On the assessment of the energy performance and environmental behaviour of social housing stock for the adjustment between simulated and measured data: the case of mild winters in the Mediterranean climate of southern Europe.

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Abstract

Current European energy policies stress the potential of housing stock retrofitting to reduce global energy consumption. In order to implement efficient measures, it is essential to know its real in-use energy behaviour. In southern Europe, social housing represents an important percentage of the residential stock built before the implementation of the first energy regulations. However, there are few studies specifically analysing their energy behaviour. Standardized use and occupancy patterns are not usually suited to Mediterranean social housing, and this mostly results in estimated consumption exceeding real consumption.

This research aims to quantify the thermal comfort and energy consumption of the social housing stock during the characteristically mild winters in a Mediterranean climate, based on the monitoring of representative case studies from southern Spain. The results show that the dwellings analysed are far from conforming to adaptive comfort standard EN-15251 and yet, their limited local heating systems are rarely turned on, reducing the expected energy consumption. In addition, real use and occupancy patterns are defined for the case studies, allowing the development of energy simulation models that are better suited to the real behaviour of this social housing stock.

Keywords: social housing stock, monitoring, thermal comfort, energy consumption, energy models calibration.

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1. Introduction

Over the last few decades, European building regulations have been establishing a common framework for the encouragement of energy efficiency [1, 2], promoting the retrofitting of housing stock. In the case of southern Europe, residential stock built prior to the first regulations which globally limit the energy demand of buildings (1976-1979) represents between 63 and 76% of the total housing stock [3, 4, 5]. Most of these residential buildings do not incorporate any specific measures for thermal insulation in their envelopes, and are therefore obsolete from an energetic point of view.

Social housing represents an important percentage of the residential stock in southern Europe, with specific socioeconomic characteristics that entail particular needs and a use pattern different from the standardized one. Field research on social housing in southern Europe [6, 7, 8, 9] shows that these buildings have much lower energy consumption than that estimated by the national energy assessment procedures derived from Directive 2002/91/EEC and its updates [10], based on general premises of intensity and habits of use of buildings and energy, not applicable in the case of social housing. An example of this is that the estimated average heating consumption of Spanish multi-family dwellings (with an average area of 88.7 m^2) in the Mediterranean climate is 3673 kWh per year per dwelling [11], while for low income households (declared annual household income below 15,000 €) in southern Europe it is around 1386 kWh per year [6].

There is extensive research analysing the divergence between real consumption and consumption estimated through simulation, either by software recognized by the scientific community or the official software of the different countries [12,13,14,15]. This 'performance gap' has generally been attributed to user behaviour and, to a lesser extent, to a poor identification of the constructive characteristics of buildings [16,17]. In order to reduce the error rate due to the poor identification of the constructive characteristics, it would suffice to carry out the relevant tests in the building, such as air permeability and infra-red thermography tests or U-measurements [12,18]. However, the error associated to user pattern definition is much more difficult to identify and reduce.

Many of the studies about occupant behaviour focus on retrofitted dwellings (low-energy) in central and northern Europe (climates with severe winters), where real consumption is frequently much higher than estimated consumption due to the Rebound effect [19, 20]. However, in many other cases, the opposite occurs: real consumption is much lower than that estimated, because users spend far less time in the dwellings than the time established by the standardized use patterns of the different countries, known as the Prebound effect [13, 20].

In the case of social housing, the divergence between real and estimated consumption is even greater due to an additional variable: when users occupy their dwellings, do they do so in conditions of thermal comfort? The standardized use patterns assume that users live in thermal comfort conditions, but in social housing in southern Europe, although it belongs to a mild winter climate zone, it is usual to forgo comfort and live in fuel poverty conditions [6, 7]. In addition, in the specific case of southern Spain, only 5% of multi-family dwellings built before 1979 have a centralized heating system, and 13% have a local heating system [3]. These data demonstrate that this housing stock does not have thermal conditioning means to ensure the maintenance of thermal comfort conditions.

Due to the fuel poverty found in this social housing stock, investments in energy retrofitting (usually focused on improving the insulation of its envelope) [21, 22, 23] are often ineffective from an energy saving point of view with excessive payback periods. Although it is very difficult to reduce energy consumption when it is so low, this does not mean that retrofitting is not beneficial, but simply means that instead the final aim ought to be the improvement of thermal comfort conditions in the dwellings, where the profit margin is very high [24].

