Field assessment of thermal comfort conditions and energy performance of social housing: the case of hot summers in the Mediterranean climate.

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Abstract

Much of the social housing stock in southern Europe is obsolete in energy terms, with users who also present very specific socio-economic profiles requiring in-depth study. Proposals for this type of housing stock of current energy retrofitting policies, based on standardized user patterns, will only contribute to increasing the 'performance gap' between real and estimated consumption.

This study evaluates the thermal comfort conditions and energy consumption in the specific case of social housing in southern Spain, under a severe summer climate. This evaluation is based on in-situ data measurements of three housing units in use. This paper aims to test which adaptive comfort models work best in the specific conditions of the case studies and to identify the user behaviours which reduce thermal comfort. Thus, real user patterns were established and measured data were analysed. The results show that the case studies are in discomfort conditions during a high percentage of occupied hours, mainly due to the severe climate and the unsuitable use of passive measures including natural night-time ventilation and solar protection. This situation worsens with limited use of local cooling systems due to financial constraints. National regulations should define different retrofitting targets based on climatic and socio-economic conditions.

Keywords: social housing; monitoring; thermal comfort; energy performance; occupant behaviour.

Abbreviations: PPD, Predicted percentage of dissatisfied (%); Tco, Optimum comfort temperature (ºC); Text, ref, Monthly average outdoor dry bulb temperature (ºC); TeR, Running mean outdoor dry bulb temperature (ºC); PMV, Predicted mean vote; MM, Thermal comfort standard for hybrid or 'Mixed Mode' buildings; V_{50}, Air leakage rate at 50 Pa (m^3/h); n_{50}, Air change rate at 50 Pa (h^{-1}).

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Highlights

- Energy retrofitting policies should consider specific socio-economic conditions.
- A method based on in-situ monitoring is proposed for quantifying thermal comfort.
- Properly matching comfort standards to social housing in southern Spain is debated.
- Relevant thermal discomfort problems are detected in the case study.
- The use of cooling systems is limited by socio-economic conditions.

1. Introduction

In recent years the scientific community has shown increasing interest in the energy performance of the building stock, which accounts for 40 % of total energy consumption in the European Union (European Parliament, 2010). This evolutionary process is reflected in the directives issued by the European Union, which first incorporated energy saving actions in 2002 (European Parliament, 2002), focused mainly on new constructions. In Spain, this directive materialized in 2006 with the approval of the Technical Building Code (Spanish Government, 2006).

The low rate at which existing buildings are being replaced by new ones (Ma et al., 2012) makes it very difficult to meet the European energy saving objectives based only on actions focused on new constructions. As a result, subsequent energy policies have broadened their focus, incorporating investment in building retrofitting as one of their main strategies, as reflected in Directive 2012/27/EU at European level (European Parliament, 2012), and in Royal Decree 235/2013 (Spanish Government, 2013) at national level. The latest European Directive on energy saving, 2018/844/EU (European Parliament, 2018), requires buildings retrofitting plans to include real measures to estimate both energy savings and benefits related to health in order to avoid large differences between estimated and real consumption.

In southern Europe specifically, between 63 % and 76 % of the existing housing stock was built prior to the first regulations establishing overall limitations for the energy demand of buildings (1976-1979) (Di Pilla et al., 2016; Theodoridou et al., 2011; Spanish Statistics National Institute, 2011). As a result, much of the housing stock was built with no specific thermal insulation measures and is therefore considered obsolete from an energy perspective (Santamouris and Kololotsa, 2015). In order to develop suitable energy retrofitting policies for this housing stock, avoiding the 'performance gap' between real and simulated consumption, prior analysis of thermal envelopes and user behaviour is required (Escandón et al., 2018; Guerra-Santín et al., 2013).

Many of the studies about this ‘performance gap’ focus on the analysis of the heating demand in low-energy housing units where, due to the Rebound effect, real consumption frequently exceeds that estimated (Hens et al., 2010; Branco et al., 2004). This research focuses on the opposite situation, when real consumption is much lower than estimated for multiple reasons (technical inaccuracies and diversity in user patterns). This situation, known as the Prebound effect, could be directly related to the household income level, energy bills and consequently energy prices (Sunikka-Blank and Galvin, 2012). According to Guerra-Santín and Silvester (2017) the specific climate and building characteristics are commonly incorporated into the energy simulations, while the user-related characteristics and occupant behaviour are not yet fully taken into account. The bibliography that can be found regarding this is focused on the evaluation of the use-of-heating profiles in cold climates of northern Europe (Guerra-Santín and Itard, 2010).

The possibility of users rejecting living in thermal comfort conditions due to financial constraints (highly likely in social housing in southern Europe) increases the divergence between real and estimated consumption (Escandón et al., 2017; Fabbri, 2015; Santamouris et al., 2014). This scenario is not considered in the standardized user patterns used for energy assessment procedures deriving from Directive 2010/31/EU (European Parliament, 2010). In the specific case of southern Spain although a high percentage of multi-family dwellings incorporate cooling equipment (66.2 %) (IDAE, 2011), in most cases these are local systems providing service to a single room of the housing units and used intermittently to reduce costs (Sendra et al., 2013).

Some studies carried out in Spain confirm the energy poverty situation experienced by a large part of the housing sector in the country. According to Boardman (1993), this situation occurs when a family living in an energy-inefficient home is unable to afford adequate indoor thermal conditions. The bibliography reviewed warns about the direct correlation between socio-economic and thermal comfort conditions, based on indicators agreed by the European Union but not contrasted with in-situ measures (Aristondo and Onaindia, 2018; Scarpellini et al., 2015). It is worth highlighting the study by San Miguel-Bellod et al. (2018) which is based on a wide sample of case studies and manages to establish a correlation between the indoor temperature measures, the constructive characterization of the building and the socio-economic information extracted from user interviews. The need to extend the monitoring campaigns to different climates and contexts in order to contrast and complement the results is concluded. Other case studies in northern (Bilbao) (Terés-Zubiaga et al., 2013) and central Spain (Madrid) (Alonso et al., 2017) also used in-situ measures, albeit with smaller samples (10 and 2 cases, respectively), to ascertain the impact of socio-economic conditions on indoor temperatures in social housing, where heating consumption is limited in order to save money and central heating systems cannot be installed or maintained.

The same conclusion is reached in an earlier study carried out in southern Spain by the authors of this document (Escandón et al., 2017). Although the climate is considered less severe in winter than in cases listed above, the results of a year-long field monitoring assessment of three cases of social housing built in the post-war period showed that users live in thermal discomfort conditions for 100 % of the hours. This is due to the total absence of central heating systems and almost zero heating consumption of local equipment. Although all the examples stated focus on the analysis of the lack of thermal comfort in social housing during the winter period, this research should be extended to the summer period, especially in dry and hot climates.

Thermal comfort evaluations are needed in order to define the thermal needs of a household. Thermal comfort can be defined - according to Fanger (1970) - as the occupants' heat balance in an indoor environment, where different personal and environmental parameters affect the process of heat exchange between the human body and the room. When evaluating comfort in naturally ventilated buildings, numerous studies hold that adaptive standards are more reliable than the standard *Predicted Mean Vote* (PMV) index (Djongyang et al., 2010; Moujalled et al., 2008; Humphreys, 1976). This is based mostly on the fact that users can change their clothes or open windows depending on outdoor conditions, thus making it very difficult to set parameters. However, what happens when the building is equipped with air conditioning systems and is also naturally ventilated? Current adaptive comfort standards such as Standard 55 (ASHRAE, 2010) or ISO-EN-15251 (CEN, 2007) do not consider this particular situation (Barbadilla-Martín et al., 2017).

The authors of Standard 55 made very limited use of case studies in the Mediterranean arc when defining it (de Dear and Brager, 2002). The European Commission subsequently promoted the development of the 'Smart Controls and Thermal Comfort' project (SCAT), which included case studies from the different European climate zones (McCartney and Nicol, 2002). As a result of this project, Nicol and Humphreys (2010) developed the comfort model defined in ISO-EN-15251. However, when applying both models in southern Europe, mainly in locations with very high temperatures during the dry summer period, the results are not a faithful match to the perceptions of the real users given that both models include indoor temperatures (above 31 ºC) that are too high within the range of acceptability (Guedes et al., 2009; Fato et al., 2004).

Through the quantification of thermal comfort conditions and energy consumption of three housing units currently in use, this paper aims to: (a) test which if any of the two adaptive comfort models aforementioned works best, or if another alternative model could be applied, and (b) find what user behaviours or other factors reduce thermal comfort. This case study focuses on the specific context of social housing stock in a southern European context, with a dry and hot summer climate. For this purpose, a method based on in-situ monitoring was applied, which also made it possible to define the real user patterns of these case studies, providing a better understanding of the environmental and energy performance of the housing units. This work complements previous analysis of the same case studies in the winter period (Escandón et al., 2017).

The current Spanish energy retrofitting plans do not set the prior step of characterizing the real user profile for the estimation of energy savings and return periods as mandatory, and the use of the standardized profile established by the national regulation is accepted. This standardized pattern was mainly established for application in energy certification tools, since it aims to set homogeneous conditions for Spanish houses in order to calculate their energy rating. Although this pattern assumes that users almost always live in thermal comfort conditions, in fact, in social housing in southern Europe, the most usual scenario is that of renouncing comfort. If this standardized pattern is applied in the estimation of energy savings from retrofitting these houses, the results obtained would be far removed from reality. Through the case studies analysed within it, this paper aims to disprove this situation of generalized comfort in all cases, so that the real needs of the most disadvantaged population (more focused on health than on energy savings) are not ignored.

2. Methods

These research methods for the analysis of the environmental and energy performance of social housing in southern Spain are based on in-situ measurements with the housing unit in use, analysing the thermal comfort conditions. These methods, already defined and applied in previous studies (Escandón et al., 2016, 2017), are summarized in the following sections and applied to three case studies whose characteristics and selection criteria are defined in Section 3.

