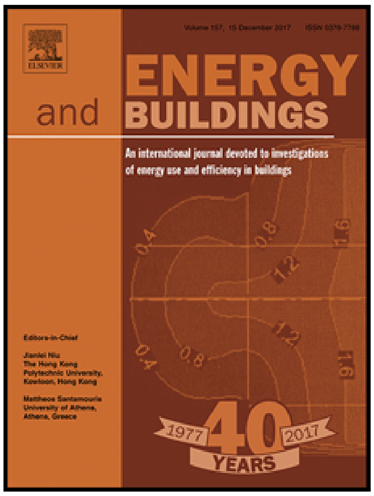

Assessing population vulnerability towards summer energy poverty: Case studies of Madrid and London

Carmen Sanchez-Guevara , Miguel Núñez Peiró , Jonathon Taylor , Anna Mavrogianni , Javier Neila González

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Assessing population vulnerability towards summer energy poverty: Case studies of Madrid and London

Abstract

Climate change is expected to increase the frequency and duration of hot weather and its associated adverse health effects. In dense urban areas, these phenomena will be exacerbated by the Urban Heat Island (UHI) effect and indoor overheating.

This paper assesses population exposure and vulnerability to high summer temperatures by exploring the geospatial connection between the UHI, housing energy efficiency and overheating risk, and social vulnerability indicators, such as income and the elderly population. Focusing on Madrid and London, two European cities with strong UHIs but contrasting drivers of indoor heat risk, the spatial distribution of selected indicators were analysed by means of Geographical Information Systems, and areas with the highest vulnerability towards summer energy poverty were identified.

It was found that while 'hot and vulnerable' areas are present in both Madrid and London, there are significant differences in climate, socioeconomic distribution and housing between the two cities. In warmer climates such as Madrid, energy poverty - traditionally defined by wintertime heating - requires its definition to be broadened to include summertime cooling needs; in the context of climate change and urban warming trends, this may soon also be the case in northern cities such as London.

Keywords: energy poverty, fuel poverty, heat vulnerability, cooling energy demand, urban heat island, low income, elderly, London, Madrid

1 Introduction

There is unequivocal evidence that climate is changing globally due to anthropogenic activities [1]. Climate change will negatively impact human health and wellbeing, with the projected increases in both the severity and frequency of extreme hot weather and heat waves predicted to be a major cause of adverse public health effects. Following the 2003 European heat wave that resulted in numerous excess deaths - 6,461 excess deaths in Spain (22.9%) and 1,987 in England and Wales (4.9%) -[2], there has been increasing awareness and public concern about the need to identify the population groups that may be disproportionately affected by climate change and, in particular, excess heat exposure. Epidemiological evidence indicates that the elderly (older than 65) are at elevated risk of heat-related mortality [3–7], a situation that can be worsened as they are more likely to suffer from Non-Communicable Diseases (NCDs), mental and physical impairment, or be socially isolated, homeless or in poverty. Carmona et al. [8] suggest that age or income indicators need to be combined to explain variations in heat wave mortality. Income has been associated with an increased risk of heat-related death in a selection of studies [9], although other similar studies were inconclusive [10–12].

A wide range of factors may influence urban heat exposure. Densely built urban areas are likely to be hardest hit by the increased occurrence of hot episodes due to the presence of the Urban Heat Island (UHI) effect. A number of studies have estimated the UHI-related increment of excess heat death risk in various cities, such as London [13], Paris [14], Quebec [15], Philadelphia [16], Berlin and Brandenburg [17], and Shanghai [18]. Building characteristics are also important modifiers of heat risk. It has been shown that those living in old buildings with no insulation or in flats with bedrooms at the top floor are at highest risk during a heat wave [19]. A possible connection between access to air conditioning – associated with income - and reduction in heat wave mortality has also been suggested [20].

These findings indicate a need to broaden current definitions of *energy poverty*. Caused by low household income, high energy bills, and low dwelling energy efficiency, the term has traditionally been associated with living on a lower income in a home which cannot be kept warm at reasonable cost [21]. In cooling-dominated climates, and increasingly in more northern climates, an extended definition of fuel poverty that addresses the ability of a household to maintain indoor temperatures at safe levels during summer is necessary. Thus, cooling needs and overheating risk need to be incorporated into the energy poverty equation [22–25]. The enhancement of the definition of energy poverty will lead to a better assessment of the problem and give the opportunity of setting better solutions for impacted households as population delimited as being vulnerable to summer extreme temperatures such as elderly, children, pregnant women, people with chronic or neurodegenerative diseases have been indicated as well as being susceptible to winter extreme temperatures [26–28]. Notably, recent studies have suggested that neither heat risks nor cold risks are perceived as personal risks by vulnerable individuals, which further necessitates work to raise awareness of temperature induced health risk and inequalities [29,30]. The identification of urban areas where excess heat exposure coincides with high heat vulnerability ('hot spots') is commonly performed by planners and public health policymakers using geospatial models of heat risk. The development of spatially explicit heat related vulnerability indices that map risk indicators to locate hot spots has been performed in multiple studies [31–33], including a number using Geographic Information Systems (GIS) [34–38].

1.1 Objective

This research aims to explore the geospatial connection between heat exposure due to the UHI and dwelling characteristics, and heat vulnerability due to age and income in order to detect urban areas where households may be affected by *summer energy poverty* under the current and future climate. The study analyses Madrid and London, two European cities with a strong UHI but contrasting climates, socioeconomic profiles, and housing characteristics. In addition, this study aims to not only give steps to assess vulnerability towards summer fuel poverty in both cities and compare them but also propose a common methodology that could be employed in other European cities.

2 Means and methods

2.1 Indicators selection and regional scope

Madrid and London were selected as case studies as they are both large urban areas with a significant UHI effect but with climate, socioeconomic and housing typology differences that would allow for a useful comparison.

In this study, to assess citizens' heat exposure and vulnerability, relevant indicators were adapted to the urban context. First, UHI intensity was considered as it introduces relevant differences in microclimate conditions that have great impact on housing thermal performance. The presence of people over 65 was also considered a key parameter as health risks increase in people over 65 [39]. On the other hand, the energy price factor was not included in the study. First, as electricity is the main energy source used for cooling energy consumption in both cities, it does not represent an inequality parameter within the same city. Furthermore, London homes do not usually have air conditioning equipment [40]. Talking strictly about summer energy poverty in London can be premature nowadays. Even so, current indoor overheating and exposure to uncomfortable temperatures combined with predicted changes in summer temperatures suggest summer energy poverty might become a problem in the near future.