The main objective of this research is to quantify the real conditions of thermal comfort in the specific context of social housing in southern Europe (mild winter climate), based on the adaptive model established by standard EN-15251 [25] and energy consumption. To this end, a specific methodology based on in-use monitoring has been developed and applied to three case studies representative of the typology, constructive system and climate of southern Spain. Through this monitoring, real use and occupancy patterns are defined in order to develop energy simulation models adjusted to the real behaviour of this housing stock, significantly reducing the ‘performance gap’ between real and estimated consumption. The conclusions obtained are expected to be the potential starting point for a future change in the standardized use and occupation patterns, and the energy retrofitting policies of social housing stock in the Mediterranean climate.

2. Methodology

In this work the methodology used has been developed based on previous research in order to further examine the characterization of the current energy conditions of social housing stock in southern Europe [26]. To do so, a detailed energy and environmental assessment of the dwellings was carried out through monitoring and subsequent energy simulation.

2.1. Monitoring

Different monitoring methodologies have been validated by the scientific community. Two methodologies are distinguished focusing on the measurement of environmental parameters [27]: spot measurements taken only once or long-term measurements taken at specific intervals, from minutes to hours. The type of measurement depends on the type of data required for the investigation.

In general, spot measurements are used when the aim is the evaluation of thermal comfort through surveys and it is necessary to link these with the internal and external environmental conditions of that point in time, or when it is not possible to carry out long-term measurements due to economic or intrusion constraints. Long-term measurements are fundamental when the purpose of the monitoring is to determine the behaviour of the building over a given period of time such as a season or a full year. In addition, these types of measures are necessary to evaluate thermal comfort following an adaptive model, one of the main aims of this research. Thus, this monitoring methodology includes long-term measurements (temperature, relative humidity, CO_2 level, and energy consumption) which are complemented with spot tests (air permeability and infra-red thermography).

2.1.1. Air permeability test and Infra-red thermography

Depressurisation tests were carried out in each case study in order to verify the airtightness of the envelope of the dwellings, according to norm UNE EN-13829 [28]. The Blower Door equipment used in this test was installed in the entrance door of the dwellings and controlled from inside the residential unit.

This information was complemented with the capture of images of dwelling envelopes using a thermographic camera, following norm UNE EN-13187 [29]. The aim of this test is to search for thermal behaviour patterns of the envelopes in the buildings under study.

2.1.2. In situ ambient measurements

The in situ data collection of environmental variables is essential for the evaluation of the environmental behaviour of the case studies. For this reason, this research has monitored air temperature, relative humidity and CO_2 levels inside the dwellings. Two WOHLER CDL 210 indoor data-loggers were placed in each dwelling (one in the living room and the other in the main bedroom) to measure the variables every 30 minutes for a full year.

Data provided by three meteorological stations belonging to the Spanish State Meteorological Agency [30] were used to analyse external environmental variables. The variables of temperature, relative humidity, solar radiation, wind speed and direction, and precipitation were measured every 30 minutes over a year.

In addition to the analysis of environmental variables in winter this research also studies the level of thermal comfort in the dwellings according to the adaptive model established by EN-15251 [25]. This model of adaptive thermal comfort analysis focuses on the interaction between people and buildings (through indoor temperature) and on their expectations (based on outdoor temperature) [31]. In order to obtain the outdoor reference temperature (T_{eR}), the daily weighted average was calculated according to equation 1. For the calculation of the optimum operating temperature (T_{op}), equation 2, established in EN-15251, was used. Case studies belong to category III, associated with existing buildings, which means an acceptability band of +/- 4 ºC in relation to the calculated T_{op}.

(1) $T_{eR} = (1 - \alpha) * T_{ed-1} + \alpha * T_{eR-1}$

where:

T_{eR}: running mean temperature for today

T_{ed-1}: daily mean external temperature for previous day;

T_{eR-1}: running mean temperature for the previous day;

α: is a constant between 0 and 1. Recommended to use 0.8.

$$(2)\ T_{op} = 0.33 * T_{eR} + 18.8$$

2.1.3. Energy consumption measurements

Another key aspect for the evaluation of the behaviour of the case studies is the in situ data collection of energy variables. As is usually the case with social housing in southern Spain, none of these case studies have gas-fuelled heating systems, and therefore the research focuses on electricity consumption. The detailed energy consumption (sub-metering) was monitored by a general consumption meter in the electrical panel and several individual meters in the sockets of some appliances (mainly local heating and cooling systems). Consumption was measured in kWh every 15 minutes over a year. This helps to establish relationships between comfort level, indoor and outdoor conditions, and user behaviour. In addition, in order to complete and contrast the monitored consumption, historical data of general electrical consumption of the case studies were compiled using past electricity bills.