2.1. Monitoring

The in-situ data collection carried out for this research addresses:

- In-situ measurements over a whole year (air temperature, relative humidity, CO_2 level, and energy consumption). Two WOHLER CDL 210 indoor data-loggers were placed in each housing unit (one in the living room and the other in the main bedroom) to measure the environmental variables at 30-minute intervals. Energy consumption was measured at 15-minute intervals throughout the year, using a general consumption meter and several individual meters (sub-metering) in the sockets of various appliances (mainly local heating and cooling systems).
- Depressurization tests using the Blower Door equipment to verify the airtightness of the building envelope, following UNE EN-13829 (AENOR, 2013a).
- Capture of images of building envelopes using a thermographic camera, following UNE EN-13187 (AENOR, 2013b). The aim of this test is evaluate the thermal behaviour of the case studies' façades.

The climate data used for the energy simulation were provided by three meteorological stations belonging to the Spanish State Meteorological Agency (AEMET, 2018), and previously validated against spot measurements taken outside the case studies.

Long-term measurements (temperature, CO_2 concentration and electric consumption) and survey data were cross-referenced to define the real user patterns for the case studies using a mixed method (Guerra-

Santín et al., 2016). This method takes technical and social aspects from user practices into account, both qualitatively and quantitatively. For the quantitative data analysis, the hourly average values for the summer period weekdays were used: temperatures (ºC), CO_2 concentration (ppm), local heating system operation on a scale of 0 to 1 (0 means off and 1 on) and general electrical consumption (kWh). This quantitative analysis was contrasted with the qualitative information collected in user surveys.

2.2. Comfort analysis

The thermal comfort level in the case studies was analysed using the in-situ measured data and according to three different adaptive comfort standards. Currently, the two most widely used adaptive comfort standards are Standard 55 (ASHRAE, 2010) and ISO-EN-15251 (CEN, 2007) (Ferrari and Zanotto, 2012).

For naturally ventilated buildings, ASHRAE Standard 55 provides an optional method for determining acceptable thermal conditions, applied only in buildings where occupants perform low metabolic rate activity (ranging from 1.0 to 1.3 met). This method establishes an optimum comfort temperature (*Tco*, equation 1) and two acceptability ranges: one corresponding to 90 % of satisfied occupants (Predicted percentage of dissatisfied (PPD) < 10 %), defined by a temperature interval of ± 2.5 ºC, and another corresponding to 80% of satisfied occupants (PPD < 20 %), with a temperature interval of ± 3.5 ºC.

$$Tco = 0.31 \times Text,ref + 17.8\ [°C] \quad (1)$$

where:

Text, ref: monthly average outdoor dry bulb temperature (i.e., average value between the maximum and minimum temperature throughout the month) [ºC].

The European Committee for Standardization (CEN) introduced the adaptive approach in standard EN 15251, only applicable to buildings used for low metabolic rate activities, without HVAC systems and where occupants can freely operate windows or change clothes. This norm establishes a *Tco* (equation 2) and three acceptability ranges based on different building categories: category I, for a high level of expectations (PPD < 6 %), defined by a temperature interval of ± 2 ºC; category II, for a normal level of expectation (PPD < 10 %), with a temperature interval of ± 3 ºC; and category III, for a moderate level of expectation (PPD < 15 %), with a temperature interval of ± 4 ºC. This research only assessed categories II and III.

$$Tco = 0.33 \times T_{eR} + 18.8\ [°C] \quad (2)$$

where:

T_{eR}*: daily running mean dry bulb outdoor temperature for today (equation 3)*

$$T_{eR} = (1 - \alpha) \times T_{ed-1} + \alpha \times T_{eR-1} \quad (3)$$

where:

T_{ed-1}*: daily mean dry bulb outdoor temperature (i.e., average value between the maximum and minimum temperature throughout the day) for previous day;*

T_{eR-1}*: daily running mean dry bulb outdoor temperature for previous day;*

α: a constant between 0 and 1. Use of 0.8 is recommended.

Aiming to adjust the adaptive comfort standards described above to the specific case of hybrid or 'Mixed Mode' buildings (with intermittently used air conditioning equipment and naturally ventilated through windows), Barbadilla-Martín et al. (2017) developed an alternative model for the Mediterranean climate. This method establishes a *Tco* defined in equation 4. In this case, the two acceptability ranges defined for ASHRAE Standard 55 were evaluated.

$$Tco = 0.24 \times T_{eR} + 19.3 \quad (4)$$

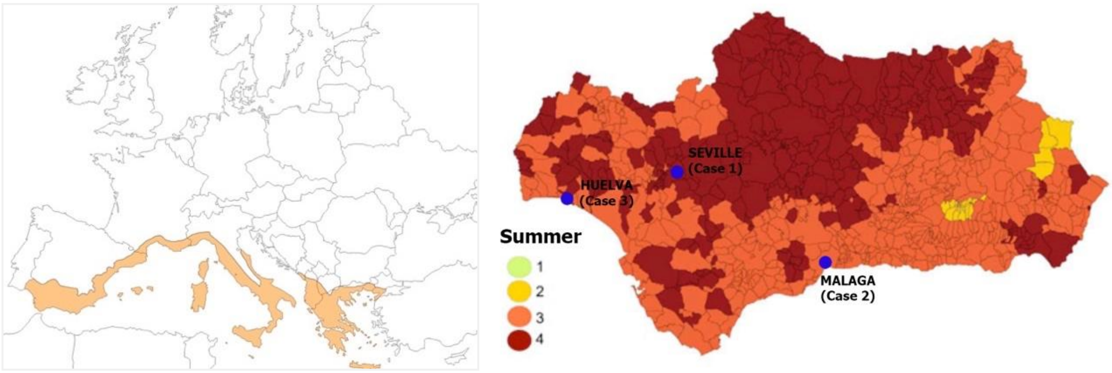
where:

T_{eR}*: daily running mean dry bulb outdoor temperature for today (equation 3)*

3. Case studies

For this research, three housing units belonging to the social housing stock in multi-family buildings built in southern Spain between the 1960s and 1980s were selected as case studies. During this period, the most representative morphological building typologies were the linear block and the H-shape, to which more than 80 % of the total housing built belongs (around 40 % to each typology). Regarding the constructive building typologies, the most representative were the single-leaf brick façades (which can be found in 30 % of the total housing built) and the two-leaf brick façades with an air chamber (50 %), as reported for the case of Seville in Domínguez-Amarillo et al. (2016, 2017). The case studies were selected based on their building typologies (they belong to the most representative) and their location in neighbourhoods identified by the Andalusian Government as cases of interest for its energy retrofitting plan (MBP, 2015).

The case studies are located in a Mediterranean climate (figure 1a), in three Spanish cities with a Csa climate according to the Köppen-Geiger classification (Peel et al., 2007) and the highest values in the scale of summer climate severity as defined by the Spanish Government (2013b): Seville and Huelva (summer climate zone 4), and Malaga (zone 3) (figure 1b). In Andalusia, which represents 17.3 % of the Spanish territory and takes up the entire south of the peninsula, 98 % of the municipalities belong to climate zones 3 and 4 (61 % and 37 % respectively), so that the case studies are located in the most representative summer climate zones. The summer climate is severe (dry and hot), with significant levels of solar radiation and high outdoor temperatures exceeding 30 °C on 90 % of days (zone 4) (Calama-González et al., 2018). Table 1 summarizes the main climate characteristics of these locations.



(a) (b)

Figure 1. Mediterranean climate map: (a) in Europe, (b) in southern Spain.

Table 1. Annual standard climate values, period 1981 – 2010 (AEMET, 2018)

	Seville (Case 1)	Malaga (Case 2)	Huelva (Case 3)
Altitude (m)	34	5	19
Latitude	37º 25' 0'' N	36º 39' 58'' N	37º 16' 42'' N
Longitude	5º 52' 45'' W	4º 28' 56'' W	6º 54' 42'' W
Average temperature (ºC)	19.2	18.5	18.2
Average maximum daily temperature (ºC)	25.4	23.3	23.9
1% summer design temperature (annual) (ºC)	37.6	33.2	34.4
Summer mean DTR (ºC)	17.4	14.7	16.9
Average relative humidity (%)	59	65	66
Average daily global irradiation (kWh/m^2)	5.23	5.20	5.22
Average hours of sunlight	2917	2905	2969

The three housing units analysed share similar morphological and constructive characteristics, summarized in table 2. Case 1 (figure 2a) is in a linear-shape building, and its main façades therefore face opposite orientations: northeast (main bedroom) and southwest (living room and secondary bedrooms). Case 2 (figure 2b), in an H-shape building, presents the largest floor area and its main façades face northwest (living room and secondary living room) and southwest (bedrooms). Case 3 (figure 2c) is also in an H-shape building, with main façades facing southwest (living room and main bedrooms) and northeast (kitchen and secondary bedroom). As this housing unit is located on the top floor of the building, immediately below the roof, it has high exposure to sun.

Cooling systems found in the three case studies are typical of the social housing stock in southern Spain: local thermal conditioning systems (reversible heat pumps) usually placed in the living room or in the main bedroom (Sendra et al., 2013). Although these are local systems, the rooms within the housing unit tend to be connected as the doors are always open.

The depressurization tests carried out on the case studies show medium air permeability for all cases, following categories established by EN-13790 (ISO, 2008). Test results are shown in table 3.

(a) (b) (c)

Figure 2. Exterior view and floor plan of case studies: (a) case 1 - Seville, (b) case 2 - Malaga, (c) case 3 - Huelva.

Table 2. Description of case studies.

