in some neighborhoods at the outskirts of the city, due to the lack of information from adjacent neighborhoods outside the city (frontier effect) (Martinez-Beneito and Botella-Rocamora, 2021).

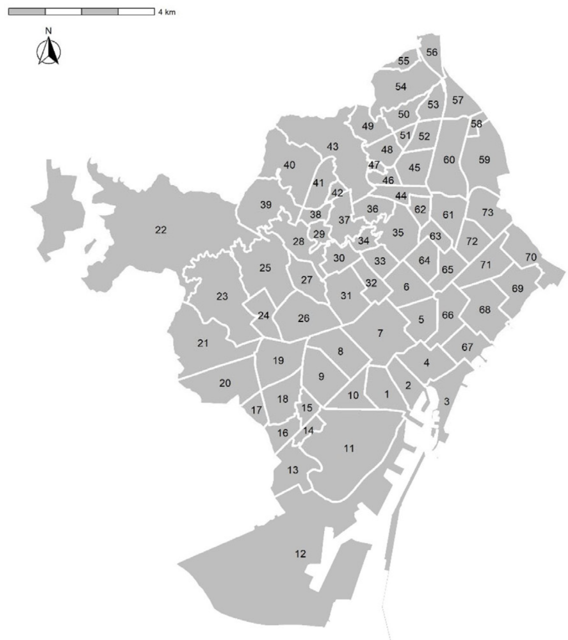
Another strength of the study is the use of the last BHS as an information source, in which questions on EP were included for the first time, providing a unique opportunity to explore this phenomenon with information from more than 3500 individuals. Nonetheless, we were unable to include EP indicators based on expenditure and income, which are the ones traditionally most used in this type of studies. The variables needed to construct them had a high percentage of missing values in the BHS, which invalidated their use. However, as previously stated, the indicators used are part of the main indicators recommended by the EU Energy Poverty Observatory and cover different expressions of EP (EU Energy Poverty Observatory, 2021). Furthermore, the subjective indicators used take into account the different energy needs of households and are considered bottom-up information, as it is the people themselves who assess whether, for example, the thermal comfort is adequate or not(Thomson et al., 2017a). Finally, it should be noted that official statistics sometimes make the most affected groups invisible, such as, in the case of the study in question, people who do not have a rental or property contract (squatters) and who therefore cannot access even regular energy supplies.

5. Policy implications, future work and conclusion

This study has different EP policy implications in Barcelona. First, local governments could implement policies to reduce geographical inequalities by focusing their EP interventions on the neighborhoods with the highest levels and specifically on the populations most vulnerable to EP within these neighborhoods. In this sense, the Barcelona City Council has implemented a network of Energy Advice Points (EAP), which offer personalized attention on energy rights to the affected population (Ajuntament de Barcelona, 2018b). Currently, there is an EAP in each of the 10 districts of Barcelona, so they are evenly distributed throughout the city. Our index could be useful to improve this service with proportional universality, taking into account the areas where there is a greater need to reinforce the EAPs and place new resources in those neighborhoods with higher levels of EP. In the same vein, interventions to improve the energy efficiency of buildings could be prioritized in neighborhoods with the worst EP SAIs related to inadequate temperatures, physical deficiencies and lack of heating or air conditioning such as, for example, funding programs for the energy rehabilitation of buildings.

Finally, in the context of a climate emergency, reliable estimates at the neighborhood level, such as the percentage of people with inadequate summer temperatures in their homes or the percentage of people who do not have air conditioning or who do not use it when necessary, could be useful from a climate justice point of view. These estimates allow both to prioritize the targeting of interventions to reduce the health impacts of heat on the most vulnerable people and to strengthen existing ones, such as increasing the quantity and quality of vegetation and shaded areas in the city, improving the heatwave early warning systems, or through the creation of climate shelters. For example, schools playgrounds of most affected neighborhoods could be transformed into climate shelters (introducing vegetation, shaded areas and aquatic components) and be opened to the wider public in non-school period (Ajuntament de Barcelona, 2019; UIA - Urban Innovative Actions, 2019) However, in all these cases, once the areas have been prioritized, interventions should focus on people who are particularly vulnerable to EP and its effects on health, such as children, the elderly, women from disadvantaged social classes, dependent people and people with illnesses (Oliveras et al., 2020; Thomson and Snell, 2013). Therefore, a good practice could be, implementing care or social superblocks, oriented to the integral attention of vulnerable people by domiciliary teams (Barcelona city council, 2020).