2.1.4. User patterns

In order to avoid the usual divergence between real and estimated consumption (Prebound effect), monitoring data was used to define user patterns. A mixed methodology was used in this research to capture the technical and social aspects from user practices qualitatively and quantitatively [32]. In order to explain and validate these aspects the qualitative data obtained from the user surveys and the user patterns obtained from the quantitative data measured in the dwellings (temperature, CO_2 concentration and electric consumption) were cross-referenced.

In order to analyse the quantitative data, the hourly average values for the entire winter period were used [33]: temperatures in degrees centigrade (ºC), CO_2 concentration in parts per million (ppm), heating local systems operation on a scale of 0 to 1 (0 means off and 1 on) and general electrical consumption in kilowatt-hour (kWh). This research focused on the analysis of weekdays, which is when patterns are usually repeated the most, whereas at weekends behaviour is usually more irregular.

2.2. Energy simulation

For the simulation of the environmental and energy behaviour of the case studies, the methodology requires two initial tasks: construction of the energy model to reproduce the rooms studied and an energy model adjustment process.

2.2.1. Energy model construction

The energy model was developed with software DesignBuilder (v.4.7.0.027), which uses EnergyPlus [34], a simulation program recognized by the US DOE [35].

Models recreating the whole dwelling and its boundary conditions were generated for each of the case studies monitored. The climate data used for the energy simulation were provided by three meteorological stations belonging to the Spanish State Meteorological Agency [30], whose data were previously validated comparing them with spot measurements taken outside the case studies. The constructive definition of the envelope (section 3.2) and the use and occupation patterns of the case studies (section 3.3) were also taken into account for the development of the model. In addition to occupation habits, the models also include lighting patterns, use of local heating systems, natural ventilation (window opening), and use of sun protection (shutters, awnings…).

Another aspect that helps to reduce the uncertainty of the model is the introduction of the rate of infiltration measured in the air permeability test.

2.2.2. Energy model adjustment

As Cipriano et al. [36] correctly point out, the literature review shows the absence of a generally accepted methodology for the calibration of energy building models. However, some authors define calibration methodologies based on the manual adjustment of the models [37, 18], while others base them on a multi-stage guided procedure [36, 38].

This is a complex task, involving many parameters with a significant degree of uncertainty. Many of the studies on calibration focus on the importance of in situ measurements as a tool for the adjustment of energy simulations [36, 38]. Therefore, as described in the previous section, all the information collected in situ in this research was incorporated into the energy models. However, there are standard criteria to determine when a model can be considered to be calibrated, focusing on how the model adjusts to measured data and analysing the degree of error [39, 40, 41].

Usually, the literature about the calibration of energy model focuses on the adjustment of the heating energy consumption [36]. However, this would make no sense in these case studies, since the heating energy consumption is very insignificant in the social housing profile in southern Spain (the dwellings are usually in conditions of free evolution). Therefore, this research focuses on the manual adjustment of environmental variables during the winter period, specifically in the interior temperature (as this is the variable involved in thermal comfort analysis). The results of energy simulations and monitoring were compared both graphically (for a representative week) and statistically (for the entire winter period). The graphs provide information about the time periods in which the two datasets diverge, while the statistical indices provide a numerical index to assess how closely the simulation matches the measured data.

ASHRAE Guideline 14-2002 [39] was followed in the statistical validation of the model, establishing two error indicators, the Mean Bias Error (MBE) and the Coefficient of Variation of the Root Mean Square Error (CVRMSE) values, according to equations (3) and (4):

$$(3)\ MBE = \frac{\sum_{i=1}^{Ni}(Mi - Si)}{\sum_{i=1}^{Ni} Mi}$$

where:

Mi: measured data at instance n;

Si: simulated data at instance n;

Ni: count of the number of dates used in the calibration.

$$(4)\ CVRMSE = \frac{\sqrt{\sum_{i=1}^{Ni}\frac{(Mi - Si)^2}{Ni}}}{\frac{1}{Ni}\sum_{i=1}^{Ni} Mi}$$

where:

Mi: measured data at instance n;

Si: simulated data at instance n;