	Case 1 (Seville)	**Case 2 (Malaga)**	**Case 3 (Huelva)**
Year of construction	1964	1974	1975
Summer climate zone (Spanish Government, 2013b)	4	3	4
Typology	Linear	H	H
No. stories	5	10	4
No. identical housing units	260	1512	540
Floor area (m^2)	58	105	58
Façade	Brick (1/2 foot); air chamber; brick (4 cm)	Brick (1/2 foot); air chamber; brick (4 cm)	Brick (1/2 foot); air chamber; brick (4 cm)
Façade (under windows)	Brick (1/2 foot)	-	-
Façade transmittance (W/m^2K)	1.58	1.69	1.69
Type of roof	Flat	Flat	Flat
Roof	Tile; coal dust; roof structure	Fibre cement; air chamber; roof structure	Tile; coal dust; roof structure
Roof transmittance (W/m^2K)	1.82	1.88	1.82
Joinery	Aluminium	Aluminium	Aluminium
Glazing	6 mm (original)	6+12+6 mm (retrofitted)	6+6+6 mm (retrofitted)
Window transmittance (W/m^2K)	5.70	3.40	3.80
Solar protection	Roller blinds	Roller blinds	Roller blinds
Hot Water production	Electric heater	Electric heater	Gas heater
Ventilation system (damp units)	Natural through window	Vent in bathrooms	Natural through window
Cooling system	Electric heat pump (2 bedrooms)	Electric heat pump (2 living rooms)	Electric heat pump (living room and 1 bedroom)

Table 3. Air permeability test results.

Air permeability	**Case 1 (Seville)**	**Case 2 (Malaga)**	**Case 3 (Huelva)**
Air leakage rate at 50 Pa: V_{50} (m^3/h)	1053	1287	1258
Air change rate at 50 Pa: n_{50} (h^{-1})	9.4	5.6	8.4

3.1. User patterns

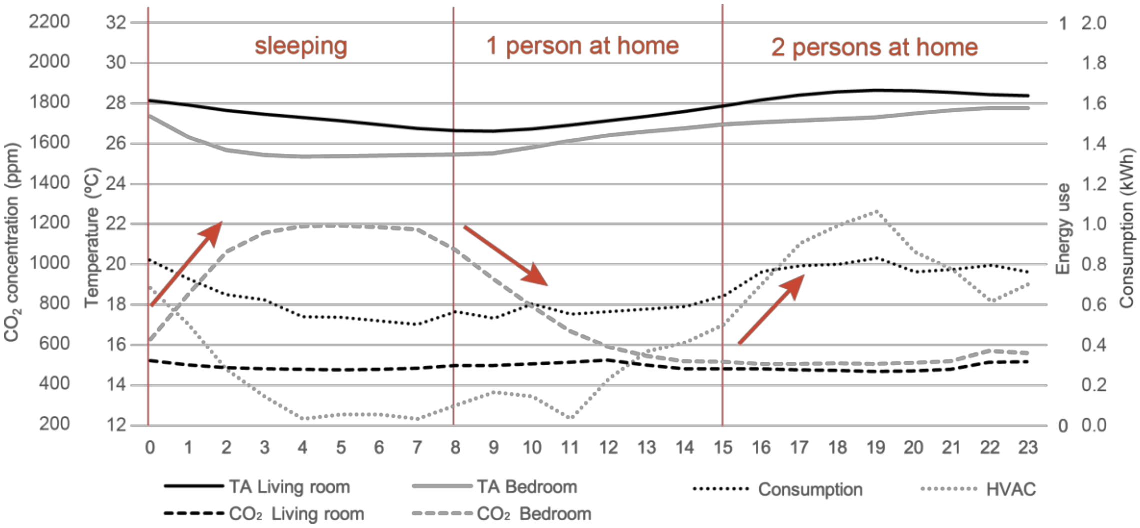
The user patterns for the summer period of the three case studies were defined following the method described in Section 2. This method is based on the analysis of the quantitative data measured in situ (temperature, CO_2 concentration and electricity consumption) which is contrasted with the qualitative data collected in user surveys. In these surveys, whose answers are summarized in table 4, the occupants of the case studies were asked (in the summer period) about their occupation habits, when do they use solar protections, in which periods do they open windows for natural ventilation, when and for how long do they make use of the local cooling systems. The habits which can have a greater impact on the thermal behaviour of homes are questioned.

Table 4. Surveys: user pattern (summer weekday).

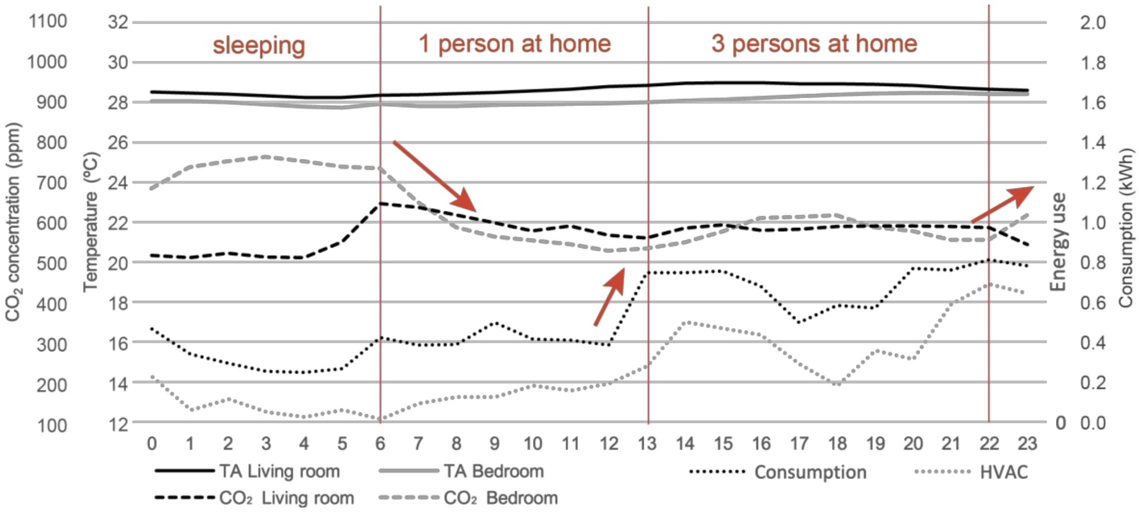
Case 1 (Seville)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Occupancy (man)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Occupancy (woman)	■	■	■	■	■	■	■								■	■	■	■	■	■	■	■	■	■
Roller blind											■	■	■	■	■	■	■	■	■	■	■			
Natural ventilation	■	■	■	■	■	■	■	■	■														■	■
Local cooling															■	■	■	■	■					
Case 2 (Malaga)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Occupancy (father)	■	■	■	■	■																	■	■	■
Occupancy (mother)	■	■	■	■	■	■	■						■	■	■	■	■	■	■	■	■	■	■	■
Occupancy (child 1)	■	■	■	■	■	■	■								■	■	■	■	■	■	■	■	■	■
Occupancy (child 2)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Roller blind	■	■	■	■	■																		■	■
Natural ventilation						■	■	■	■	■														
Local cooling													■	■							■	■		
Case 3 (Huelva)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Occupancy (man)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Occupancy (woman)	■	■	■	■	■	■	■						■	■	■	■	■	■	■	■	■	■	■	■
Roller blind	■	■	■	■	■	■	■																■	■
Natural ventilation								■	■	■	■								■	■				
Local cooling																					■	■		

Case 1 (figure 3a) is inhabited by a young couple, one of whom works from home with computers for long periods of time. In this case, it is the CO_2 level in the bedroom that indicates the sleep hours (24.00 - 8.00 h). The occupation pattern defined by the surveys is confirmed by the consumption increase in the afternoon, (table 4), showing that the housing unit is fully occupied after 15:00 h. In this case, the cooling equipment (located in bedroom 2) is often used in the afternoons, but barely manages to lower the indoor temperature of the two monitored rooms. These users ventilate through the windows during the night and make use of solar protection during the hottest hours of the day.

Case 2 (figure 3b) is inhabited by a family consisting of three adults and one teenager, who spend most of the day away from home (except the teenager, who is on holiday during the summer period measured). Again, it is the CO_2 level in the main bedroom which indicates the users' sleep hours (22.00 - 6.00 h). The increase in energy consumption indicates that at midday two of three users who were working outside return home, as confirmed by the survey (table 4). This housing unit is not completely occupied until around 22.00 h at night. Although local cooling systems are used on occasion, they are more frequently detected between 14:00 and 21:00 h.



(a)



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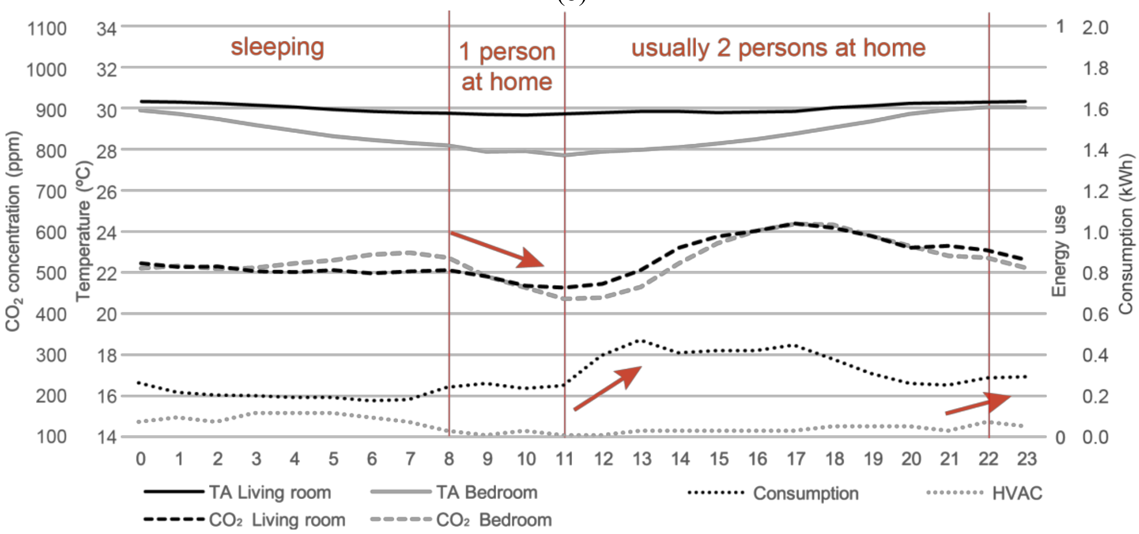


(c)

Figure 3. User pattern (summer weekday), based on the evaluation of the average hourly values of temperature (ºC), CO_2 concentration (ppm), local cooling system operation (energy use: 0/off - 1/on) and general electric consumption (kWh): (a) case 1 - Seville, (b) case 2 - Malaga, (c) case 3 - Huelva.

