Building and Environment 207 (2022) 108482

Contents lists available at ScienceDirect

Building and Environment

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

Is indoor overheating an upcoming risk in southern Spain social housing stocks? Predictive assessment under a climate change scenario

Rocío Escandón [a,*], Rafael Suárez [a], Alicia Alonso [a], Gerardo Maria Mauro [b]

[a] Instituto Universitario de Arquitectura y Ciencias de La Construcción, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla, Av. de Reina Mercedes 2, 41012, Seville, Spain
[b] Università Degli Studi Del Sannio, Department of Engineering, Piazza Roma 21, 82100, Benevento, Italy

ARTICLE INFO

Keywords:
Heat discomfort
Global warming
Building performance simulation
Mediterranean climate
Healthy buildings
Energy poverty

ABSTRACT

Beyond thermal comfort, the future outlook of climate change poses a challenge for the health of the most vulnerable inhabitants of the existing residential stock. In southern Spain specifically there is extensive social housing stock that is obsolete from an energy perspective and occupied by an aging population with economic constraints for the use of energy. The main aim of this work is to evaluate the possible comfort risks in terms of overheating following the different criteria established by the Chartered Institution of Building Services Engineers (CIBSE), both under current conditions and in a climate change scenario. For this purpose, a parametric simulation model was developed to reliably evaluate the category of linear-type social housing from the postwar period, a total of more than 42,000 dwellings. The results show that around 38% of the evaluated cases are already at risk of overheating as they fail to meet two of the three adaptive criteria set in TM52. By 2050 this figure will be almost 100%. In addition, it is expected that global warming will result in an increase of up to 40% in the percentage of Hours of Exceedance.

1. Introduction

The COVID-19 health crisis has highlighted the need to review the capacity of the existing residential stock to guarantee comfortable and healthy conditions for occupants. Moreover, due to this pandemic, the use and occupation patterns of homes have changed as intensity of use has increased and many dwellings have turned into workspaces. This in turn leads to a greater need to guarantee users' well-being in their homes. During this lockdown, the lack of thermal and light comfort, poor air quality and an increase in energy expenditure have all become more apparent to users [1].

This situation is expected to worsen due to the new climate panorama and proven global warming, which will have a particular impact on the southern regions of Europe [2]. The projections of the Intergovernmental Panel on Climate Change [3] for southern Europe warn of more extreme warm temperatures, similar to those currently found in regions of North Africa and the Middle East, together with an increase in the frequency and intensity of heat waves and tropical nights.

In recent decades, numerous studies throughout Europe have shown the direct relationship between very low outdoor temperatures, housing energy efficiency, and the mortality increase in the population [4]. Fowler et al. [5] evaluated the Excess Winter Deaths Index between 2002 and 2011 in 31 European countries, concluding that Spain has one of the highest values, above 18%. An important part of this percentage is attributed to cold housing. According to Ortiz et al. [6] the energy retrofitting of the Spanish residential stock would reduce diseases linked to low indoor temperatures, such as cardiovascular and respiratory ones, by 15%, while also minimizing the severity of influenza and rheumatic diseases [7].

Nevertheless, the increase in temperature in a relatively near future is expected to lead to an improvement in indoor thermal conditions during the heating season. However, the cooling season will be a major cause for concern. For this reason, the preoccupation with thermal comfort and the interest in analyzing the negative effects on people's health as a result of the very high temperatures have increased noticeably in recent years [8].

Most of the research analyzing the implications of climate change in the built environment focuses on evaluating the impact on energy consumption and the consequent emissions, or on the performance of air conditioning systems and energy retrofitting measures for buildings under the new climatic conditions [9]. However, some studies also confirm the impact of global warming or heat waves on indoor thermal comfort. Sakka et al. [10] report a 35% increase in hours with indoor

* Corresponding author.
E-mail address: rescandon@us.es (R. Escandón).

https://doi.org/10.1016/j.buildenv.2021.108482
Received 5 July 2021; Received in revised form 18 October 2021; Accepted 21 October 2021
Available online 26 October 2021

Abbreviations

CIBSE	Chartered Institution of Building Services Engineers
DE	Percentage of Days exceeding Weighted exceedance limit (%)
HE	Percentage of Hours of Exceedance (%)
HE_{ULT}	Percentage of Hours exceeding Upper Limit Temperature (%)
HVAC	Heating, Ventilating and Air Conditioning
IPCC	Intergovernmental Panel on Climate Change
OH	Overheating Hours percentage (%)
OHn	Night-time Overheating Hours percentage (%)
SRRC	Standardized Rank Regression Coefficient
T_{op}	Operative temperature (°C)
T_{max}	Maximum temperature (°C)

temperatures above 30 °C in low income housing during heat waves in Greece. In social housing stock in southern Spain, a 36% increase in discomfort hours is predicted for the summer of 2050 [11]. This situation is aggravated by the energy obsolescence of the existing residential stock, leading to a possible threat to people's health [12].

There are quite a few studies that analyze the effect of very high outdoor temperatures on people's health and well-being. Baccini et al. [13] carried out a study in 15 European cities determining that, in the Mediterranean area, an increase of 1 °C in the maximum outdoor temperature above the threshold of 29.4 °C results in a 3% increase in mortality. This increase in mortality is fundamentally associated with the worsening of respiratory diseases in the elderly [14] and sudden deaths due to cardiovascular problems [15]. It is also worth highlighting the research developed by Royé et al. [16], that found positive correlations between mortality and duration of tropical nights (minimum temperature greater than or equal to 20 °C) in some Southern European cities.

Global warming and the progressively aging population are expected to aggravate this situation, increasing the risk of energy poverty and social exclusion [17]. Nevertheless, studies predicting the increase in heat-related mortality based on climate projections are still linked to uncertainties focusing on the possibility of mitigating climate change and on the population's ability to adapt [18].

Therefore, the correlation between very high outdoor temperatures and the worsening of human health is widely accepted within the scientific community, while the impact of high indoor temperatures has been much less studied [19]. It is worth highlighting the recent literature review by Tham et al. [20] which found that high indoor temperatures fundamentally affect respiratory health and cause a worsening of symptoms derived from diabetes, schizophrenia and dementia. However, there are insufficient data available to set a maximum indoor temperature threshold above which human health begins to deteriorate.