As a result, the risk from summer energy poverty was delimitated as a combination of the heat exposure of the population, measured by the UHI intensity and housing thermal performance during summer, plus the vulnerability of households, as a function of income and the presence of elderly people. The spatial distribution of these parameters was mapped and analysed for each city. A first comparison between cities was carried out classifying values of selected variables by deciles to allow for a more meaningful, direct comparison of these variables between the two cities. Second, the overlap of these variables was analysed to understand possible relations amongst them within each city and how these relationships varied across cities. The analysis of the overlap of selected variables was conducted using the statistical hot spot analysis tool available in the Spatial Statistics toolbox from ArcGIS 10.5 [41]. The hot spot analysis is based in the Getis-Ord statistic (Gi*), which evaluates the autocorrelation of a variable according to its spatial distribution. This statistical technique allows the identification of both *hot spots* (positive spatial autocorrelation) and *cold spots* (negative spatial autocorrelation), according to aa certain confidence interval (90%, 95% and 99%). In this study, 90% of confidence was used and only the *hot spots* were considered in the analysis, as they identified the locations where higher values of each variable concentrated; only in the case of the income the *cold spots* were considered instead of the *hot spots*.

2.2 UHI intensity

In Madrid, UHI data were derived from a network of 20 temperature and humidity sensors, which was installed by the MODIFICA project (Predictive Model For Dwellings Energy Performance Under The Urban Heat Island Effect) and has been functioning since July 2016. In addition to these 20 points, data from three urban weather stations from the State Meteorology Agency were also used. All the records were gathered on an hourly basis and from June to August 2017.

In London, UHI temperatures for the period May 26th- August 31st 2006 were obtained from a 1 km grid of hourly air temperatures, modelled for the LUCID project (Local Urban Climate Model and its

Application to the Intelligent Design of Cities) by Bohnenstengel [42]. The model, which accounts for building geometry within grid cells when calculating the urban surface energy balance, was performed using the Met Office Unified Model and the urban surface energy balance parametrisation (MORUSES) [43].

We sought to evaluate UHI heat exposure in a manner that would account for population adaptation to heat. For both cities, the spatial variation in UHI intensity was appraised by means of cooling degree hours (CDH). Here, the baseline temperature threshold to calculate these CDHs was derived from the upper adaptive *indoor* comfort temperature threshold estimated for each city [44]. The adaptive comfort criterion was considered the most appropriate for this study for several reasons. First, this standard assesses the occupants' ability to adapt to climate, which enables the consideration of climatic and population acclimatisation differences between Madrid and London. Second, adaptive comfort thresholds better reflect minimum thermal habitability conditions that should be granted for energy poor households [45,46]. Third, people enjoy the widest range of adaptation abilities in domestic settings, which is in accordance with the adaptive standard.

According to the adaptive thermal standard in ASHRAE 55-2013 [47,48], indoor comfort temperature is dependent on external temperature and can be determined as follows:

$$T_{ot} = 0.31T_o + 17.8$$

Where T_{ot} is indoor comfort operative temperature and T_o is the mean outdoor temperature of previous days. The standard also enables the calculation of T_o with monthly mean values making the method suitable for cities where hourly data are not accessible. Comfort thresholds were calculated with 90% acceptability as energy vulnerable households (with high presence of elderly, children or people with chronic diseases) tend to have slightly higher thermal requirements. Furthermore, this standard is appropriate for a metabolic rate between 1 and 1.3 met and clothing rates between 0.5 and 1, all of them like activity and clothing levels in dwellings as set in EN 15251:2007 [49].

Adaptive comfort thresholds were calculated for June, July and August and the mean outdoor temperature (T_o) was obtained from monthly mean values according to the standard. For the city of Madrid, T_o was derived from the temperature data registered at the weather stations from Barajas Airport. In London these data were extracted from the UHI model for the location of Heathrow Airport. Summer outdoor temperatures for both cities as well as the obtained adaptive comfort thresholds are presented in Table 1.

Table 1. Summer weather data overview of selected cities

		Mean temp. (ºC)	Maximum (mean) temp. (ºC)	Minimum (mean) temp. (ºC)	Upper 90% acceptability (ºC)	Lower 90% acceptability (ºC)
Madrid	June	25.9	32.5	18.1	28.3	23.3
	July	26.2	32.9	18.1	28.4	23.4
	August	26.1	32.7	18.3	28.4	23.4
London	June	17.7	22.0	12.8	25.8	20.8
	July	21.0	25.9	15.8	26.8	21.8
	August	16.8	20.2	13.3	25.5	20.5

For night time some variations were made as the standard does not reflect sleeping hours (from 11 pm to 7 am). Fixed thresholds along the summer but adapted by city were considered: 24 ºC in London, based on CIBSE Guide A [50]; and 27ºC for Madrid as reflected in the Spanish Technical Code criteria for evaluating the energy performance of Spanish buildings [51]. Based on obtained thresholds, cooling degree hours were broken down by months, and by day and night. Distinguishing between day and night was considered important as the UHI effect varies during the day, reaching its peak of intensity during the night-time. Previous studies have defined the night-time UHI as a determinant driver of heat-related mortality and morbidity in urban areas [5,52]. The reason is that the relatively high minimum temperatures originated by the UHI during the night, in combination with high maximum temperatures during the day, usually lead to a greater level of heat stress in comparison to rural areas [53–55]. This is particularly relevant during heatwaves [56–58], when dwellers might experience heat stress for several days. During such events, energy-poor users, who might not be able to access or to afford air conditioning, might also get no respite from daytime heat at night [59,60].

Last, degree hours were interpolated across both cities and adapted to administrative delimitations for further comparison (sub-cities in Madrid and wards in London). For London, the CDHs were calculated within the modelled grid. For Madrid, the kriging geostatistical analysis method from ArcGIS 10.5 software was used to interpolate between the computed CDHs at each sensor location. The variogram was set to be exponential, as it has been widely used in meteorology and contamination prediction and it gave a smaller mean-squared error than the spherical and the gaussian variograms [61–63]. To make data comparable between cities, values were classified into deciles, with the first decile representing the highest temperature values and hence the most severe weather conditions. Additionally, the arithmetic mean value of all the records within each *sub-city* (Madrid) and ward (London) delimitation was estimated using the *zonal statistical tool* from the same software.