Case 3 (figure 3c) is inhabited by a retired older couple, who spend most of the time at home during the summer. In this case, the low concentration of CO_2 during the night makes it more difficult to draw conclusions about the sleep hours, but the survey (table 4) shows use of the local cooling equipment in the bedroom before going to sleep (22.00 h) and the level of CO_2 drops at around 8.00 h. One of the users is away during the morning and returns around 12.00 h, when the energy consumption rises and the housing unit is completely occupied. This case is naturally ventilated for just a few hours in the morning and afternoon.

The three housing units analysed belong to social neighbourhoods, which tend to be associated with medium-low incomes. According to the Spahousec report (IDAE, 2011), cases 1 and 3 belong to a small-size household category (1-2 members) and case 2 to a medium-size one (3-4 members). 50 % and 42 % of Spanish households belong to each of the categories mentioned above. Despite the difficulty entering the houses for monitoring, since they are private properties, different categories of households were analysed. Despite having similar socio-economic conditions and an occasional use of local cooling systems, user profiles present very different patterns and intensity of use of natural ventilation and solar protections (case 1 versus cases 2 and 3). This diversity aids in the evaluation in the following sections of the influence of ventilation rate and schedule and the use of solar protections on the thermal behaviour of the case studies.

4. Results

4.1. Indoor environmental conditions

The hourly temperature, relative humidity and CO_2 concentration level for the hottest month of the summer period were analysed and represented in a graph, while periods of use of the local cooling systems in the housing units monitored were also identified in graphs. The CO_2 graphs included a reference limit below which indoor air quality is considered good (1200 ppm), following the FSIAQ (Finnish Classification of indoor climate 2000) standard for category S3 (a less demanding category which may be associated with existing buildings) (FiSIAQ, 2001).

In case 1, in August 2014, outdoor temperatures in Seville varied from 18 ºC to 39 ºC (figure 4), while average indoor temperatures were 28.6 °C in the living room and 25.8 °C in the bedroom. It should be noted that in this case the intermittent use of the local cooling system (located in bedroom 2, with the doors open) lowers the indoor temperature of the living room by barely 1 ºC. The use of high natural night-time ventilation rates significantly reduces indoor temperature by up to 5 ºC. The suitable use of solar protection and the northeast orientation of the main bedroom are also beneficial for the good environmental performance of this housing unit despite the severe outdoor conditions.

Analysing other environmental variables (figure 5), outdoor relative humidity ranges from 20 % to 90 %, while indoor relative humidity is between 30 % and 70 %. When the bedroom is naturally ventilated, the indoor relative humidity rises, approaching the outdoor value. The indoor CO_2 concentration level shows two very different ways of use of the monitored rooms. While in the living room a stable value remains around 500 ppm (except when occasionally receiving visitors), in the bedroom a value of 1000 ppm is reached when it is occupied (the door of the room is kept closed at night). Indoor air quality is good for 99 % of the time, due to an adequate use of natural ventilation.

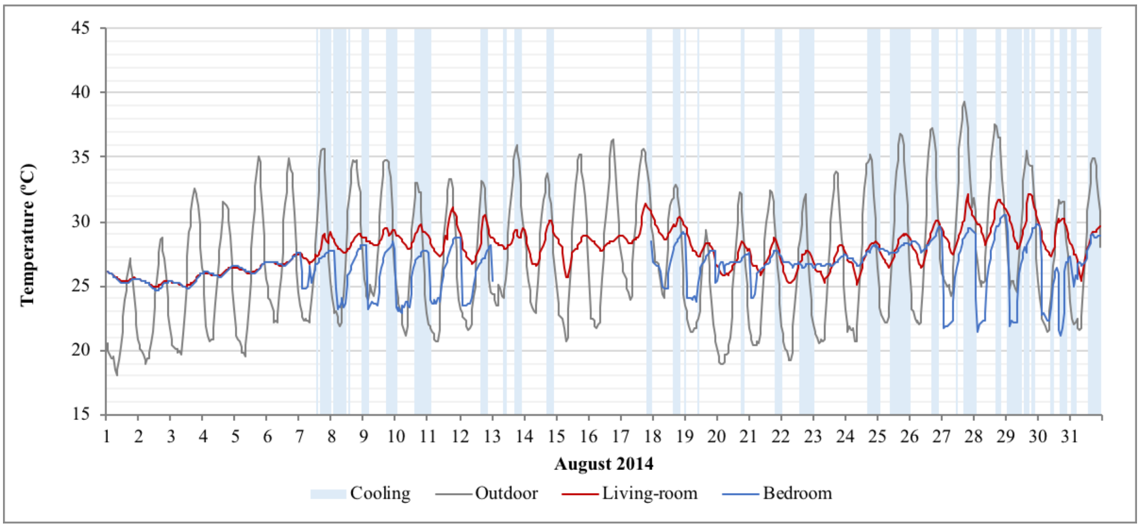


Figure 4. Case 1 - Seville: hourly temperature during August.

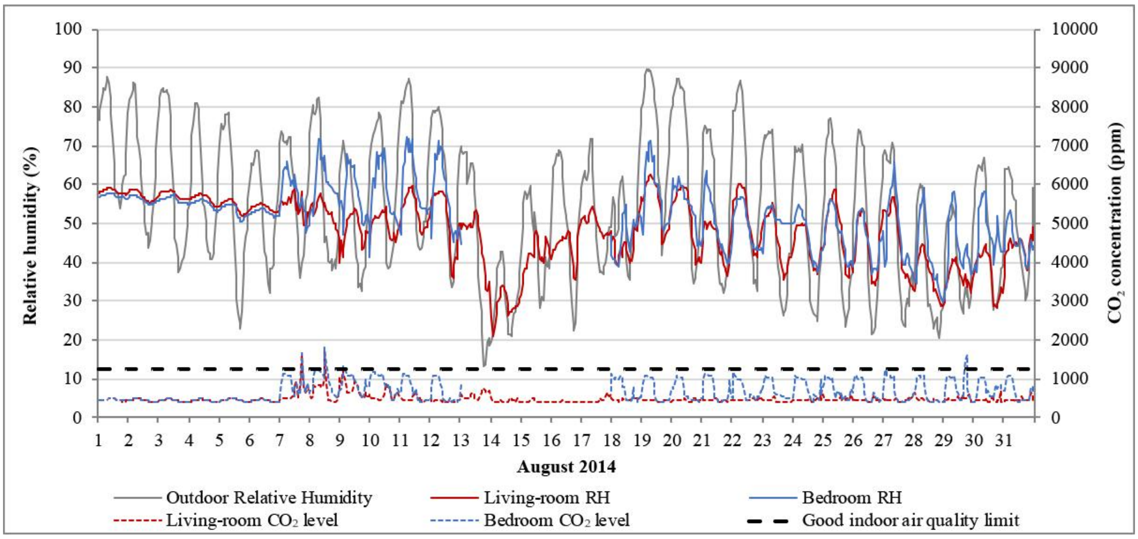


Figure 5. Case 1 - Seville: hourly relative humidity and CO_2 concentration during August.

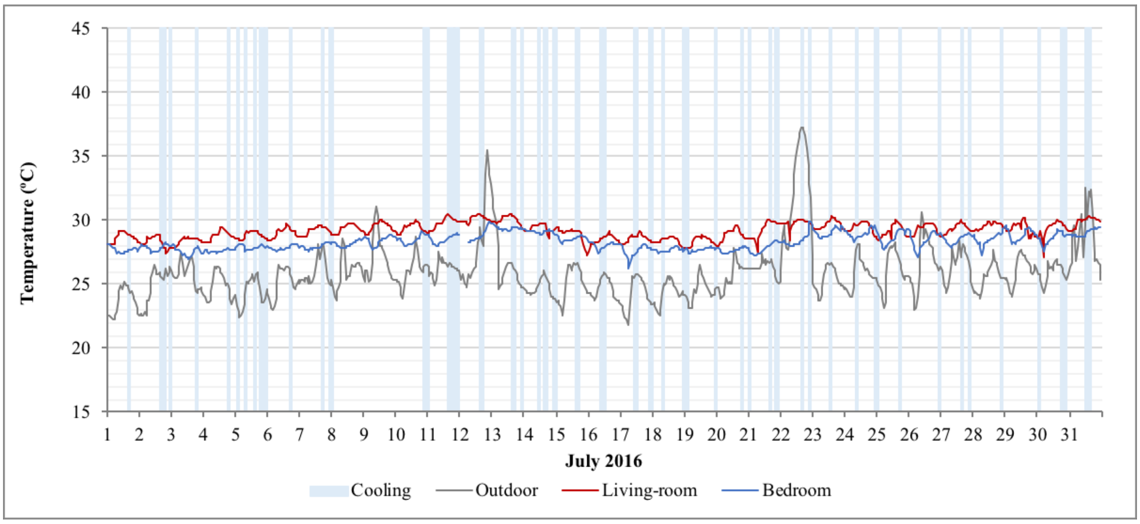


Figure 6. Case 2 - Malaga: hourly temperature during July.