The literary review carried out by the government of the United Kingdom [21] also concludes that there is a lack of sufficient information to determine a maximum indoor temperature value to safeguard the health of the building's occupants from an epidemiological point of view. As an alternative to epidemiological studies, research based on the physiological reactions of humans at certain temperatures is proposed [22], the concept on which overheating standards are based to protect users from thermal discomfort due to heat.

There are numerous studies evaluating the risk of overheating in residential stocks in northern and central Europe. Dodoo et al. [23] evaluate the risk of overheating in Swedish multi-story residential buildings under different climate scenarios, concluding that those with a higher mass envelope are at higher risk than lightweight constructions. Research carried out by Hamdy et al. [24] on the Dutch housing stock built between 1964 and 2013 determines that poorly ventilated dwellings and those lacking shading devices will be the most vulnerable to climate change. In the United Kingdom, there is considerable concern regarding the risk of overheating in highly isolated and airtight buildings constructed or renovated according to Passivhaus criteria [25]. Sameni et al. [26] state that two thirds of the residential buildings analyzed exceeded the established overheating limits, basically affecting the most vulnerable sector of the population. It is also worth highlighting the extensive study carried out by Lomas et al. [27], evaluating overheating through monitored data on the English housing stock, also comparing the results with data self-reported by households.

In contrast, the existing literature on southern Europe is relatively scarce. It is worth highlighting the work carried out by Panão et al. [28] in Portugal, which shows that the current standards limiting energy demand in buildings will not be enough to prevent the risk of overheating in the near future, mainly emphasizing factors that limit solar gains through windows. Heracleous and Michael [29] focus their study on the potential of natural night-time ventilation to mitigate the risk of overheating in the Mediterranean climate, predicting a reduction of up to 35% in overheating hours in educational buildings in Cyprus by 2050, according to the criteria of the Chartered Institution of Building Services Engineers (CIBSE).

There is consensus among the scientific community that the residential stock, obsolete and with low thermal and energy performance, will be the most vulnerable to the new climatic conditions if no investment is made in retrofitting [30]. Furthermore, this vulnerability is heightened in the case of low-income households [19,31] and elderly people [32,33]. Thus, this research faces the challenge of complementing the existing literature, where the lack of an approach for the southern Europe residential stock (or similar social-climatic conditions) is perceived, being an area that will be further affected by climate change. This work also aims to take a further step in the thermal comfort analysis developed in earlier research, evaluating the risk of overheating according to steady-state and adaptive criteria, under current and future climate conditions. This paper specifically focuses on the case study of social housing built between 1950 and 1980 in Seville (southern Spain), in which the three most-cited risk factors are met: energy obsolescence, low income and aging population. The suitability of the criteria applied to the particular conditions of the case study will be discussed based on the results.

2. Methods

The methods for the development of the large-scale parametric model used in this work to characterize the environmental behavior of the social housing stock was previously validated through in-situ measurements and explained in detail [34]. This model focuses on the simulation of a set of buildings representing an entire category selected as characteristic of social housing stock in southern Spain. This building category is defined in Section 3 of this document.

This model was developed using the SLABE (Simulation-based Large-scale uncertainty/sensitivity Analysis of Building Energy performance) method defined by Mauro et al. [35]. This method takes as a starting point the establishment of a series of characteristic parameters that define the building category through variability ranges and probable distribution (uniform or normal). Latin hypercube sampling was applied to these parameters, within a Monte Carlo framework, to ensure the generation of a uniform and representative study sample representing the building category.

In this case, the optimal sample size was determined to be 750 simulation models [34]. An uncertainty analysis was performed to obtain this value, verifying that the trends of the mean value and the standard deviation of the simulation results was stabilized from a number of samples under 100. However, if the results obtained are to be used in the future to generate a predictive model using artificial neural networks, the reliability of the model will not be optimal with a sample size under 750 cases. From this point, a mathematical function was generated for the automatic launch of the 750 simulation models in EnergyPlus software.

To fulfill the main aim of this work, this initial model was supplemented with the evaluation of the overheating conditions applying steady-state and adaptive criteria to the results of the thermal behavior obtained from the simulation models. In addition, the projection of the climate data from the initial model to the year 2050 was carried out in order to assess the risk of overheating under the climate change scenario. A comparative analysis of the results of the initial model, that of the current climate scenario, and the model projected to 2050, makes it possible to evaluate the impact of climate change on the thermal discomfort conditions of the building category selected.

The initial model uses a climate data file generated from the data provided by the Spanish State Meteorological Agency (AEMET) from the meteorological station at Seville Airport. The variables of air temperature, relative humidity, solar radiation, wind speed and direction, and precipitation, measured at 30-min intervals during 2014 and 2015 (coinciding with the period of in-situ measurements for the model validation) were used.

Finally, a sensitivity analysis was carried out to identify the parameters with the greatest influence on overheating in this case study. This sensitivity analysis was done by evaluating the Standardized Rank Regression Coefficients (SRRC), as the existing literature suggests that this is the most suitable method for non-linear but monotonic relations [36,37] such as those observed between the inputs and outputs of this work. The methodology defined is summarized in Fig. 1.

2.1. Overheating criteria

Although the debate on the minimum conditions considered acceptable for health inside a home during the summer period has been taking place for many years, so far the scientific community has been unable to reach widespread consensus. In this work, the effect of continuous exposure to high temperatures on users is evaluated in terms of thermal discomfort, applying the overheating criteria most used in the existing literature. However, as stated by Laouadi et al. [38], these criteria display certain limitations as they have been developed in a general way for healthy adults with an average age of 35 years, not taking into account the particular cases of the most vulnerable (over 65 years or in ill health).

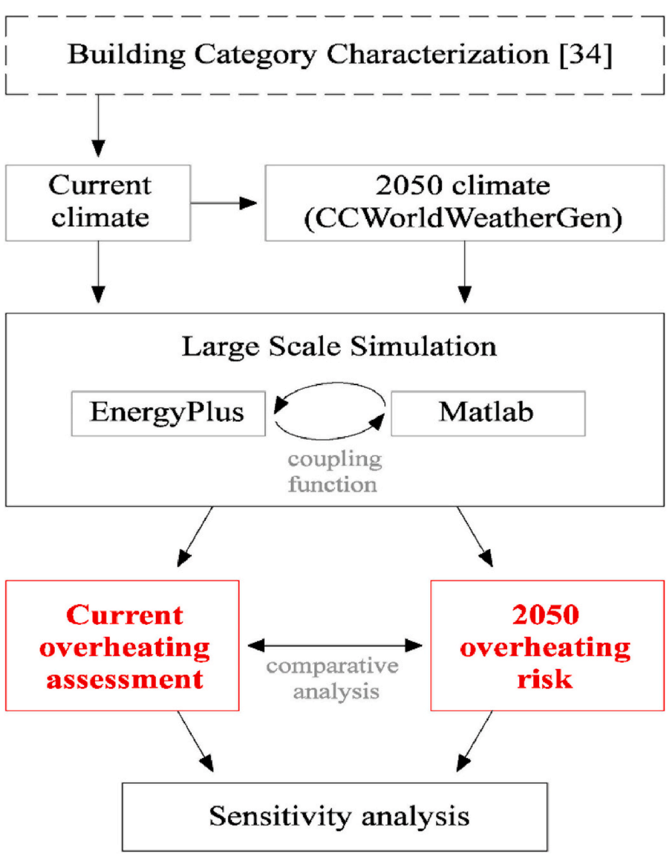


Fig. 1. Methodology scheme.