2.3 Housing stock energy efficiency

The performance of the housing stock under hot outdoor conditions was considered the other key parameter to measure population exposure to heat. In Madrid, energy efficiency can be measured by means of theoretical cooling demand. In the London housing stock, air conditioning ownership rates are very low and, therefore, the most appropriate approach is the evaluation of indoor overheating. Therefore, the assessment of this indicator was conducted differently for each city.

For the city of Madrid, there is still no detailed census regarding the housing stock energy consumption or a database containing the Energy Performance Certificates (EPC) of dwellings that enables mapping this indicator. Cooling energy demand was therefore derived from the Technical Study on Energy Poverty in the city of Madrid [64], wherein housing energy demand was related to the year of construction as this parameter implies certain building typologies, construction system characteristics, amount of glazing, or the building standards in place at the time of construction [65,66]. Madrid housing stock can be divided into five construction periods, wherein relevant common characteristics can be found [67]:

1) A first period prior to 1940, that represents the 11% of all dwellings, contains the oldest housing stock built with thick masonry walls with high thermal inertia and wooden window frames with solar protection devices.

2) Dwellings constructed between 1940-1960, which accounts for 17% of the stock and is characterised by a cheap construction with low thermal quality.

3) Dwellings constructed between 1960 and 1980, accounting for 40% of Madrid housing stock

4) From 1979 housing production changes due to the first Spanish Thermal Regulation that forces minimum thermal performance in new constructions what supposes the effective introduction of insulation in dwellings enclosure [65].

5) Dwellings constructed up to 2006, which account for 25% of Madrid dwellings, and which were constructed after the adoption of the Spanish Technical Code [66] and the Building Thermal Mechanical Systems Regulation (RITE by its initial in Spanish) [68].

Housing year of construction was extracted from the Spanish Land registry [69]. The Madrid housing stock was then classified as follows by letters, from B (the lowest cooling demand) to D (the highest cooling demand): before 1940 (B), from 1941 to 1980 (D), from 1981 to 2006 (C), from 2007 onwards (B).

The estimate of indoor overheating risk for London is based on the building physics modelling framework described by Taylor et al [70]. The outputs of these building physics models have been used to develop a neural network (NN) metamodel for overheating [71], enabling more rapid estimate of indoor overheating risk based on a reduced set of building parameters. In addition, the coverage and detail of the housing stock model has been significantly improved by parameterising individual housing data from the Energy Performance Certificate (EPC) database on housing geometry, construction, and energy performance characteristics [72] as inputs to the NN metamodel. In this study, we employ the NN model on the EPC dataset to estimate daily maximum indoor temperatures during a 'warm but not extreme' current summer scenario for 2.5 million London dwellings. For each day, we calculate the difference in temperature for the individual dwellings, and the average for all the London dwellings – the so-called temperature anomaly. We then aggregate the anomalies, calculating the average across the summer on days when temperatures exceed the 24.8C London heat mortality threshold, and then by dwelling postcode.

In order to make variables from both cities comparable, housing stock was reclassified into those with high performance, average performance and lower performance as shown in Table 2.

Table 2. Summer Energy Performance of housing stock

	Madrid cooling energy demand classification	London average indoor temperature anomaly* (ºC)
Low	B	≤-0.16
Average	C	> 0.16 & ≤ 0.04
High	D	> 0.04

* Estimated by an indoor temperature exposure metamodel run on a parameterised version of the Energy Performance Certificate (EPC) dataset

2.4 Household Income

In addition to determining the exposure of population towards summer energy poverty, household vulnerability was determined using income and age data. Household income data for Madrid households were obtained from the Urban Audit database [73]. Urban Audit is a European project that started in the late 1990s and gathers statistical information that enables the comparison of life quality amongst main

European cities. Since its inception, information has been collected around every three years. Data are disaggregated by *sub-city districts* for those cities with more than 250,000 inhabitants. Each sub-city comprises a population between 5,000 and 40,000 inhabitants. The variable selected from this database was household mean annual net income (€) for the 141 sub-cities of Madrid. The use of this data source makes the method transferrable to other European cities interested in exploring the geography of summer energy poverty.

In London, household income data for 2011 were obtained from the Greater London Authority for 625 wards [74], which have populations approximately equivalent to the Madrid sub-city districts (between 2,018 and 27,139 inhabitants). The income was converted to 2015 euros to enable comparison with Madrid. Household income was classified by deciles in both cities weighted by the number of households contained in Madrid sub-cities [73] and London wards [75].

Table 3. Households' mean annual net income deciles (€ - 2015)

	Madrid	London [1]
D1	24,165	47,191
D2	26,233	50,211
D3	27,251	53,277
D4	29,186	55,953
D5 (median income)	32,217	59,296
D6	35,910	63,621
D7	40,893	67,162
D8	47,227	73,447
D9	57,291	85,228
D10	113,001	215,950

[1] 2011 British Pounds (GBP) were converted to 2015 Euros (EUR) by multiplying them by the average GBP-EUR exchange rate of 2011 (1.16) and by the accumulated inflation rate between 2011 and 2015 given by the Bank of England (9.9%).

2.5 People over 65

Another key parameter of household vulnerability towards heat is age. The percentage of people older than 65 years old was extracted from the Madrid Municipal Census [76] while in London the percentage of population older than 65 was extracted from the 2011 Census [75]. These data were analysed in the sub-city district (Madrid) and Ward (London) delimitations.

3 Results

In this research, heat risk was considered a combination between population exposure to heat, expressed through UHI intensity and housing thermal performance under high outdoor temperature conditions, and household socioeconomic vulnerability, expressed by income and proportion of older people in an area. This section shows, first, the results of the geographical distribution of the heat exposure and socioeconomic vulnerability variables under examination, and second, the overlap between heat exposure and socioeconomic vulnerability in the two cities, in order to identify urban areas at risk of suffering from summer energy poverty.