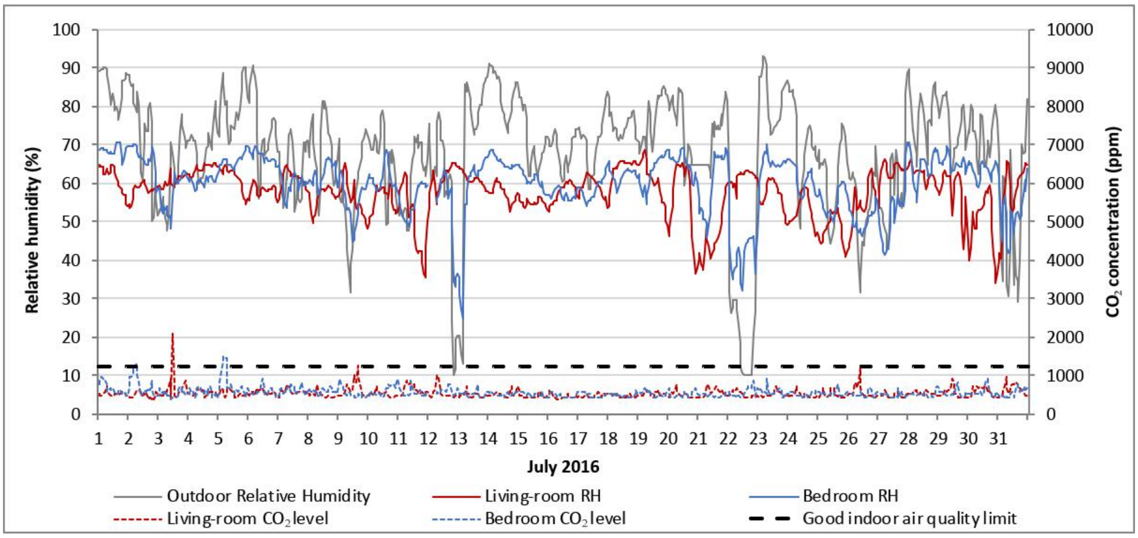


Figure 7. Case 2 - Malaga: hourly relative humidity and CO_2 concentration during July.

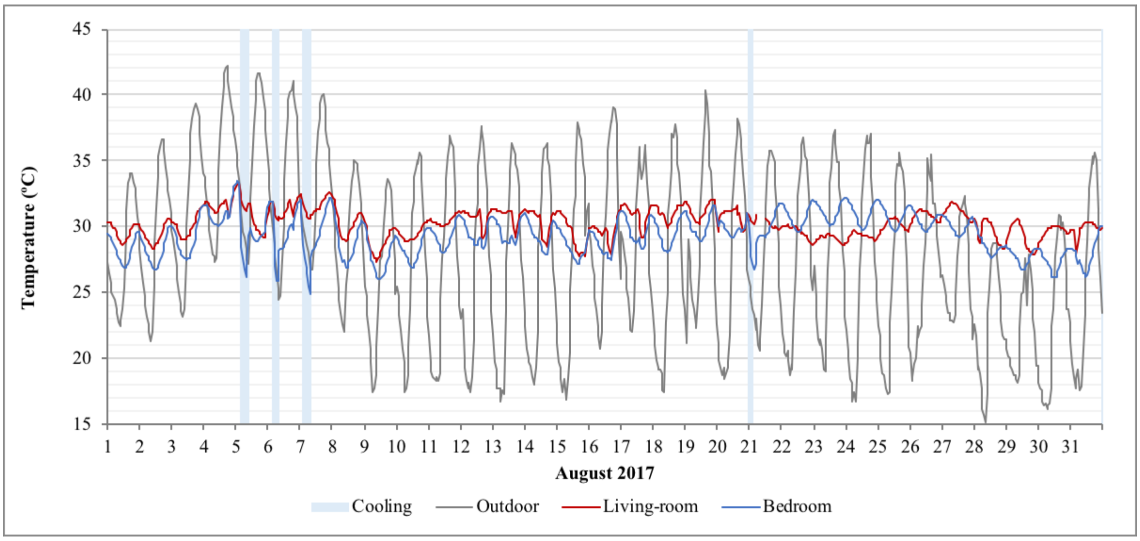


Figure 8. Case 3 - Huelva: hourly temperature during August.

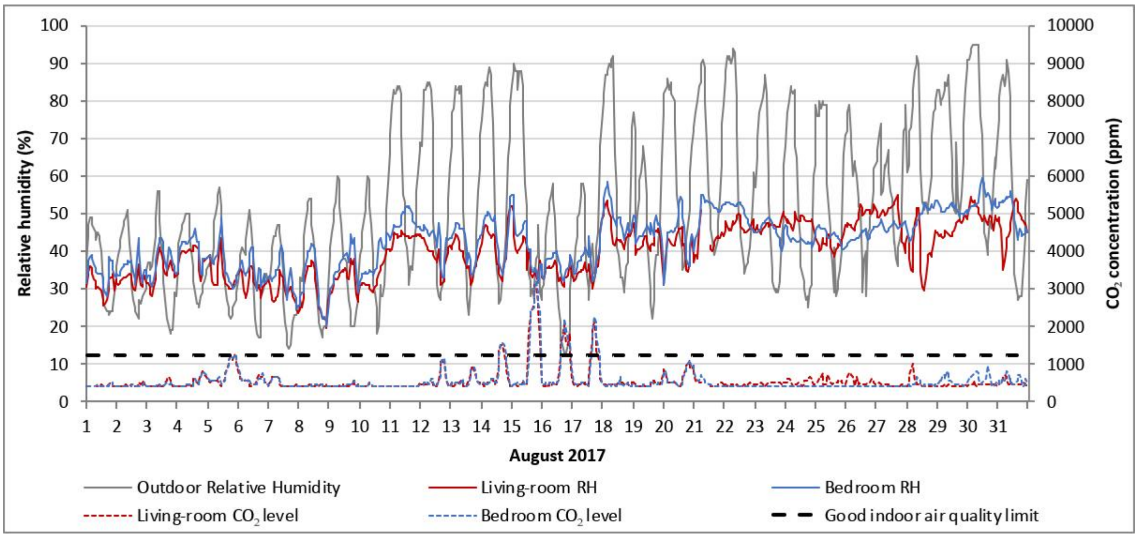


Figure 9. Case 3 - Huelva: hourly relative humidity and CO_2 concentration during August.

In case 2, during July 2016, outdoor temperatures in Malaga ranged between 22 °C and 30 °C, except on several specific days in which 37 °C were reached (figure 6). In this case, the average indoor temperatures were 28.8 ºC in the living room and 28.1 ºC in the bedroom. As local cooling systems were used very intermittently, their effect on indoor temperature was negligible, resulting in reductions of just 1 ºC - 2 ºC. In addition, the use of natural ventilation was inadequate and therefore insufficient to dissipate the heat accumulated in the residential unit so that indoor temperatures remained almost constantly above the outdoor ones. In this case, despite being in a more moderate climate than case 1, the northwest (living room) and southwest orientation (bedroom) and the absence of solar protection also contribute to poor environmental performance. In this case, thanks to the moderate outdoor temperatures, an adequate ventilation rate could lower the indoor temperatures to close to the outdoor ones, with a decrease of between 2 ºC and 3 ºC in the average indoor temperature.

The outdoor relative humidity in Malaga varied between 30 % and 90 %, compared to the indoor values between 40 % and 70 % (figure 7). Indoor CO_2 concentration level showed two similar forms of use of the rooms monitored, mainly because all these rooms are kept continually connected with the doors open. Both rooms were usually below 1000 ppm. Although the use of natural ventilation was inadequate, keeping the doors open helped to prevent high concentrations of CO_2.

In case 3, during August 2017, outdoor temperatures in Huelva were in the wide range of 15 ºC to 40 ºC (figure 8). Under these conditions, the average indoor temperatures were 30.3 ºC in the living room and 29.2 ºC in the bedroom. Despite the high indoor temperatures, the use of local cooling systems is limited to four specific points in time with the temperature set around 26 ºC. In this case, an insufficient use was also made of natural night-time ventilation for the dissipation of the heat accumulated during sun hours. This southwest-facing housing unit is very exposed to the sun (as it is also located on the top floor of the building) and makes unsuitable use of solar protection, clearly causing overheating. If a more intensive use of the natural night-time ventilation had been made in the bedroom, as in case 1 (with similar outdoor temperatures during the monitoring period), indoor temperatures could have been around 25 °C at night, lowering the average indoor temperature of the bedroom by around 1 °C.

Analysis of other environmental variables (figure 9) showed that the range of outdoor relative humidity went from 20 % to 90 % while the indoor range varied between 20 % and 60 %. The indoor CO_2 concentration level showed that the rooms monitored were used in two similar ways as connecting doors were also kept open in this case. Both rooms were usually below 1000 ppm, except for a few days when the number of occupants increased and 3000 ppm were reached. As in case 2, keeping the doors of the rooms open prevents a high concentration of CO_2.

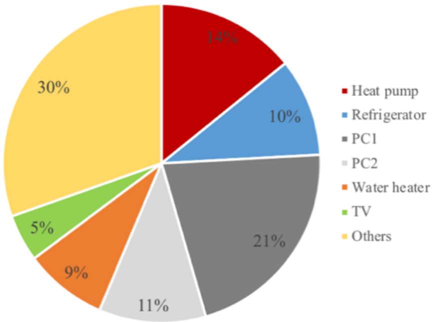
4.2. Energy consumption

The global and detailed electricity consumption was monitored during a whole year and analysed for all three case studies during the summer period. The distribution of detailed electrical consumption (cooling, hot water production, main appliances, etc.) during the hottest month was represented in a graph, as was the information of global and cooling consumption of the three months of summer (June, July and August) and of the whole summer (figure 10). In order to evaluate the cooling consumption, the total consumption of all local cooling systems (kWh) was divided by the cooled area, which in this case was the total area of the housing unit except kitchen and bathrooms (room doors were always kept open). Low levels of cooling consumption were detected for the three case studies.

In case 1, the user profile included one occupant working from home, causing a different consumption distribution than usual, with 32 % of total consumption associated to computer use (figure 10a). The second highest consumption was from the local cooling system, which accounted for 14 % of total consumption, reaching almost 5 kWh per cooled square metre during the period studied. As the period studied was in summer, the hot water production system was not as important as other types of consumption. In case 2, a balanced distribution of the consumptions was detected, with cooling accounting for around 19 % of total consumption and almost 4 kWh per cooled square metre during the summer period (figure 10b).