The most commonly used overheating criteria are those established by CIBSE [39]. The last version of the CIBSE Guide A for Environmental Design [40] maintains the historical option which bases the evaluation of the overheating condition on not exceeding a steady limit temperature. Specifically, it is established that there is a risk of overheating when the operative temperature exceeds 28 °C during more than 1% of the occupied hours in offices, schools and the living areas of dwellings. In addition, the risk of overheating for bedrooms is determined when the operative temperature exceeds 26 °C for more than 1% of the occupied hours.

However, these steady-state criteria do not consider the climatic adaptation of the occupants depending on the outdoor temperature or how the buildings are used. Thus, for buildings with natural ventilation where users have greater control of indoor conditions, CIBSE revised its steady-state criteria in the Technical Memorandum TM52 [41], proposing a method for the evaluation of the risk of overheating based on the thermal comfort adaptive criteria set out in European Standard EN 15251:2007 [42]. Although this standard was recently updated [43], no changes affected the upper limits of optimal operative temperature referred to in TM52.

Three criteria defined are evaluated during the occupied hours of the non-heating season (from the 1st May to the 30th September). When any two of these three adaptive criteria are not met, the risk of overheating can be determined. These three criteria are defined below:

- Criterion 1 - Hours of exceedance: states that the percentage of hours in which the operative temperature (T_{op}) exceeds the maximum temperature (T_{max}) by 1° (K) or more, should be less than 3%. In this case, T_{max} (Equation (1)) is defined as the upper threshold of the adaptive comfort criterion established in Standard EN 15251:2007 for category II (Predicted Percentage of Dissatisfied <10%).

$$\boldsymbol{T}_{max} = 0.33 \times \boldsymbol{T}_{rm} + 21.8\ (^{\circ}\mathbf{C}) \tag{1}$$

where:
T_{rm}: running mean dry bulb outdoor temperature for today [42].

- Criterion 2 - Daily Weighted Exceedance: assesses the daily severity of overheating, both in temperature rise and in duration over time. It is established that the weighted exceedance (W_e) (Equation (2)) should be less than 6 degree-hours (Kh) in any one day:

$$W_e = \sum he \times wf \tag{2}$$

where:
he: number of hours of exceedance (Criterion 1)
wf: weighting factor. wf = 0 if $T_{op} < T_{max}$, otherwise wf = T_{op} - T_{max}

- Criterion 3 - Upper Limit Temperature: the maximum acceptable indoor temperature is determined, in which the usual adaptive means are not sufficient to restore thermal comfort. Thus, T_{op} should never exceed T_{max} (Equation (1)) by more than 4° (K).

Technical Memorandum TM59, published more recently [44], specifies for dwellings that are predominantly naturally ventilated that avoiding overheating is based on passing both of the following criteria: Criterion 1 of CIBSE TM52 (referred to Hours of exceedance); and, only for bedrooms, the steady-state criterion for night-time defined in CIBSE

Guide A for Environmental Design. In this Technical Memorandum non-fulfillment of Criteria 2 and 3 of CIBSE TM52 is allowed, providing that the other two criteria mentioned above are met in all relevant rooms.

2.2. Climatic conditions projection for 2050

The CCWorldWeatherGen® tool, version 1.9 (May 2017), developed at the University of Southampton [45], was used for the development of the future climate scenario in this paper. This tool is the most commonly used and validated by the scientific community for the development of weather data projections [9]. For this, it takes a climate data file of the Typical Meteorological Year (TMY) of the selected location as a starting point and requires the input of the data offered in the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report model summary data of the Hadley Centre Coupled Model version 3 (HadCM3) for the A2 family of future scenarios.

Among the four scenarios defined by the IPCC (A1, A2, B1 and B2), A2 was selected in this research because it is the one that predicts a higher CO_2 concentration at the end of the 21st century. This scenario assumes fast and continuous population growth and slow economic and technological development.

In this work, the TMY provided by the EnergyPlus Weather Database [46] was used as the original climate data file, which has its origin in the climate data of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). These data were obtained from the AEMET meteorological station located at Seville airport.

3. Case study

In general terms, the case study featured in this paper is the existing social housing stock in southern Spain. This residential stock was mostly built from 1940, in a period of urban growth arising from the housing needs of the postwar period, until 1980 [47], without any global regulation limiting energy demand. Thus, this case study brings together some of the main vulnerability indices highlighted as risk factors in case of long exposure to high indoor temperatures by the scientific community:

- Obsolete buildings from the energy point of view, without thermal insulation measures or efficient air conditioning systems, given their construction period;
- Users with low economic income, which clearly limits their use of energy;
- The age of these dwellings indicates a general aging of users (most of whom are the original owners).

For the development of the large-scale parametric simulation model, the study had to focus on a specific building category. A building category should represent a set of buildings with a certain climate, and similar geometric and constructive characteristics, to avoid excessively wide variability ranges for defining the characteristic parameters, which would reduce the model reliability [35]. Therefore, this study focused on the city of Seville and on the most representative geometric typology of the study period: the linear multi-family building (Fig. 2). In Seville, this typology accounts for more than 40% of the existing social housing stock, according to data collected in an R&D&I project that cataloged more than 100,000 dwellings [48]. Thus, the building category model simulated in this paper represents more than 42,000 dwellings.