3.1 Spatial distribution and incidence of heat exposure and socioeconomic vulnerability variables

Figure 1 presents results of the CDHs based on the UHI analysis for Madrid and London during daytime hours. As is illustrated in the figure, a clear cool island arises in Madrid during daytime in central areas while the highest temperatures are registered in the south. Similarly, a cool island can be observed in the northern centre of London whereas the hottest areas are concentrated in the west part of the city. In Madrid, CDHs range from 2,571 to 3,394 for the whole summer, while in London they range from 136 to 353 CDHs. Along with the representation of CDHs by deciles, Figure 1 shows the delimitation of the area of hot spots for daytime UHI.

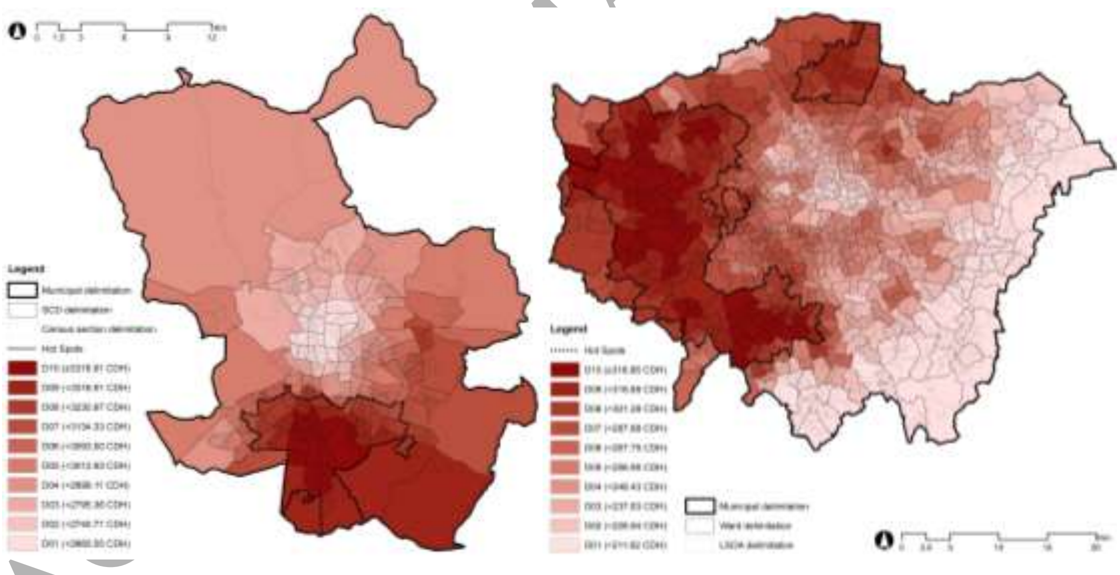

Figure 1 UHI intensity during daytime hours for Madrid (left) and London (right)

UHIs during night hours radically changes the thermal image of both cities as can be seen in Figure 2. In Madrid, the UHI moves towards the central areas of the city while some southern areas remain amonsgst the hottest areas as well. During these hours, CDHs range between 41 and 118. In London, the UHI moves towards the centre and northern areas of the city. In this case CDHs range from 0 to 6. As expected, CDHs are much lower during night time than during daytime.

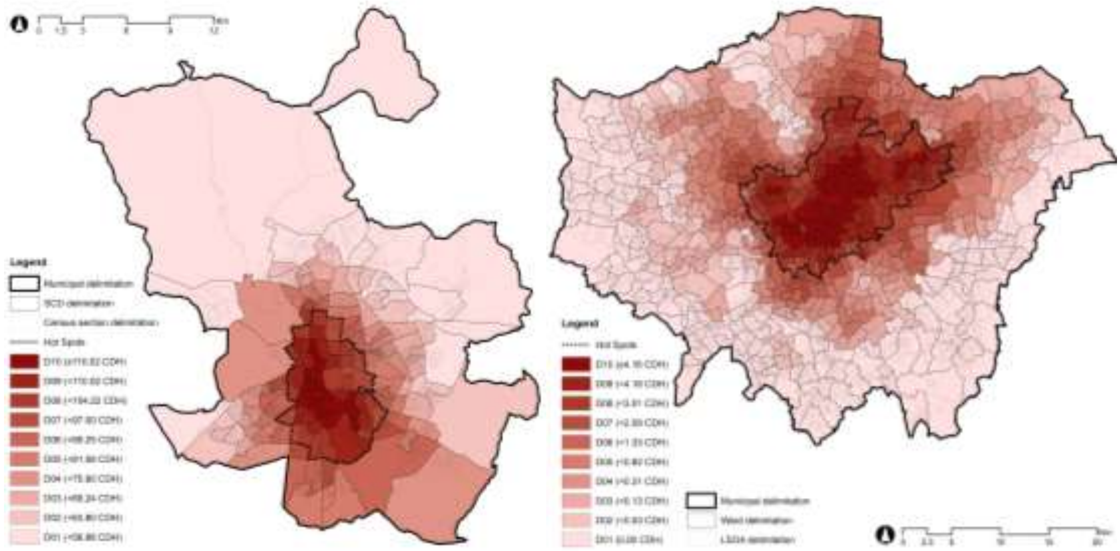

Figure 2 UHI intensity during night hours for Madrid (left) and London (right)

The analysis of the overheating risk of the London and Madrid housing stocks also shows an unequal urban distribution of summer thermal performance as plotted in Figure 3. In Madrid, the city centre presents a better response to summer heat severity given the construction characteristics of older buildings. Newest developments in the outskirts of the city built under higher energy efficiency requirements also belong to the lowest demand group. The housing stock with the highest cooling demand is located in the belt that surrounds the centre. This housing stock corresponds to a period before the introduction of the first energy efficiency regulations in 1979. In London, the highest risk of overheating can be found in dwellings located in the centre of the city, while this overheating risk decreases towards urban outskirts.