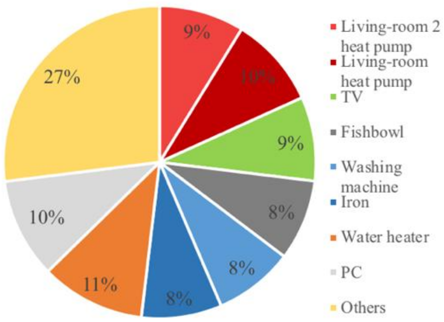
Finally, case 3 had very low general consumption (it had a gas-fuelled hot water production system), which made issues such as lighting and cooking (not discretized, counted in 'others') highly relevant, as in the case of the refrigerator consumption, which accounted for 21 % of the total (figure 10c). Despite having the highest indoor temperatures, this case, showed the lowest cooling consumption, only 8 % and 1.5 kWh per cooled square metre during the summer period.

Case 1 had the highest general and cooling consumption, despite being occupied by only two people compared to the four occupants of case 2. It should be noted that the economic level of users in case 1 was slightly higher than in the other cases. The general consumption for case 2 was almost double that of case 3, corresponding to the ratio of occupants (four versus two) in similar economic conditions.



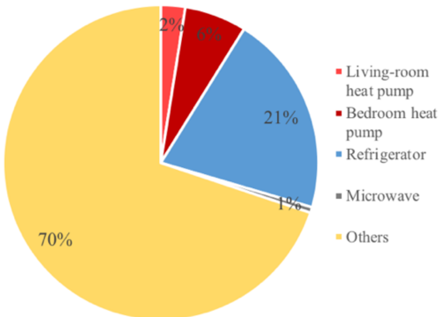
Period	Total consumption (kWh)	Total consumption (kWh/m² cooled)	Cooling consumption (kWh)	Cooling consumption (kWh/m² cooled)
June 2015	407.27	9.26	80.52	1.83
July 2014	509.71	11.58	58.96	1.34
August 2014	548.54	12.47	77.88	1.77
Summer	1465.51	33.31	217.36	4.94

(a)



Period	Total consumption (kWh)	Total consumption (kWh/m² cooled)	Cooling consumption (kWh)	Cooling consumption (kWh/m² cooled)
June 2016	292.59	5.13	64.41	1.13
July 2016	322.80	5.66	65.55	1.15
August 2015	507.57	8.90	90.63	1.59
Summer	1122.96	19.69	220.59	3.87

(b)



Period	Total consumption (kWh)	Total consumption (kWh/m² cooled)	Cooling consumption (kWh)	Cooling consumption (kWh/m² cooled)
June 2017	189.61	5.27	21.82	0.61
July 2017	216.96	6.03	11.48	0.32
August 2017	216.02	6.00	19.15	0.53
Summer	622.58	17.30	52.45	1.46

(c)

Figure 10. Evaluation of electric consumption during the summer period: (a) case 1 - Seville, (b) case 2 - Malaga, (c) case 3 - Huelva.

4.3. Comfort analysis

The thermal comfort level was evaluated in all three case studies, analysing the percentage of occupied hours of discomfort and the average deviation of the indoor temperatures with respect to the comfort band. It was also contrasted with the percentage of hours of use of the local cooling systems in each housing unit. As explained in Section 2.1, three adaptive comfort standards were used to calculate *Tco*: Standard 55 (ASHRAE, 2010), ISO-EN-15251 (CEN, 2007) and the model proposed by Barbadilla-Martín et al. (2017) for 'Mixed Mode' (MM) buildings. The acceptability ranges of 90 % and 80 % were selected for Standard 55 and MM, and categories II and III for ISO-EN-15251.

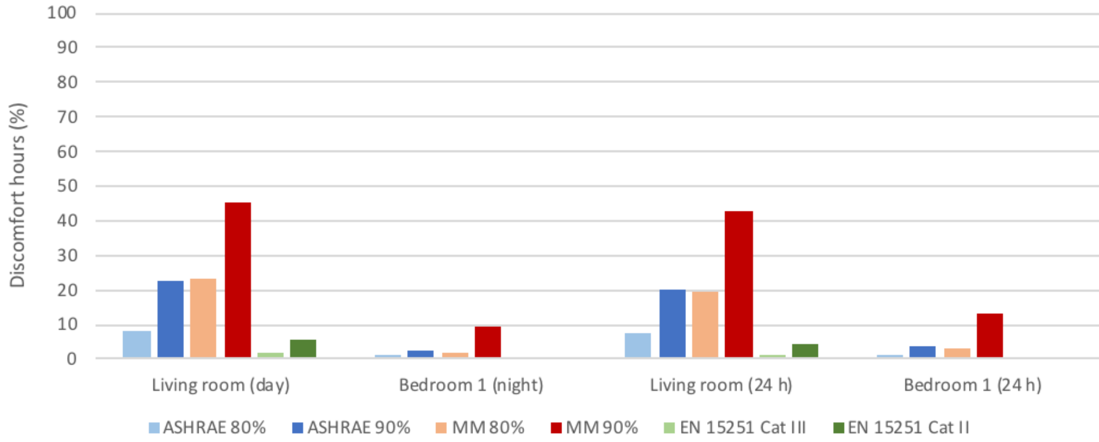
The standardized user profile established by Spanish regulations (Spanish Government, 2013b) does not distinguish between daily and nightly occupation of the rooms, and a positive occupation load is maintained throughout the day in all rooms. In order to analyse how the occupation profile affected the comfort analysis, two different profiles were evaluated: both rooms occupied during 24 hours; and the living room occupied during the day and the bedroom during the night. The day/night schedule was set for the user profile defined in Section 3.1. Figure 11 summarizes the main results obtained, while figures 12-17 show a detailed analysis of thermal comfort during the summer period for the case studies.

In case 1 (figure 11a), the percentage of discomfort hours in the living room during the occupied hours (according to the user profile) went from 45 %, applying the most severe standard (MM with 90 % of acceptability), to 2 % for the least severe (ISO-EN-15251 Category III). When these results were compared with the percentage of discomfort hours in the living room throughout the whole day, the difference was not significant, reaching a maximum difference of -3 % with MM standard with 80 % acceptability. The percentage of hours of discomfort in the bedroom at night was significantly lower than in the living room in daytime, since its occupants make an intensive use of natural night-time ventilation. During the occupied hours (according to the user profile), it went from 9 % with the most severe standard (MM with 90% of acceptability) applied, to 0 % applying the least severe (ISO-EN-15251 in any of its categories). If compared with the percentage of discomfort hours in the bedroom throughout the whole day, the percentage increased slightly in this case, with a maximum difference of +4 % with MM standard with 90 % acceptability.

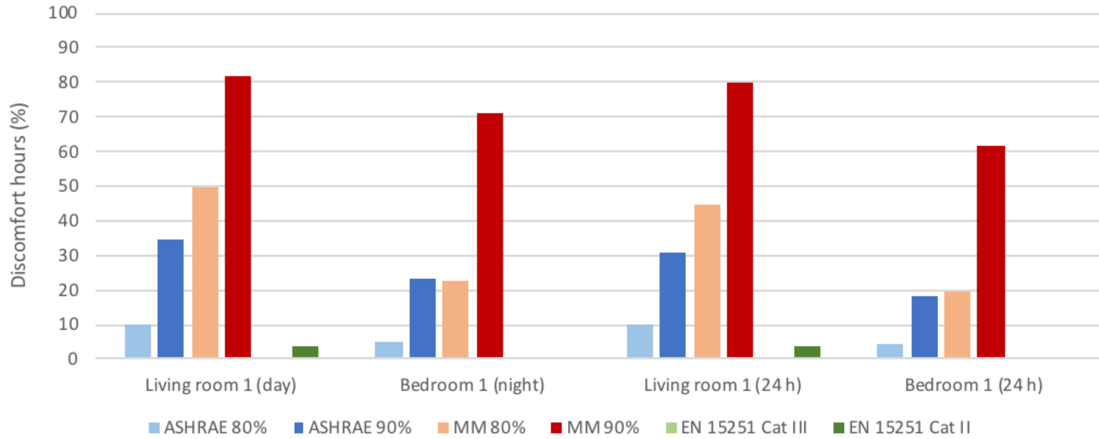
In case 2 (figure 11b), the percentage of discomfort hours in the living room during the occupied hours (according to the user profile) went from 82 %, when the most severe standard (MM with 90% acceptability) was applied, to 0 % with the least severe one (ISO-EN-15251 Category III). Comparing these results with the percentage of discomfort hours in the living room throughout the whole day, the maximum difference was -5 % with MM standard with 80 % of acceptability. The percentage of discomfort hours in the bedroom during the night was similar to that of the living room in the daytime, despite having outdoor night-time temperatures of around 23 °C. During the occupied hours (according to user profile), it went from 71 %, when the most severe standard (MM with 90 % of acceptability) was applied, to 0 % with the least severe one (ISO-EN-15251 in any of its categories). Comparing the percentage of discomfort hours in the bedroom throughout the whole day, the maximum difference reached -9 % with MM standard with 90 % acceptability.

Finally, in case 3 (figure 11c), the percentage of discomfort hours in the living room during the occupied hours (according to user profile) went from 83 %, when the most severe standard (MM with 90% of acceptability) was applied, to 7 % with the least severe on (ISO-EN-15251 Category III). Comparing these results with the percentage of discomfort hours in the living room throughout the whole day, the difference was not significant, with a maximum difference of +3 % with MM standard with 80 % acceptability. The percentage of discomfort hours in the bedroom during the night was similar to that of the living room in the daytime, despite night-time outdoor temperatures almost always below 21 ºC. During the occupied hours (according to user profile), it went from 76 %, when the most severe standard (MM with 90% of acceptability) was applied, to 3 % with the least severe one (ISO-EN-15251 in any of its categories). When comparing with the percentage of discomfort hours in the bedroom throughout the whole day, the maximum difference reached -11 % with MM standard with 80% acceptability.