The data compiled in this research project were used to define the variability ranges of the characteristic parameters defining the building category. These are summarized in Table 1 and can be consulted in greater detail in Ref. [34]. Regarding the parameters for Heating, Ventilating, and Air Conditioning systems (HVAC), this building category is generally characterized by the lack of mechanical ventilation systems (using only natural ventilation through windows), and by free-running operation (sporadically using mechanical local cooling or heating systems due to economic restrictions). An occupation schedule of 100% between 3:00 p.m. and 7:00 a.m. and 25% for the rest of the hours has been assumed, following the schedule most frequently detected in previous studies [49,50]. The night-time ventilation schedule is established between 12:00 p.m. and 9:00 a.m., following the indications established in the user profiles of the Spanish regulations.

The climate of the city of Seville is Mediterranean, with high temperatures and low humidity in summer and a mild climate in winter. During the climatic period referenced in the initial model (2014/2015), the maximum average daily outdoor temperature was 33 °C (with a 1% summer design temperature of 39.9 °C), and the minimum average daily

Table 1
Characteristic parameters of the building category.

Characteristic Parameter		Variability Range
Geometry	Dwelling area	45–150 m^2
	Form ratio[a]	1–5
	Floor height	2.4–3.5 m
	Window to wall ratio	10–40%
	Number of stories	3–7
Envelope	Roof solar absorptance (a)	0.1–0.9
	Façade solar absorptance (a)	0.1–0.9
	Floor U value	4.70–7.00 W/m^2 K
	Roof U value	1.25–2.40 W/m^2 K
	Façade U value	0.75–4.35 W/m^2 K
	Window U value	2.80–5.70 W/m^2 K
Operation	People density	0.01–0.15 $people/m^2$
	Infiltration rate	0.3–1.0 h^{-1}
	Night-time natural ventilation rate	0–6 h^{-1}

[a] Form ratio = Major façade length/Minor façade length.

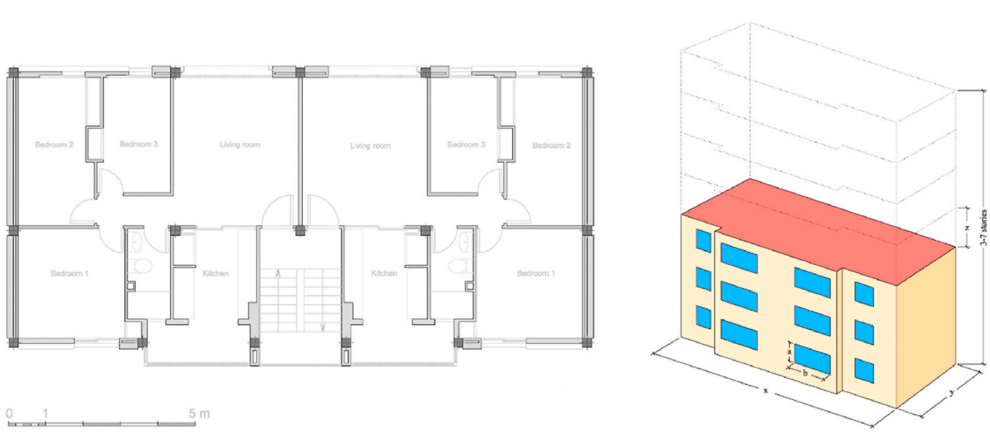


Fig. 2. Example case of the building category: floor plan and graphical summary of its geometric characteristics.

outdoor temperature was 7.5 °C (with a 99% winter design temperature of 3.9 °C). Average relative humidity was 65%, and average daily global radiation during the non-heating season (1st May - 30th September) was 5.2 kWh/m^{2}day.

3.1. Climate change scenario

The climate file generated to evaluate the future scenario, according to the methodology described in Section 2.2 shows a relevant increase in maximum outdoor dry bulb temperatures throughout the whole year (Fig. 3). By 2050, an average maximum daily outdoor temperature of 36 °C is predicted, involving an increase of 3 °C compared to the current climate. An even greater increase will occur in the 1% summer design temperature, which increases by more than 5 °C to exceed 45 °C. However, the average minimum daily outdoor temperature will maintain its current value, although during certain periods the minimum temperatures will be lower than in the current climate (Fig. 3). Average relative humidity will drop slightly to 58% and average daily global radiation during the non-heating season will increase to 7 kWh/m^{2}day.

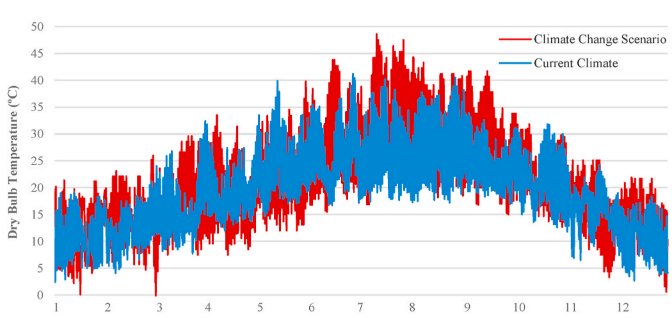


Fig. 3. Outdoor temperature projection.

4. Results and discussion

4.1. Indoor overheating assessment: steady-state criteria

In this section, the results obtained from applying the steady-state overheating criteria of the CIBSE Guide A [40] (defined in Section 2.1.) in the 750 multi-family buildings simulated during the non-heating season (May–September) are evaluated. The figures represent the histogram of the results obtained, as well as the normal distribution considered the best fit, both for the current climate and for the projected climate change scenario.

Evaluation of the Overheating Hours percentage (OH) for the current climate shows that almost all cases already exceed the maximum criterion set by CIBSE in 1% of the occupied hours (Fig. 4a). The results follow a distribution close to normal, varying between 0 and 65%, although the most representative value is around 20%. As can be seen in Fig. 4b, future global warming entails a notable increase in OH. In 2050, OH values for the building category analyzed are expected to vary between 30 and 90%. In this case, the mean OH value is 65%, an increase of more than 40% in the most representative results of overheating hours.

Focusing on the night hours, where the indoor temperature limits in bedrooms established by CIBSE are stricter, the results are in keeping with those of OH during the whole day (Fig. 5). In the current climate, the results of the night-time Overheating Hours percentage (OHn) are concentrated between 10 and 80%, exceeding in all cases the maximum criterion set by CIBSE at a value of 1%. In this case, the most representative results are around 20%, since the distribution of the results is far from normal. In the climate change scenario, OHn increases between 40 and 98%, with its most representative value considered to be around 80%. Therefore, the future impact of global warming on thermal discomfort at night will be even greater than during the day.