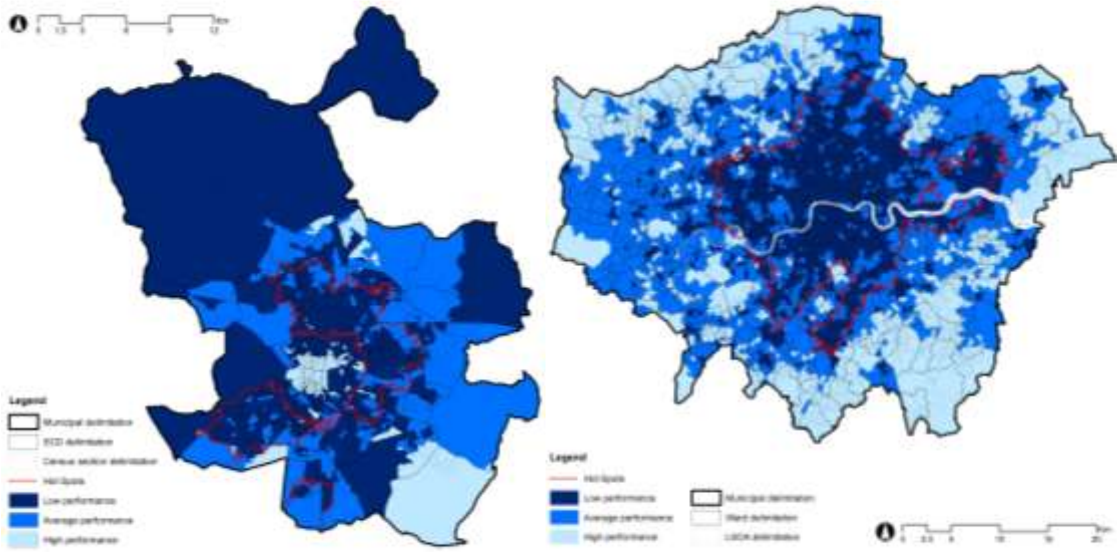

Figure 3 Housing stock summer thermal performance demand classification for Madrid (left) and London (right)

The spatial distribution of household's mean annual net income (€) for Madrid and London is presented in Figure 4. Inequalities in both cities can be observed. In Madrid the median income is about 32,217€ per family and the three lowest income deciles are under 27,251€. Neighbourhoods whose income is below the third decile are located in the south while the wealthiest ones are found in the northern parts of the city. London presents its wealthiest households living in an edge that crosses the city from northwest to southwest. The median household income is set in 59,296 € and the three lowest deciles are below 53,277€. Low-income families are distributed along the city; some low-income areas are concentrated in the west, northeast and east.

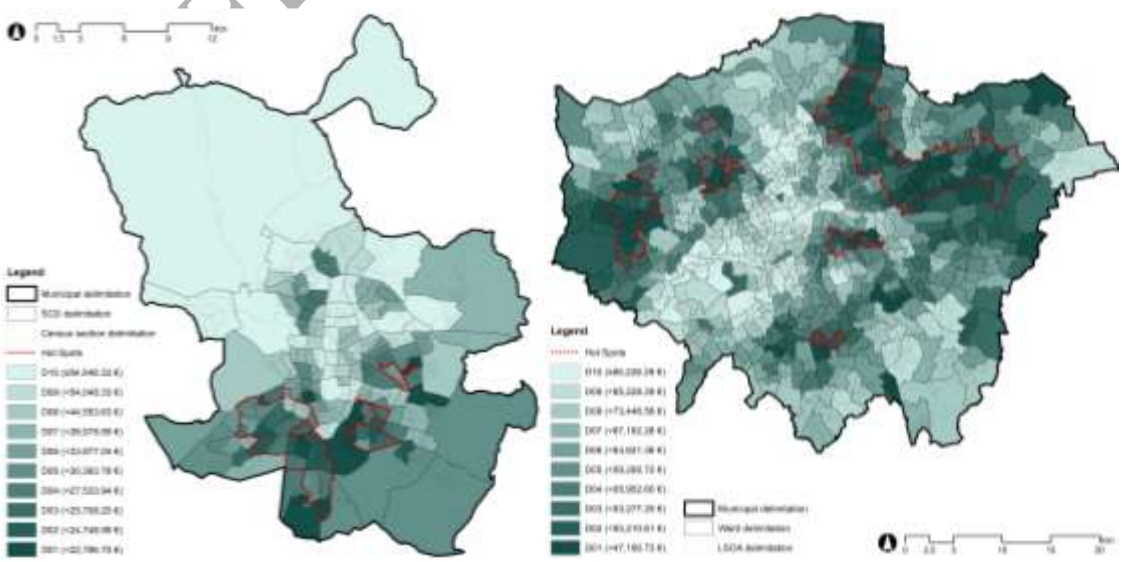

Figure 4 Households' income by sub-city for Madrid (left) and wards for London (right)

Finally, areas of the city with the highest percentage of elderly population were plotted in Figure *5*. In Madrid, these areas are located in the centre east and in the southwest. In London, the wards with the greatest proportion of elderly are distributed towards outer London.

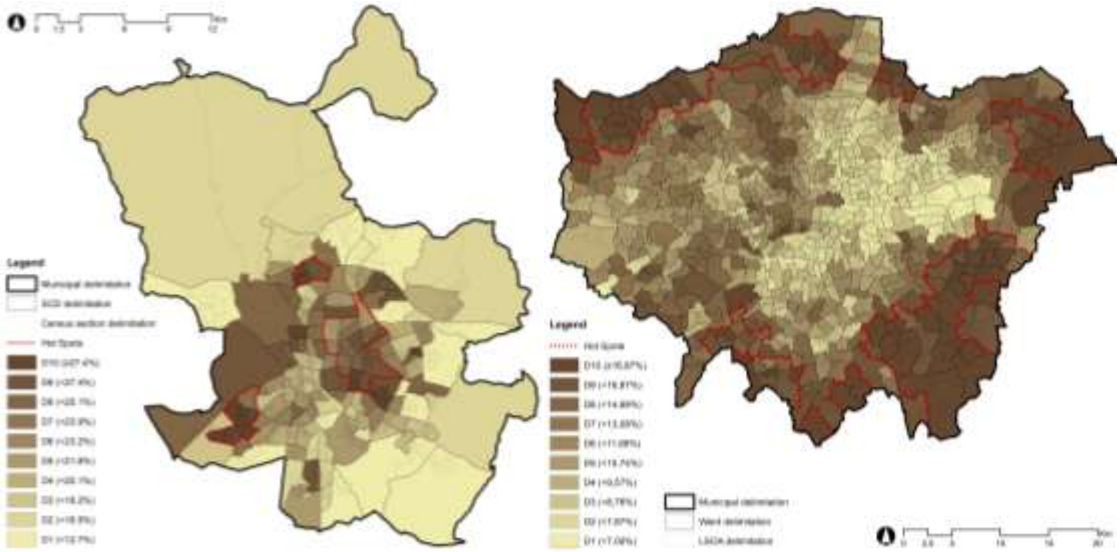

Figure 5 Distribution of elderly in Madrid (left) and London (right)