The estimation of EP indicators and the EP index at small-area level as well as the proposed methodology may lead to interesting future research. The EP index could be used to study hypotheses in groups of neighborhoods according to their EP or to study its association or interaction with other indicators as, for example, health indicators or other situations of socioeconomic hardship, like residential or food insecurity. On the other hand, from the next editions of the city health survey, it will be possible to perform a spatio-temporal small-area analysis that will allow to study the evolution of the geographical pattern of EP, to quantify the evolution of EP in each neighborhood in a reliable manner and to detect those neighborhoods where EP is increasing significantly. For example, in Barcelona, this would allow assessment of



ID number	Neighborhood name	ID number	Neighborhood name
1	el Raval	38	la Teixonera
2	el Barri Gòtic	39	Sant Genís dels Agudells
3	la Barceloneta	40	Montbau
4	Sant Pere, Santa Caterina i la Ribera	41	la Vall d'Hebron
5	el Fort Pienc	42	la Clota
6	la Sagrada Família	43	Horta
7	la Dreta de l'Eixample	44	Vilapicina i la Torre Llobeta
8	l'Antiga Esquerra de l'Eixample	45	Porta
9	la Nova Esquerra de l'Eixample	46	el Turó de la Peira
10	Sant Antoni	47	Can Peguera
11	el Poble Sec	48	la Guineueta
12	la Marina del Prat Vermell	49	Canyelles
13	la Marina de Port	50	les Roquetes
14	la Font de la Guatlla	51	Verdun
15	Hostafrancs	52	la Prosperitat
16	la Bordeta	53	la Trinitat Nova
17	Sants - Badal	54	Torre Baró
18	Sants	55	Ciutat Meridiana
19	les Corts	56	Vallbona
20	la Maternitat i Sant Ramon	57	la Trinitat Vella
21	Pedralbes	58	Baró de Viver
22	Vallvidrera, el Tibidabo i les Planes	59	el Bon Pastor
23	Sarrià	60	Sant Andreu
24	les Tres Torres	61	la Sagrera
25	Sant Gervasi - la Bonanova	62	el Congrés i els Indians
26	Sant Gervasi - Galvany	63	Navas
27	el Putxet i el Farró	64	el Camp de l'Arpa del Clot
28	Vallcarca i els Penitents	65	el Clot
29	el Coll	66	el Parc i la Llacuna del Poblenou
30	la Salut	67	la Vila Olímpica del Poblenou
31	la Vila de Gràcia	68	el Poblenou
32	el Camp d'en Grassot i Gràcia Nova	69	Diagonal Mar i el Front Marítim del Poblenou
33	el Baix Guinardó	70	el Besòs i el Maresme
34	Can Baró	71	Provençals del Poblenou
35	el Guinardó	72	Sant Martí de Provençals
36	la Font d'en Fargues	73	la Verneda i la Pau
37	el Carmel		

Fig. A.1. Geographical distribution, identification (ID) number and name of the neighborhoods of Barcelona city.

neighborhood compliance with the climate plan target of eliminating EP by 2030 (Ajuntament de Barcelona, 2018a). Moreover, the methodology developed in this study can be replicated in representative surveys of specific population groups with greater vulnerability to EP, such as children and adolescents, thus also favoring the visibility of geographical inequalities in these groups. This study can also be replicated in regions with surveys that include questions on EP and with representative registers in the small-area of study that have some socioeconomic indicators shared with the surveys and, therefore, a detailed document (Appendix B) is provided to replicate the method used in this study. In addition, calculation of these indicators before and after the implementation of a local policy or intervention, could also allow evaluation of its effectiveness (Gouveia et al., 2019). Finally, the EP index or indicators obtained can be used for the construction of other indexes at the small area level, for example, to create heat wave vulnerability indexes.

In conclusion, this study has obtained several indicators and a composite indicator (index) of EP at the small-area level in the city of Barcelona using a novel method. These SAIs have allowed analysis of the multidimensionality of EP in the city and its diverse geographical patterns, and identification of the most affected neighborhoods and, therefore, those most susceptible to interventions to alleviate EP. Moreover, the calculation of these SAIs in future surveys will allow improved surveillance of EP and monitoring and evaluating its trends over time at the small-area level. In short, these indicators are a very useful tool for policy makers and local authorities.

Institutional review board statement

This study was approved by the Clinical Research Ethics Committee of Hospital del Mar (2015/6155/I).

CRediT authorship contribution statement

Marc Marí-Dell'Olmo: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Supervision. **Laura Oliveras:** Conceptualization, Methodology, Formal analysis, Writing – review & editing. **Carlos Vergara-Hernández:** Conceptualization, Methodology, Formal analysis, Writing – review & editing. **Lucia Artazcoz:** Conceptualization, Writing – review & editing. **Carme Borrell:** Conceptualization, Writing – review & editing. **Mercè Gotsens:** Conceptualization, Writing – review & editing. **Laia Palència:** Conceptualization, Writing – review & editing. **María José López:** Conceptualization, Writing – review & editing. **Miguel A. Martinez-Beneito:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision.

Declaration of competing interest

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

Data availability statement

Data available upon request.

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Appendix A

See Fig. A.1.

Appendix B. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.egyr.2021.12.025.

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