However, many studies hold that these steady-state criteria are not representative when it comes to naturally ventilated buildings, where the user has greater control of the environment [51]. Overheating criteria that take into account the adaptability of users depending on the outside climate will therefore be evaluated in the following section.

4.2. Indoor overheating assessment: adaptive criteria

The three adaptive overheating criteria established by CIBSE in TM52 [41] (defined in Section 2.1.) were applied in the 750 multi-family buildings simulated. These criteria are: Hours of Exceedance, Daily Weighted Exceedance, and Upper Limit Temperature. The results obtained are analyzed in this section.

The first criterion refers to the percentage of hours in which the indoor operative temperature exceeds the adaptive threshold set as maximum, referred to hereafter as HE. For the current climate, the results show that most cases have a very low or non-existent HE, with a distribution far from normal (Fig. 6a). However, the increase in outdoor temperatures due to climate change will cause a clear rise in HE. The simulations show that, by 2050, almost all cases will exceed the maximum criteria established by CIBSE at a value of 3% (Fig. 6b). In this case, the results will vary between approximately 2 and 80%, with the most frequent value at around 20%.

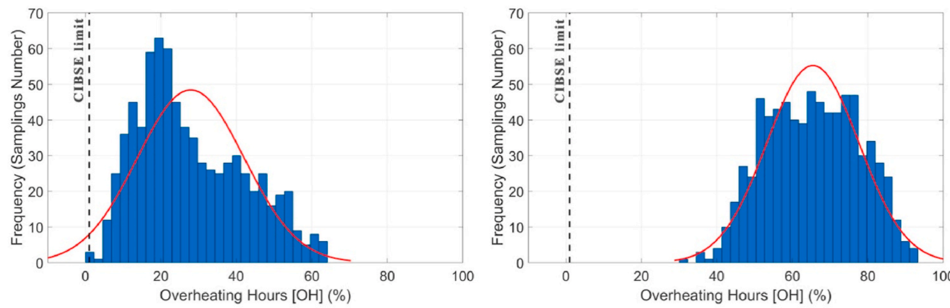
The second criterion limits the heat excess both in degrees and length, establishing that this excess (*We*) should not be more than six degree-hours any given day. Fig. 7 shows DE, the percentage of days during the non-heating season in which *We* in the study sample exceeds the limit set by CIBSE. The distribution of results for the current climate is similar to that of HE, since most cases have a very low DE value of around 2%. Most cases do not meet this criterion, with CIBSE stipulating that this value should not be exceeded on any day. For the 2050 scenario, the DE values for the building category analyzed are expected to vary between 5 and 85%. In this case, the most representative DE values are between 30 and 40%, widely exceeding the limit established by CIBSE (0% of the days).

Finally, the third criterion establishes a temperature limit, based on the maximum adaptive threshold set, which should never be exceeded. Fig. 8 shows the percentage of hours that exceed this Upper Limit Temperature, which will be referred to as HE_{ULT}, in the simulated cases. For the current climate, most cases have a minimum value of HE_{ULT}, where the most frequent result is 0%, thus fulfilling the CIBSE criteria. This criterion is the most restrictive, as seen from the results for the climate change scenario (Fig. 8b). While HE_{ULT} results are expected to range from 0 to 45%, the most common value is around 4%. However, hardly any of the cases analyzed are expected to meet this criterion by 2050, given the CIBSE stipulation that the Upper Limit Temperature should never be exceeded.

4.3. Sensitivity analysis

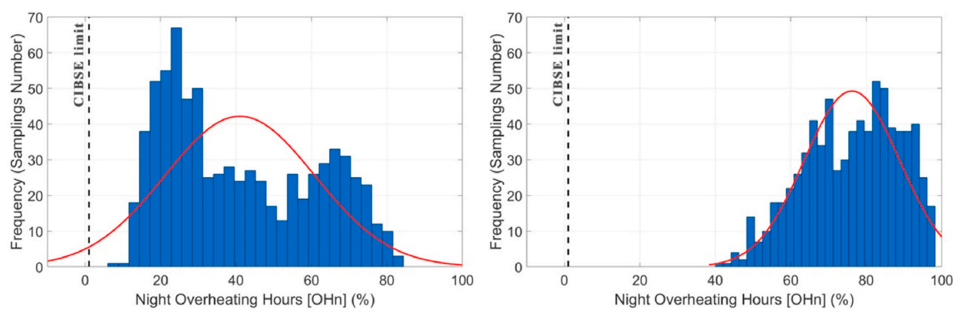
Finally, based on the results obtained, a sensitivity analysis was carried out to determine the parameters with the greatest influence on overheating, according to the adaptive criteria established by CIBSE [41]. Fig. 9 shows the evaluation of the Standardized Rank Regression Coefficients (SRRC) for the characteristic parameters that define the building category. The SRRC ranges from −1 to 1. A positive value means that the input and output parameters change with the same sign, while a negative one does the opposite.

The parameter with the greatest influence on indoor overheating in the building category evaluated, the one with the highest |SRRC| value, is clearly the natural night-time ventilation rate. This influence has even more weight in the climate change scenario. Although this responsibility currently lies with the user, future retrofitting proposals should enforce night-time ventilation patterns for the dissipation of the heat accumulated during the day.



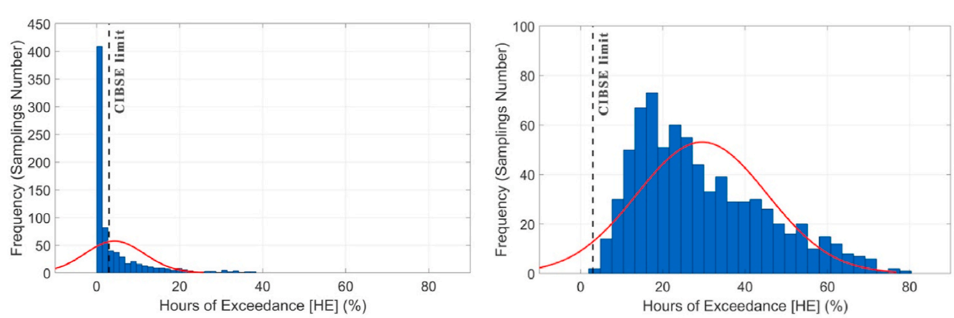
(a) (b)

Fig. 4. Distribution of the Percentage of Indoor Overheating Hours in the building category. Non-heating season (May–September): (**a**) current climate; (**b**) 2050 climate scenario.