3.2 Detection of areas at risk of summer energy poverty

Table 4 shows the number of people and percentage of population that live in areas identified as hot spots in each city. Hot spots of low summer thermal performance housing contain the highest amount of people in both cities: 44% in Madrid and 46% in London. Following with exposure-related indicators, 35% of inhabitants of Madrid and 27% in London live in those areas with the highest UHI intensity during sleeping hours. Similar values are found for the population living in the hottest areas during daytime: 29% in Madrid and the 26% in London. The percentage of population living in daytime and night-time UHI vulnerable hot spot areas is slightly lower. 23% of the population in Madrid and 15% in London live in those urban areas delimitated as low-income hot spots. Regarding the elderly, 24% of all people above 65 of Madrid live in those areas with the highest concentration of old people and set as hot spots in this study. This percentage is the 21% of all elders in London.

Table 4. Population living in hot spots of exposure or vulnerability indicators for each city

Indicators	Madrid	London

		Population	% of total	Population	% of total
Exposure	UHI Daytime	906,946	29%	2126,612	26%
	UHI Nighttime	1099,152	35%	2174,331	27%
	Housing summer thermal performance	1381,145	44%	3724,780	46%
Vulnerability	Low income	714,521	23%	1251,620	15%
	Elderly*	155,082	24%	193,335	21%

* This percentage is referred to the total number of elders in each city

Areas wherein all hot spots overlap were not found neither in London nor in Madrid. However, different risk levels were set by the combination of vulnerability and exposure hot spots.

Figure 6 shows the overlap and several risk levels between low income hot spot areas and the three exposure indicators. In Madrid, these areas are grouped in the south of the city and, in London, highest risk levels are found in the northeast. The percentage of population living in these hot spot areas as well as overlap specifications are shown in Table 5. In Madrid, the highest risk is found among 2% of the population, who live under the effects of the UHI during day and night, and in areas with the highest presence of low summer thermal performance housing and the lowest household income rate of the city. In addition, 10% of the population of Madrid, which corresponds to 43% of those living in low income hot spots, live in the hottest areas of the city during the whole day. Also, 8% of the population (the 35% of those living in low income hot spots) live in areas with the highest daytime UHI intensity and with the lowest housing summer thermal performance. Almost half of the population living in low income hot spots face the hottest night temperatures during summer time.

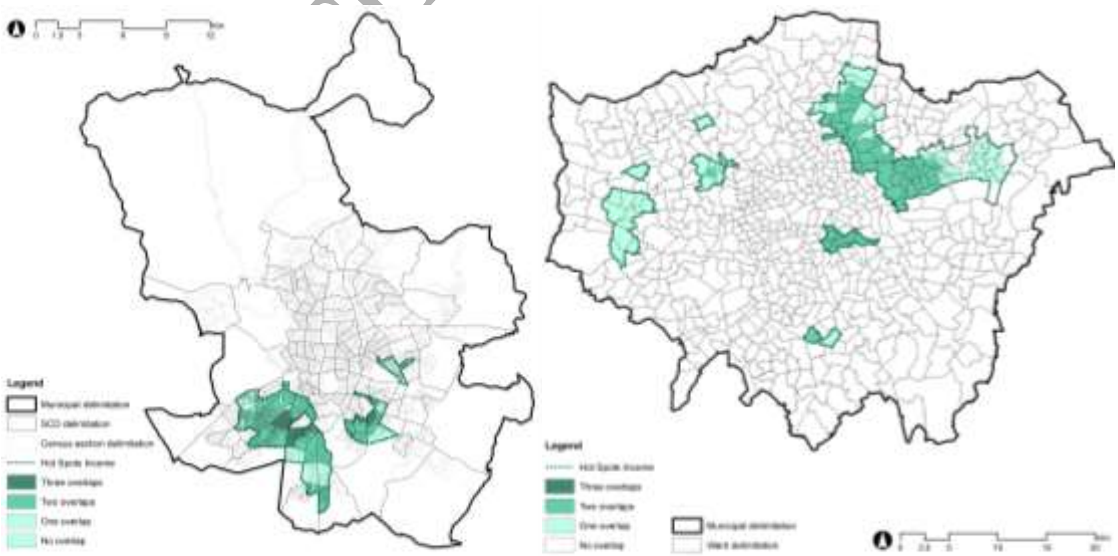

Figure 6 Risk in low income areas as a function of the number of overlapped vulnerability indicators. Values for Madrid (left) and London (right) are presented.

These areas are located mainly in the southwest part of the city, within the neighbourhoods of Zofio, Almendrales and Pradolongo (which belong to the district of Usera) and the neighbourhoods of Opañel and Comillas (district of Carabanchel). Another two neighbourhoods, Portazgo and Palomeras Bajas, which are situated in the south-east district of Puente de Vallecas, are also predicted to suffer from an elevated risk of summer energy poverty. In London this level of risk is not found. There were a total of 48 wards that had an overlap between income, UHI, and housing overheating risk, while a 24 had an overlap between the high proportion of elderly population and UHI or housing heat exposure. Overlaps of low income, night-time UHI, and housing overheating risk can be found in wards to the North East of the city, and below the city centre. Particularly at risk is the Borough of Newham – characterised by dense housing and low incomes - where 17 of 22 wards are identified as being at elevated risk.