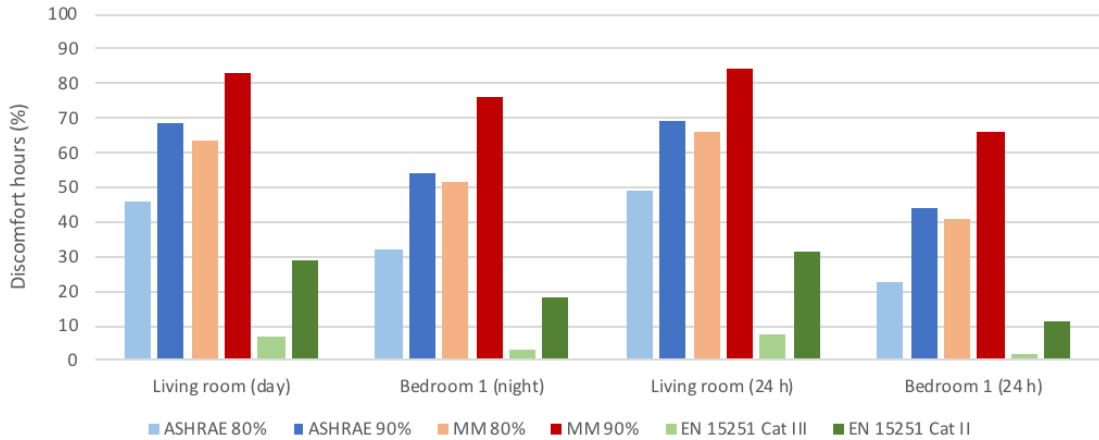
Logically, as in case 1, hours of discomfort in the living room were concentrated in the daytime so that evaluating it at only those hours increased the percentage of discomfort hours. The bedroom also concentrated its discomfort hours during the daytime, when outdoor and indoor temperatures are higher, so that evaluating it only during night-time would lower the percentage of discomfort hours. However, in cases 2 and 3, the opposite occurred since the passive resource of natural night-time ventilation was not used and there was no heat dissipation. The indoor temperature was also high at night but *Tco* was lower than during the day (because night-time outdoor temperature was also lower), so that the bedroom increased its discomfort hours during the night.



(a)

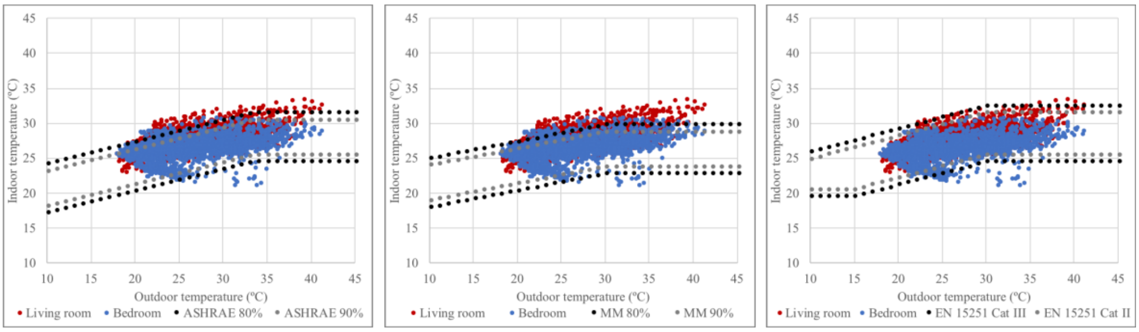


(b)



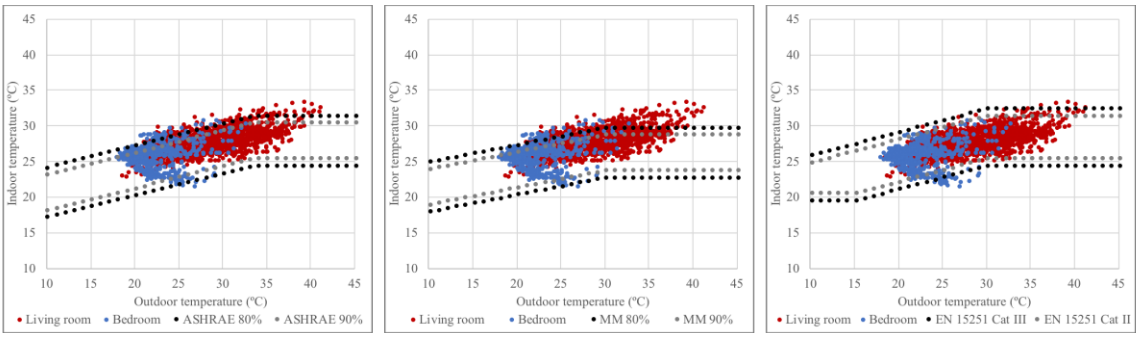
(c)

Figure 11. Evaluation of thermal comfort and use of cooling systems during the summer period. Comparison between different standards (Standard 55, MM and ISO-EN-15251) and user patterns (24 hours or day/night): (a) case 1 - Seville, (b) case 2 - Malaga, (c) case 3 - Huelva.



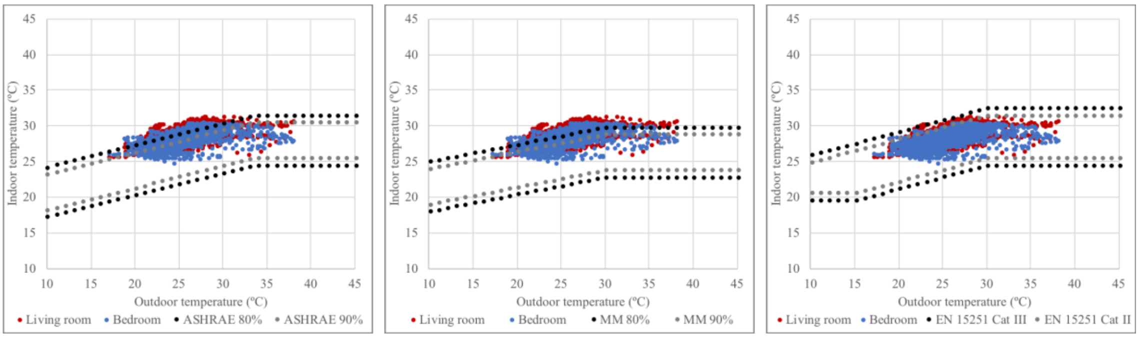
Standard	ASHRAE 80%	ASHRAE 90%	MM 80%	MM 90%	EN 15251 Cat III	EN 15251 Cat II
% hours of discomfort						
Living room	7.52	20.28	19.74	42.55	1.33	4.31
Bedroom 1	1.11	3.85	3.11	13.47	0.00	0.00
Average deviation Indoor temperature - Comfort band (ºC)						
Living room	0.60	1.22	1.56	2.61	0.11	0.29
Bedroom 1	0.08	0.22	0.23	0.76	0.00	0.00
% hours of use of local cooling systems						
Bedroom 2			23.29			

Figure 12. Case 1 - Seville: evaluation of thermal comfort and use of cooling systems during the summer period. Occupation 24 hours.



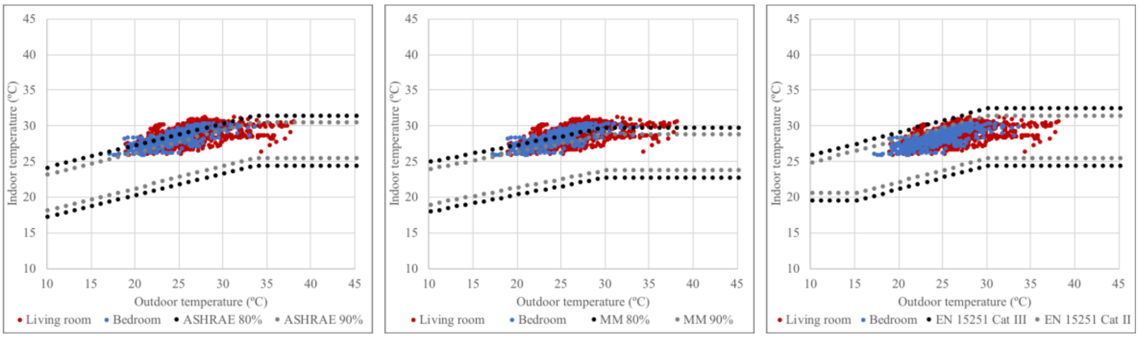
Standard	ASHRAE 80%	ASHRAE 90%	MM 80%	MM 90%	EN 15251 Cat III	EN 15251 Cat II
% hours of discomfort						
Living room	8.40	22.82	23.07	45.27	1.99	5.54
Bedroom 1	1.11	2.32	2.00	9.36	0.00	0.00
Average deviation Indoor temperature - Comfort band (ºC)						
Living room	0.68	1.38	1.83	2.81	0.17	0.38
Bedroom 1	0.08	0.14	0.15	0.52	0.00	0.00
% hours of use of local cooling systems						
Bedroom 2			34.93			

Figure 13. Case 1 - Seville: evaluation of thermal comfort and use of cooling systems during the summer period. Occupation according to user profile.



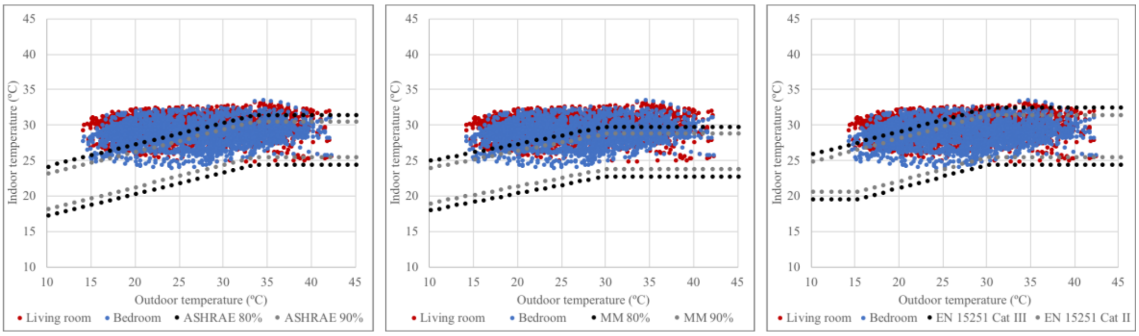
Standard	ASHRAE 80%	ASHRAE 90%	MM 80%	MM 90%	EN 15251 Cat III	EN 15251 Cat II
% hours of discomfort						
Living room	9.89	30.89	44.91	79.89	0.05	3.63
Bedroom 1	4.12	18.28	19.38	61.36	0.00	0.00
Average deviation Indoor temperature - Comfort band (ºC)						
Living room	0.74	1.79	3.44	4.92	0.00	0.23
Bedroom 1	0.30	1.03	1.44	3.52	0.00	0.00
% hours of use of local cooling systems						
Living room			12.94			
Living room 2			12.71			

Figure 14. Case 2 - Malaga: evaluation of thermal comfort and use of cooling systems during the summer period. Occupation 24 hours.