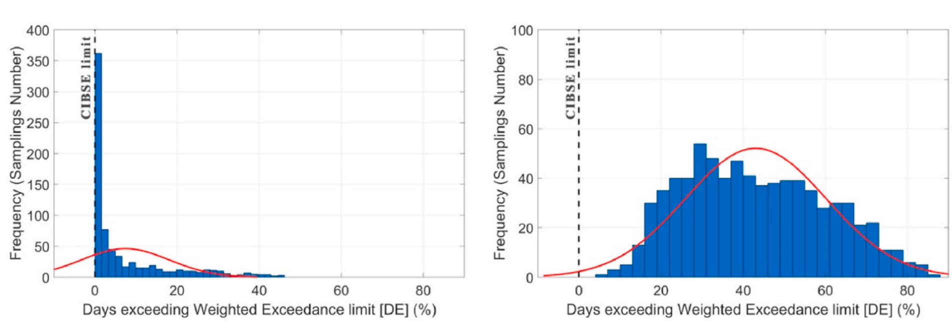
(a) (b)

Fig. 5. Distribution of the Percentage of Indoor Overheating Hours at Night in the building category. Non-heating season (May–September): (**a**) current climate; (**b**) 2050 climate scenario.



(a) (b)

Fig. 6. Distribution of the Percentage of Hours of Exceedance in the building category. Non-heating season (May–September): (**a**) current climate; (**b**) 2050 climate scenario.



(a) (b)

Fig. 7. Distribution of the Percentage of Days exceeding Weighted Exceedance limit in the building category. Non-heating season (May–September): (**a**) current climate; (**b**) 2050 climate scenario.

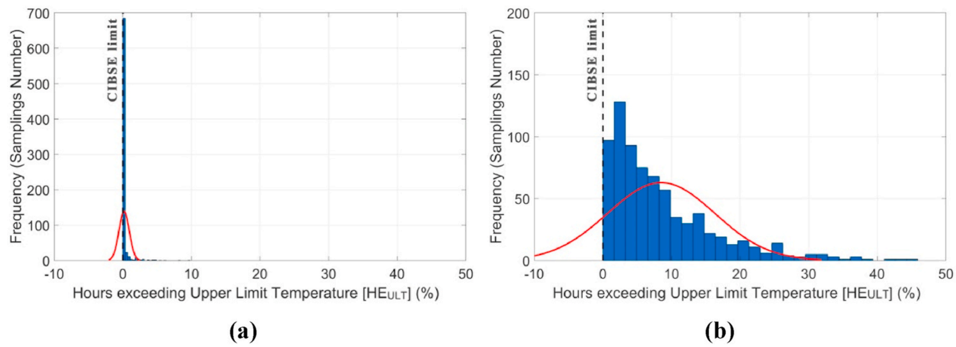


Fig. 8. Distribution of the Percentage of Hours exceeding Upper Limit Temperature in the building category. Non-heating season (May–September): (**a**) current climate; (**b**) 2050 climate scenario.

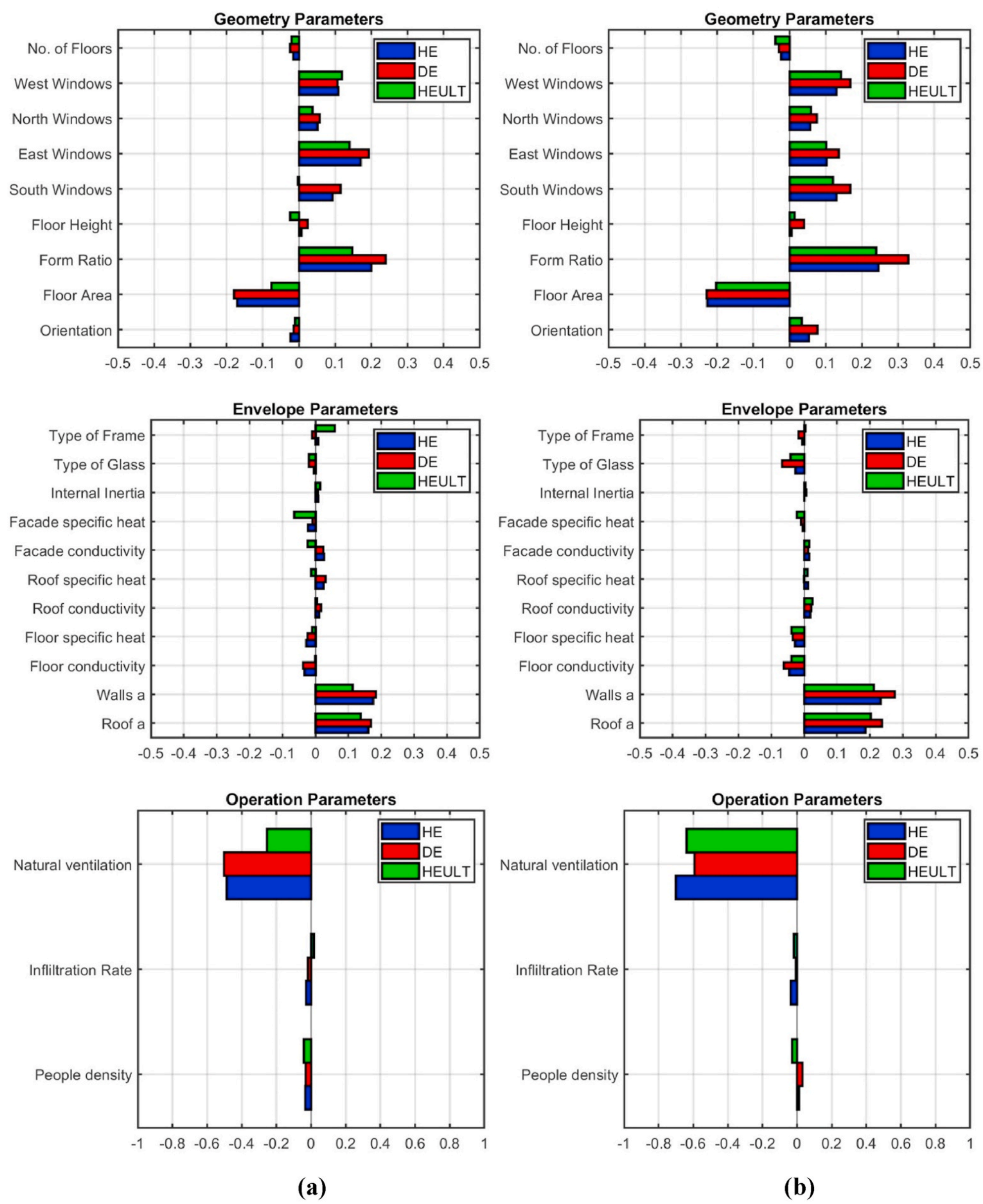


Fig. 9. Standard Rank Regression Coefficients (SRRC) in relation to adaptive overheating criteria (HE, DE and HE_{ULT}) for geometry, envelope and operation parameters: (**a**) current climate; (**b**) 2050 climate scenario.