Table 5. Population living in areas wherein low income and exposure hot spots overlap for each city

Indicators of exposure		Madrid		London	
No. overlap		% of total population	% of total low income	% of total population	% of total low income
1	UHI Daytime	20%	87%	4%	24%
	UHI Nighttime	10%	43%	8%	49%
	Housing summer thermal performance	11%	48%	11%	74%
2	UHI Daytime + UHI Nighttime	10%	43%	0%	0%
	UHI Daytime + Housing summer thermal performance	8%	35%	1%	7%
	UHI Nighttime + Housing summer thermal performance	2%	9%	0%	0%
3	UHI Daytime + UHI Nighttime + Housing summer thermal performance	2%	9%	0%	0%

The overlap between hot spots with a high proportion of older residents and the three exposure indicators is plotted in Figure 7. In Madrid, areas at risk can be set in the centre, the southwest and northwest. Three neighbourhoods from the districts of ChamartinS (El Viso), Moratalaz (Media Legua) and Latina (Aluche) are highlighted amongst the others, as two exposure indicators are overlapped. In London, the risk for the elderly is presented in a lower degree, where only one indicator is found in some areas at the north, northeast and southeast of the outskirts. Table 6 show the percentage of the total elderly living in these areas. In London, no overlaps can be found except for elderly people and hottest areas during daytime, which represents the 4% of the elderly population. In Madrid, 18% of the elderly lives in hot spots with the lowest housing summer thermal performance. The 7% of the elderly lives in areas with the highest UHI intensity during night time hours.

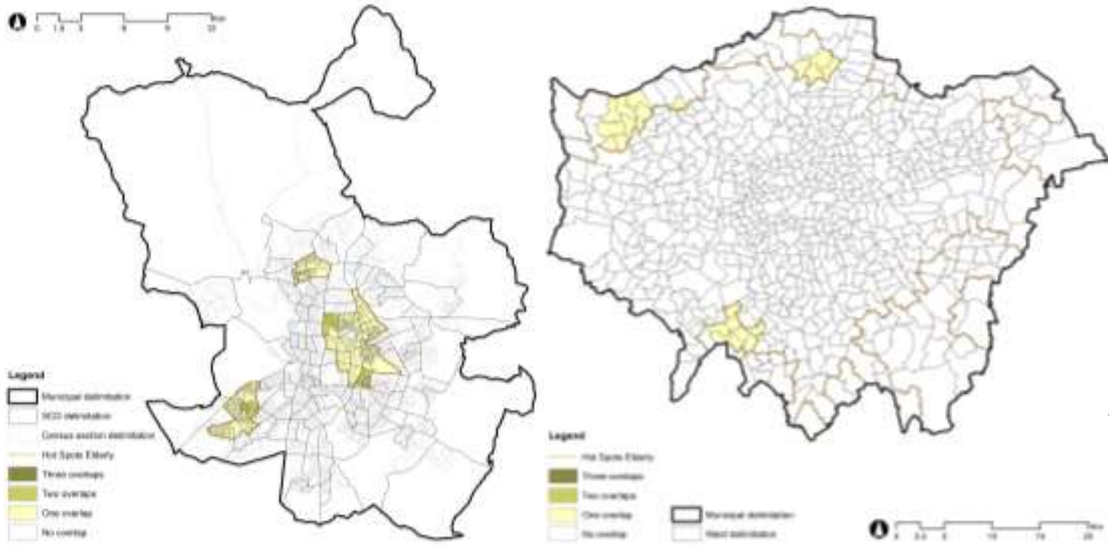

Figure 7 Risk in elderly areas as a function of the number of overlapped vulnerability indicators. Values for Madrid (left) and London (right) are presented.

Table 6. Elderly population living in areas where in elderly and exposure hot spots overlap for each city

Indicators of exposure		Madrid		London	
No. overlap		% of total elders	% of total elders in hot spots	% of total elders	% of total elders in hot spots
1	UHI Daytime	1%	4%	4%	19%
	UHI Nighttime	7%	29%	0%	0%
	Housing summer thermal performance	18%	76%	0%	0%
2	UHI Daytime + UHI Nighttime	0%	0%	0%	0%
	UHI Daytime + Housing summer thermal performance	1%	4%	0%	0%
	UHI Nighttime + Housing summer thermal performance	1%	5%	0%	0%
3	UHI Daytime + UHI Nighttime + Housing summer thermal performance	0%	0%	0%	0%

Finally, no overlap between elderly and low-income hot spots areas were found for London. In Madrid these overlaps take place in two neighbourhoods located in the Southwest of the city. In Aluche, hot spots of elderly and low income overlap with low housing summer thermal performance and UHI daytime while in Lucero elderly and low-income hot spots overlap with low housing summer thermal performance.

4 Discussion

The assessment of heat risk in Madrid and London as combination between heat exposure and population vulnerability shows different degree levels of the phenomenon in both analysed cities. Regarding the exposure to heat of the population, the incorporation of the UHI parameter enabled considering thermal inequalities within the same city. This study was possible due to the existence of previous research that monitored urban heat island temperatures with innovative sensor system networks (Madrid) and modelled the UHI effect using state-of-the art local urban climate modelling techniques (London). Unfortunately, UHI data from these two different sources were not generated for the same year; work on the quantification of the UHI effect is still limited in most cities and there are currently no consistent, widely accepted methods or definitions. However, the currently available datasets were considered sufficient for the identification of the hottest and most vulnerable areas within each city for the purposes of this study. In addition, the analysis of the UHI intensity by means of CDHs based on adaptive thermal comfort criteria permitted the assessment of summer weather severity within each city context. However, some limitations regarding the lack of adaptive standards for sleeping hours are worth noting. Results showed a higher summer exposure of the population of Madrid, according to its highest summer severity. Strong and centred UHIs are observed in both cities during night time, where similarities in the nocturnal urban climate might be set. Despite this, passive night time strategies might differ. While in Madrid high values of CDHs might impede night ventilation, this strategy could be amongst the most efficient measures to combat overheating in London dwellings, at least under the current climate. The low thermal performance of Madrid housing stock, with poor insulation, lack of appropriate solar shading and inefficient ventilation is increasing the installation of individual air conditioning systems [20] with the corresponding backlash effect that reinforces the UHI intensity. Another source of uncertainty is in the evaluation of the housing stock in Madrid. First, due to the lack of harmonised data, the data used in this study referred to overheating risk in London and cooling energy demand in Madrid. Specifically, only aggregate energy demand data based on the year of construction was available for Madrid. Despite the year of construction being a key variable for building thermal performance as it considers construction material characteristics and glazing properties, further research should incorporate variables such as orientation, solar gains and urban canyon proportions, etc. Furthermore, cooling needs for the whole building were considered as otherwise the analysis of the whole city could not have been possible. However, there are important differences in cooling energy needs within the same block. Dwellings located in the top floors have the highest energy requirements while the street level floors present the lowest ones. Finally, harmonised income data was also not available for the two case study cities. Urban Audit income data was not available for London and was, therefore, obtained from the Greater London Authority and converted so as to be comparable to Madrid data.