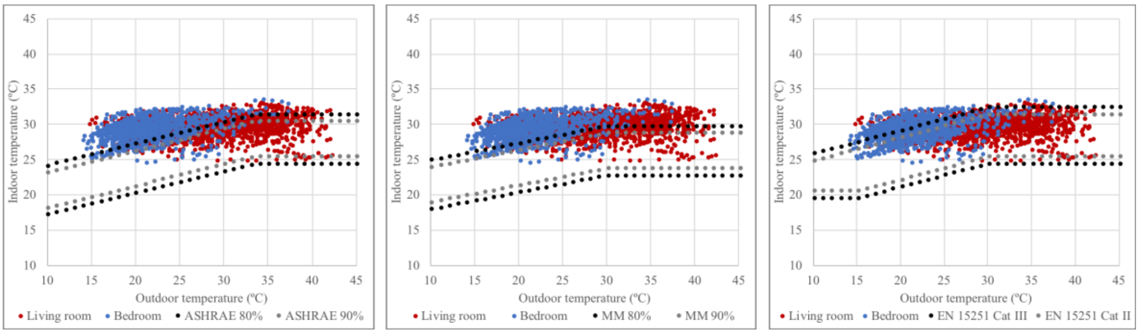
Standard	ASHRAE 80%	ASHRAE 90%	MM 80%	MM 90%	EN 15251 Cat III	EN 15251 Cat II
% hours of discomfort						
Living room	9.79	34.42	49.67	82.03	0.07	3.88
Bedroom 1	4.97	22.94	22.47	70.83	0.00	0.00
Average deviation Indoor temperature - Comfort band (ºC)						
Living room	0.73	1.97	3.81	5.10	0.01	0.25
Bedroom 1	0.36	1.29	1.67	4.07	0.00	0.00
% hours of use of local cooling systems						
Living room			19.41			
Living room 2			19.07			

Figure 15. Case 2 - Malaga: evaluation of thermal comfort and use of cooling systems during the summer period. Occupation according to user profile.



Standard	ASHRAE 80%	ASHRAE 90%	MM 80%	MM 90%	EN 15251 Cat III	EN 15251 Cat II
% hours of discomfort						
Living room	48.75	69.46	66.12	84.43	7.71	31.46
Bedroom 1	22.29	43.97	40.97	65.76	2.14	11.46
Average deviation Indoor temperature - Comfort band (ºC)						
Living room	3.85	4.51	5.57	5.92	0.65	2.10
Bedroom 1	1.75	2.71	3.29	4.24	0.18	0.76
% hours of use of local cooling systems						
Living room				0.04		
Bedroom 1				2.36		

Figure 16. Case 3 - Huelva: evaluation of thermal comfort and use of cooling systems during the summer period. Occupation 24 hours.



Standard	ASHRAE 80%	ASHRAE 90%	MM 80%	MM 90%	EN 15251 Cat III	EN 15251 Cat II
% hours of discomfort						
Living room	46.03	68.31	63.27	82.80	6.63	29.18
Bedroom 1	32.08	53.93	51.51	75.94	2.83	18.23
Average deviation Indoor temperature - Comfort band (ºC)						
Living room	3.62	4.39	5.31	5.76	0.56	1.95
Bedroom 1	2.54	3.41	4.21	5.04	0.24	1.20
% hours of use of local cooling systems						
Living room				0.15		
Bedroom 1				5.67		

Figure 17. Case 3 - Huelva: evaluation of thermal comfort and use of cooling systems during the summer period. Occupation according to user profile.

Although the most severe outdoor conditions were observed in cases 1 and 3, case 1 showed the lowest percentage of discomfort hours, due to an intensive use of natural night-time ventilation and the highest percentage of hours of use of the local cooling system. This case also presented the lowest average deviation between the indoor temperature during discomfort hours and the comfort temperature band, remaining below +3 ° C in the living room and +1 ° C in the bedroom when the more severe standard (MM with 90% acceptability) was applied. In case 2, the average deviation exceeded +5 °C in the living room and +4 °C in the bedroom, and in case 3 almost reached +6 °C in the living room and +5 °C in the bedroom (standard MM with 90% acceptability). Since the outdoor thermal conditions are similar to those of case 1, case 3 could have achieved a decrease of up to 4 ºC in the deviation between the indoor temperature in the bedroom during the night discomfort hours and the comfort temperature band with a ventilation rate similar to that of case 1.

In the periods of highest use of cooling systems, the percentage of use was around 42 % in Seville (daily use) while it remained under 7 % in Huelva (nightly use). Case 3 made least use of local cooling systems, despite having the highest percentage of discomfort hours. With similar outdoor conditions, the difference between case 3 indoor conditions and those in case 1 was fundamentally due to the excess of solar radiation during the day through the roof and the lack of night-time natural ventilation. Although the climate in case 2 was less severe than in cases 1 and 3, the percentage of discomfort hours was considerably greater than in case 1 and similar to case 3. In this case, the percentage of hours of use of the local cooling system was between that of cases 1 and 3, around 24 % during the period of greatest use (daytime).

5. Conclusions and Policy Implications

This study has analysed the environmental and energy performance of a social housing sample in southern Spain, with results showing that the case studies lack adequate thermal comfort conditions. However, these conditions are not solely attributable to the energy and constructive obsolescence of this housing stock, as the influence of user behaviour is very relevant during the summer period. Retrofitting for these case studies cannot be tackled without first analysing the real user profiles. This analysis reflects a lack of thermal comfort but it is a small sample with different user patterns, and therefore these results cannot be extrapolated without first confirming that these are in line with findings from studies with larger samples and different user profiles.

In a Mediterranean climate with high outdoor temperatures during the summer period (reaching over 40 ºC) and a weak thermal envelope, the indoor temperatures of the housing unit analysed largely depend on a suitable use of night-time natural ventilation, which reduces the phenomenon of overheating, and on solar protection. User behaviour according to natural ventilation could reduce mean indoor temperature by up to 3 ºC.

The two most widely used adaptive thermal comfort standards, Standard 55 (ASHRAE, 2010) and ISO-EN-15251 (CEN, 2007), are not well adapted to the indoor overheating conditions, with average indoor temperatures above 30 °C. Adaptive comfort models that are closer to the real perception of users, such as that proposed by Barbadilla-Martín et al. (2017) for 'Mixed Mode' buildings, are considered more suitable in these case studies. Applying this standard with 90 % acceptability and evaluating only the occupied hours according to real user profiles, the percentage of hours outside the comfort temperature band reach over 80 % in the living room and 70 % in the bedroom. User behaviour according to natural ventilation could reduce the deviation between the indoor temperature in discomfort hours and the comfort temperature band by up to 4 ºC.

In general, when evaluating according to the daily or nightly occupation of each room or with a 24-hour occupation profile the difference between the percentages of discomfort hours is not too significant, as it is no more than 10 %. However, it is considered that the values closest to the real perception of the user are those evaluated by individual real occupation profile, since that is when users are really affected by discomfort. Relevant differences can be found between the standardized user profile defined by national regulations (Spanish Government, 2013b), which sets a use-of-cooling pattern ensuring the householders to be 67 % of the hours in comfort conditions, and the results found in the case studies, with just 20-30 % of the hours in comfort conditions when the natural ventilation rate is insufficient to dissipate the heat accumulation.

Despite the uncomfortable indoor temperatures detected, the percentage of hours of use of local cooling systems in the case studies is usually less than 10 %, due to the specific socio-economic characteristics of users. This translates into low general energy consumption with values below 10 kWh/m^2 for a month. Future research should aim to demonstrate whether users are actually perceiving these comfort conditions despite the deviation from standards or whether they are concerned about high electricity bills due to their low income.

The results suggest that, when estimating energy consumption in social housing in southern Spain, the set point temperature stipulated in national regulations (25 ºC) (Spanish Government, 2013b), could justifiably be called into question. The resulting *Tco* indicates the advisability of increasing this set point temperature by a minimum of 1.5 ºC. In addition, as indicated by the margins of acceptability, there is a band around this *Tco* in which the user is in comfort and will not make use of air conditioning systems.

Although the Mediterranean climate is globally known for its severe climatic conditions during the summer, previous studies showed that social housing in southern Spain is in discomfort for 100 % of the hours in the winter period (Escandón et al., 2017). If we add these results to those obtained in this analysis, it can be suggested that these case studies are completely at risk of fuel poverty unless an energy rehabilitation campaign is carried out. This situation would be further aggravated by global warming (Suárez et al., 2018) to which this social group of the population is barely contributing, given the low consumption. They will however suffer the most if proper political measures are not taken. Although European policies established that energy poverty was to be eradicated by 2016 (Boardman, 2004), this has been hindered by national policies which fail to focus their economic efforts on improving building performance so that energy poverty can be disassociated from economic conditions.

Therefore, future energy retrofitting policies for the residential stock should focus on passive measures to improve indoor environmental conditions, avoiding dependence on the use of HVAC systems which are unaffordable to these users due to their socio-economic status. Retrofitting proposals must require a prior step, characterizing the real user profile for the estimation of energy savings and return periods, and avoiding the use of standardized patterns for this aim. To this end, future research steps should include the analysis of an extended case study sample to define a sufficiently high number of user patterns to be considered representative of all individual climate zone and socio-economic conditions (Guerra-Santín and Silvester, 2017). Furthermore, this real variety of user patterns should be recognized by national regulations so that the objectives of the retrofitting policies and the funding priorities may be changed.

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Declarations of interest: none.

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