Two other relevant parameters for the risk of overheating in this case study, depending on the geometric design of the buildings, are the 'form ratio' and 'floor area'. A greater compactness of the building (lower 'form ratio') and less exposure to the outdoor environment help to reduce the risk of indoor overheating, even more so when outdoor conditions become more extreme.

Furthermore, with respect to the geometric parameters of the buildings, it should be noted that in the current climate east- and south-facing windows cause more overheating. Nevertheless, by 2050 the afternoon sun is expected to be more intense and longer-lasting, so that the percentage of windows facing west will increasingly gain influence in the risk of building overheating in the Mediterranean climate.

According to the literature, |SRRC| values under 0.1 can be considered non-relevant [52]. Therefore, in the thermal envelope parameters, only the absorptance of the wall and roof external layer ('wall a' and 'roof a') stand out. At this point, it is important to remember that the thermal envelope of these existing buildings does not have any type of specific insulating material, which causes overheating in many new buildings.

4.4. Discussion of the results

Table 2 summarizes the results obtained from the evaluation of the overheating risk in the building category studied, according to different steady-state and adaptive criteria established by CIBSE. Overheating increases in the climate change scenario according to all the criteria applied. For the steady-state criteria, the median of both the percentage of hours of overheating during all occupied hours (OH) and that of the night hours (OHn) increases by more than 40% due to global warming. But there are some studies that indicate that static criteria could overestimate the risk of overheating, especially at night [27].

For the adaptive criteria, a clear trend of increased risk of overheating is also observed in the climate change scenario. The median percentage of Hours of Exceedance (HE) and Days exceeding Weighted Exceedance limit (DE) increased by approximately 40 and 25% respectively. These results are in line with previous studies evaluating thermal comfort in southern Europe during heat wave periods [10] and under climate change scenarios [53], reporting an increase of between 20 and 50% in discomfort hours in the most extreme climatic periods.

The median value of the percentage of Hours exceeding the Upper Limit Temperature (HE_{ULT}) increases around 6% (Table 2), since it is the strictest criterion. However, it should be noted that in the most unfavorable cases this percentage of HE_{ULT} could increase by almost 36% in 2050.

Thus, focusing on the adaptive criteria established in CIBSE TM52 [41], it is expected that by 2050 there will be an increase of almost 67% in cases that do not meet Criterion 1 (Table 3). Under the climate change scenario hardly any of the study samples would meet this criterion. In the current climate Criterion 2 is not met in more than 85% of cases, and the situation is projected to worsen in 2050, with non-compliance of the full study sample. The non-compliance values observed for Criterion 3 are very similar to those of Criterion 1. According to TM52 there is a risk of overheating when two of the three criteria established are not met. In the study sample, almost 38% of the cases are currently at risk of overheating, while it is expected that by 2050 almost the entire sample will be at risk, representing an increase of more than 60% of cases (Table 3). However, it should also be noted that there is still significant uncertainty regarding the potential of humans to adapt to high temperatures in the future, under the climate change scenario [8].

Table 2
Main results of the Overheating Assessment of the building category.

		Value	Current Climate	2050	Difference
Steady Criteria	**OH (%)**	Median	24.7	65.4	+40.7
		Maximum	64.1	93.1	+29.0
		Minimum	0.8	30.8	+30.0
	OHn (%)	Median	36.2	77.7	+41.5
		Maximum	84.3	98.2	+13.9
		Minimum	8.0	40.2	+32.2
Adaptive Criteria	**HE (%)**	Median	1.0	25.7	+24.7
		Maximum	38.2	78.6	+40.4
		Minimum	0.0	2.5	+2.5
	DE (%)	Median	1.9	41.9	+40.0
		Maximum	46.0	87.4	+41.4
		Minimum	0.0	5.1	+5.1
	HE_{ULT} (%)	Median	0.0	6.1	+6.1
		Maximum	9.7	45.6	+35.9
		Minimum	0.0	0.0	0.0

Table 3
Percentage of cases of the building category non-compliant with the Overheating Criteria.

		Current Climate	2050	Difference
Steady Criteria	**OH (%)**	99.9	100	+0.1
	OHn (%)	100	100	0.0
Adaptive Criteria	**HE (%)**	33.1	99.9	+66.8
	DE (%)	86.1	100	+13.9
	HE_{ULT} (%)	29.3	99.7	+70.4
	> 1 Criteria (%)	37.6	99.9	+62.3

If the overheating risk assessment were to be carried out as established in CIBSE TM59 [44], in which both the steady-state criterion of OHn and the adaptive criterion of HE must be met, 100% of cases would be considered to already be at risk in the current climate. However, some studies have called for the need to review these criteria as they are extremely difficult to meet [54]. The results of this study in a projected climate change scenario also show the need for more specific studies underpinning these overheating criteria by means of empirical evidence, including adaptability surveys answered by users.

The results obtained in the sensitivity analysis (Section 4.3) show that natural night-time ventilation rate is the parameter with the greatest influence on the risk of overheating in the building category evaluated. To complement this research, the risk of overheating under the climate change scenario was evaluated by establishing a night-time natural ventilation rate of 6 h^{-1} for the entire study sample. Fig. 10 shows the results for adaptive Criteria 1 and 2 of CIBSE TM52 [41]. By increasing the natural night-time ventilation rate to dissipate the heat accumulated during the day, the median HE value could be reduced by 9.5% and DE by 13%.

However, even implementing this passive conditioning strategy, 99.7% of the cases would remain at risk of overheating as they would fail to meet at least two of the three criteria set in the TM52. To a certain extent these results are far from the reduction in the percentage of overheating hours of between 28 and 35% estimated by Heracleous and Michael [29] for educational buildings in Cyprus in the year 2050. Despite this, they also conclude that natural ventilation alone will not be able to completely eliminate increasing overheating in the future.