The overlap of hot spots showed the existence of higher summer energy poverty risk in Madrid. 2% of its population live in the hottest areas during day and night, with the highest presence of low summer thermal performance housing and with the lowest household income rate of the city. Furthermore, 43% of people living in low income areas also face the highest temperatures during day and night as a result of the UHI distribution. These data suggest the existence of poor households exposed to very high temperatures who cannot afford adequate indoor temperatures. Despite the fact that such risks are relatively lower in London, as just the 1% of the total population live in low income areas and experience the highest temperatures during daytime, it is worth pointing out that 74% of those living in low income areas of the city also live in areas presenting the lowest housing thermal performance in summer. This indicates that they will become heat vulnerable in the future under the projected temperature rise due to climate change. The correlation between the presence of the elderly, who are more vulnerable towards heat, and the exposure indicators showed also higher levels of risk in Madrid than in London. It is remarkable that in London the elder population is in the outskirts with the lowest intensity of the UHI. In Madrid, 1% of the elderly (about 6500 people) live in areas in which housing is characterised by low thermal performance and people experience the highest night temperatures. This can provoke an important heat stress and have relevant consequences on their health. The correlation between the presence of the elderly, who are more vulnerable towards heat, and the exposure indicators showed also higher levels of risk in Madrid than in London. It is remarkable that in London the elder population concentrates in the outskirts, where the lowest intensity of the UHI and the highest housing performance happen to be more frequent. In Madrid, however, an appreciable 18% of the elderly live in urban areas with low housing thermal performance. Even though this population may not live in the hottest areas of the city, the combination of the low thermal performance of buildings and Madrid's extreme summer temperature episodes can also have relevant negative health impacts on elders..

According to the results presented in section 3.2, the areas that were delimitated as most prone to suffer summer energy poverty in Madrid belong to three districts: Usera, Carabanchel and Puente de Vallecas. These findings are consistent with the Technical Study on Energy Poverty in the city of Madrid, where Carabanchel and Usera are also labelled amongst the districts with the largest number of indicators related to energy poverty. By contrast, the analysis of the risk within the elderly points towards other areas of the city. Three neighbourhoods from the districts of Chamartin, Moratalaz and Latina are highlighted amongst the others, presenting significant differences that must be underlined. Chamartin is the district with the highest income and percentage of people with higher studies and presents the highest presence of installed air conditioning systems butit is highlighted as a hot spot due to its old housing stock, a high UHI intensity and its ageing population. The district of Moratalaz presents the highest rate of single households with women over 65. Households' income from the district of Latina is among the lowest ones of the city with this households living in an old and inefficient housing stock. In London, the results in 3.2 identify a selection of wards that that are at elevated heat risk due to heat exposure from the UHI and/or housing, and population vulnerability. Combinations of heat exposure and population deprivation were found clustered in areas such as Newham, traditionally a deprived area with an older housing stock. Combinations of heat exposure and heat exposure due to housing or UHI were found in the North, Northwest, and Southwest outskirts of the city, where the proportion of elderly population is greatest; this is consistent with the results of Taylor et al [31], who predicted that such areas may be at elevated risk of heat mortality, rather than the relatively younger population in the city centre.

5 Conclusions

The present study set out to explore population at risk of summer energy poverty. The study was conducted in two cities, Madrid and London, with different weather conditions to understand the disparities of this often underresearched type of energy poverty. In the context of ongoing and future climate change, insights about differences between Northern and Southern European cities in terms of summer energy poverty must be set as well as prevention and action plans should not be neglected. The method designed to explore summer energy poverty in the urban context revealed being useful to detect the phenomenon. The selected indicators to build the risk by means of the heat exposure (UHI intensity during day and night and housing thermal performance) and vulnerability (household income and proportion of older people) enable conducting similar studies in other European countries.

In both cities, this study detected areas with certain risk of summer energy poverty. Mainly due to differences in summer weather severity, these areas are larger in Madrid compared to London as well as the percentage of affected population. In London, 1% of its population live in low-income areas with low housing thermal performance in summer and the highest temperatures during day and night time. 4% of its older population live in the hottest areas during daytime hours. These percentages are low and, given the mild temperatures registered in summer in London, may not be currently alarming. However, in an increasing temperatures scenario, these areas ed as well as other hot spot detected areas in which summer energy poverty could arise should be examined closely. In Madrid, 2% of the population live in low-income areas with an inefficient housing stock and under the highest temperatures during the whole day. Along with that, 18% of older people in Madrid live in areas with a low summer thermal performance housing stock what can pose some health risks for them.

While the results showed clear areas of overlap between vulnerable population and heat exposure, some barriers were found regarding the availability and harmonisation of data, as set in previous section. Advances in protocols for UHI measurement would enable comparable data to be obtained among cities. Also, further research is required regarding the impact of the UHI on building energy performance. The research presented here used the adaptive thermal comfort standard as a way to evaluate heat exposure and potential cooling loads related to temperature gradient caused by UHI. Criteria regarding adaptive thermal comfort for sleeping hours should be developed due to the importance of night-time heat exposure. Further research should be undertaken also in evaluating energy performance of urban fabrics, considering urban canyon proportions, orientations and solar obstructions and gains. Finally, income data could be enhanced with better households' information such as household's composition so equivalised incomes could be calculated.

Results show the importance of carrying out studies so summer energy poverty can be defined and identified. Understanding related deprivations in the urban environment is crucial to implement actions and policies that adequately tackle the problem of urban heat risk and prioritise the most deprived and vulnerable neighbourhoods. Policies aimed at mitigating the heat island will also have a positive impact on indoor overheating and cooling needs. In this line, avoiding air conditioning penetration through the implementation of effective summer passive strategies will prevent for more urban overheating. In London, promoting night ventilation to drop indoor temperatures would be a good prevention strategy currently while, in Madrid, strong urban adaptation actions are required such as the incorporation of green areas and urban shading systems.

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