4.5. Limitations and future research

Therefore, future research should include the optimized evaluation of combined retrofitting measures leading to a relevant reduction in the risk of overheating in the climate change scenario predicted for the Mediterranean area [55]. These measures will include the aspects which, according to this work and the existing literature, have the greatest influence on the risk of overheating, such as the already evaluated night-time ventilation, the absorptance of the building envelope, and window shading devices [56].

Another factor to be considered in future research steps is the thermal insulation of the envelope. The building category analyzed in this paper has a limited thermal transmittance range, with high values due to the generalized lack of insulation. This means that the results of the sensitivity analysis developed about the influence of thermal insulation

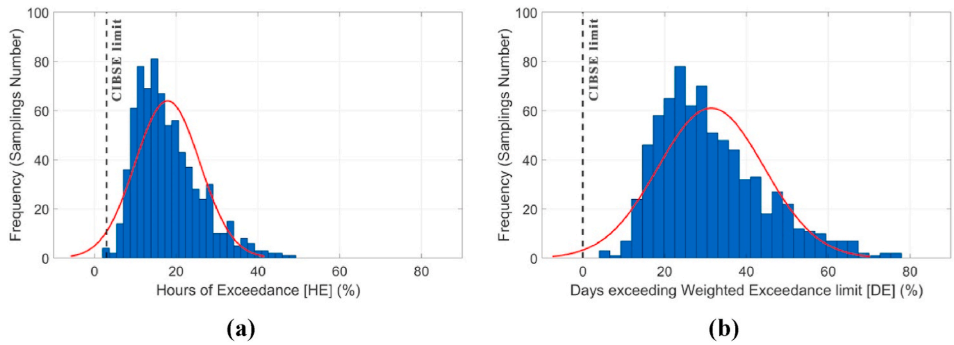


Fig. 10. Distribution of the (**a**) Percentage of Hours of Exceedance and (**b**) Percentage of Days exceeding Weighted Exceedance limit in the building category. Non-heating season (May–September). Maximum night-time natural ventilation rate scenario.

on the risk of overheating are also limited. Therefore, it would be necessary to analyze what would happen if the thermal transmittance of its envelope was reduced to the values established by the current regulations, as is common practice in energy retrofitting processes.

Working with large-scale models has a great potential to reduce computational efforts in wide samples, but this requires the simplification of some variables involved in the simulation to avoid compromising the reliability of the model. For example, it was necessary to reduce the dwelling to a single thermal zone. To accept this simplification, this work is based on previous studies in this sample, which indicated that there are negligible differences between indoor conditions in bedrooms and living room, since the rooms do not have an active air conditioning system and the doors of all rooms are generally open with the consequent circulation of air throughout the house [50]. In future detailed studies of particular cases, each room must be modelled as an independent thermal zone. In addition, operational parameters and occupancy hours are based on profiles defined through on-site measurements in a limited study sample [49,50]. In addition, Spanish regulations allow the generalization of the use pattern of solar protections for energy simulations, using roller blinds 50% open during the day (a practice that was also contrasted in the monitored case studies). Once general conclusions are drawn through these large-scale models, for future retrofitting of specific cases it will be necessary to apply real use and occupation patterns in the simulations.

One more limitation of this study includes its focus on a particular building category, but it is feasible to complete this characterization in future research by expanding the methods applied in this work to other significant residential typologies and other long-term uses, such as schools or hospitals. A method of weighting dwellings to scale up the results to the national stock could be additionally developed, considering the weighting parameters aligned with factors that impact on overheating. Also, other specific indexes to evaluate heat stress are intended to be evaluated in future research steps, such as Universal Thermal Climate Index and Heat Index. Finally, different climate change scenarios and the worsening of global warming due to urban heat island effects should also be considered in the future steps of this research, since it is a problem widely verified by the scientific community [8].

5. Conclusions

This study carried out an evaluation of the risk of overheating affecting the social housing stock in southern Spain, both currently and in a climate change scenario. To do this, a large-scale simulation model of a building category representing more than 42,000 dwellings, and previously calibrated through in-situ monitored data, was used. This building category is mostly inhabited by a population vulnerable from a health point of view and at risk of energy poverty.

The results, according to the adaptive criteria established by CIBSE in TM52, show that almost 38% of the cases evaluated are already at risk of overheating and in 2050 almost 100% will be. If we take as reference TM59 requirements, combining the steady-state criterion of night-time overheating and the adaptive one of Percentage of Hours of Exceedance, all the cases would be at risk of overheating at present due to an excess of heat at night.

Focusing on the adaptive criterion of Percentage of Hours of Exceedance, the median of the results of the category studied under current conditions is 1%, which complies with CIBSE limit set in a maximum of 3% of the occupied hours. However, this value will increase by almost 25% for the climate change scenario, which will mean that almost 100% of the sample no longer complies with the CIBSE limit. The same trend is observed in the results of the Percentage of Days exceeding Weighted exceedance limit, which would go from a median of almost 2% under current conditions to increase this value to 42% in 2050.

The sensitivity analysis developed concludes that the parameter that has the greatest influence on the risk of overheating, both currently and in 2050, is the natural night-time ventilation rate, followed by the geometric factors of form rate and area, and the absorptance of the wall and roof external layers. Given these conclusions, it was evaluated what effect the imposition of a protocol of night-time ventilation of 6 air changes per hour in all the cases evaluated would have in 2050. According to the results obtained, this measure achieves an average decrease of almost 10% of the Hours of Exceedance, but barely manages to reduce the percentage of cases at risk of overheating.

The conclusions of this work highlight the situation of environmental vulnerability observed in the social housing stock in southern Spain. If no action is taken soon to retrofit it, the overheating problem will be notably aggravated, leading to long periods of exposure to high temperatures, which could turn to serious health problems for the most vulnerable population living in this residential stock.

All of this means that we are in a state of climate emergency, making it necessary to incorporate retrofitting actions in order to respond not only to normative criteria focused on reducing consumption and emissions (energy improvement) but also to comfort needs associated with overheating (health and wellness improvement). These adaptation actions or strategies should not focus on current climatic conditions but should be projected to the 2050 horizon, with clearly more adverse conditions. Moreover, the results of this work indicate that overheating evaluation should better be carried out through adaptive models, which will also probably be modified to respond to how users adapt to new climatic conditions, since the steady-state criteria seem excessively strict.

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.

Acknowledgements

This work has been financially supported by the European Social Fund and by Regional Andalusian Government (Aid for the recruitment, incorporation of Research PhD Staff), and by the Spanish Government (ref. IJC2018-035336-I).

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