Ni: count of the number of dates used in the calibration

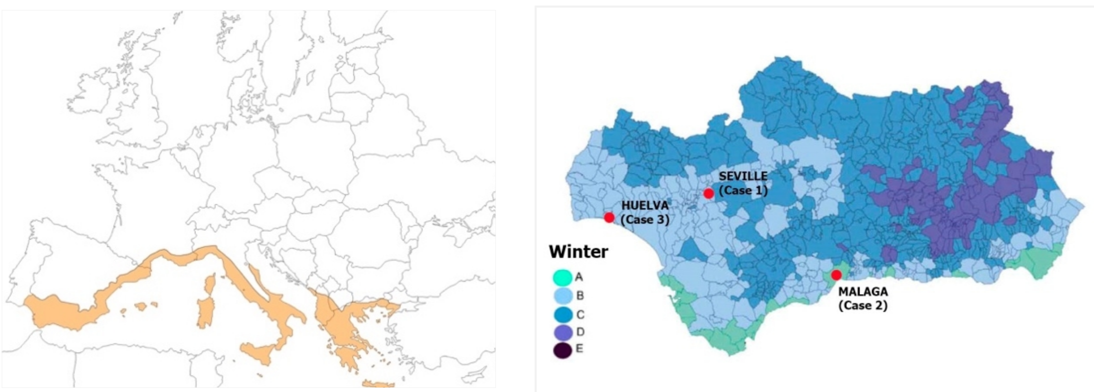
ASHRAE Guideline 14 considers a building model calibrated when hourly MBE values fall within ±10% and hourly CVRMSE values fall below 30%. The MBE provide an indication of errors averaged to the mean of measured values but may be influenced by offsetting errors, while the CVRMSE index is a measure of accumulated error normalized to the mean of the measured values.

3. Case studies: social housing

Whenever a detailed analysis is carried out, involving long campaigns of monitoring and evaluation of the thermal envelope of buildings, it is complicated to have a large sample of case studies, due to financial and time constraints [27]. For this reason, based on a previous analysis of the social housing stock of southern Spain [42], the statistically more representative morphological and constructive building typologies were determined and some neighbourhoods were selected by the Andalusian Government as cases of interest for its energy retrofitting plan [43]. Three dwellings belonging to these cases of interest were selected as case studies in this research. The main characteristics of the climate in which they are located, morphological typology, constructive characteristics of its envelope and the user patterns will be described below.

3.1. Location and climate

The three case studies are located in places with a Mediterranean climate (figure 1a), specifically three Spanish cities with the lowest values in the scale of winter climate severity: Seville (winter climate zone B), Huelva and Malaga (winter climate zone A) (figure 1b). Table 1 summarizes the main climate characteristics of these locations.



(a) (b)

Figure 1. Mediterranean climate map: (a) in Europe, (b) in southern Spain [44].

Table 1. Annual standard climate values, period 1981 – 2010 [30]

	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
Average minimum daily temperature (ºC)	13.0	13.7	12.4
99% winter design temperature (annual) (ºC)	4.5	5.8	3.6
Winter mean DTR (ºC)	12.9	12.3	13.8
Average relative humidity (%)	59	65	66
Average rainfall (mm)	539	534	525
Average nº days of rainfall ⩾ 1 mm	50.5	42.3	51.5
Average hours of sunlight	2917	2905	2969

3.2. Description of case studies and envelope characterization

The case studies are three social houses in multi-family buildings built between the 1960s and 1980s. Case 1 (figure 2a), located in Seville, is a dwelling with an area of 58 m^2 inhabited by a young couple who spend long periods at home working on computers. The main façades of the dwelling face Northeast (main bedroom) and Southwest (living room and secondary bedrooms), but in addition most of the time the users lower the blinds for shade (besides which for many hours during the year the building is shaded by the surrounding buildings). As usual in social housing in southern Spain, case 1 has only local thermal conditioning systems (a reversible heat pump in the secondary bedroom, which has not been monitored, and a portable electric air heater). Although these are local systems, the users keep the doors of all rooms open when the heat pump is turned on.

Case 2 (figure 2b), situated in Malaga, is a dwelling with an area of 105 m^2 inhabited by a family composed of two adults and two teenagers, who spend long periods of work/study outside home. The main façades of the dwelling face Northwest (living room and secondary living room) and Southwest (bedrooms), and are very exposed to the sun as the dwelling is on the eighth floor. In this case, there are two reversible heat pumps, one in the main living room and the other in the secondary living room. Although these are local systems, usually in this dwelling all the rooms are connected as the doors are always open.

Table 2 summarizes the main typological and constructive characteristics of the case studies.

(a) (b) (c)

Figure 2. Exterior view and floor plan of the 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
Winter climate zone [43]	B	A	A
Typology	Linear	H	H
No. stories	5	10	4
No. identical dwellings	260	1512	540
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^{2}K)	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^{2}K)	1.82	1.88	1.82
Joinery	Aluminium	Aluminium	Aluminium
Glazing	6 mm	6+12+6 mm	6+6+6 mm
Window transmittance (W/m^{2}K)	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
Heating system	Electric heat pump (1 bedroom)	Electric heat pump (2 living rooms)	Electric heat pump (living room and 1 bedroom)
Cooling system	Electric heat pump (2 bedrooms)	Electric heat pump (2 living rooms)	Electric heat pump (living room and 1 bedroom)

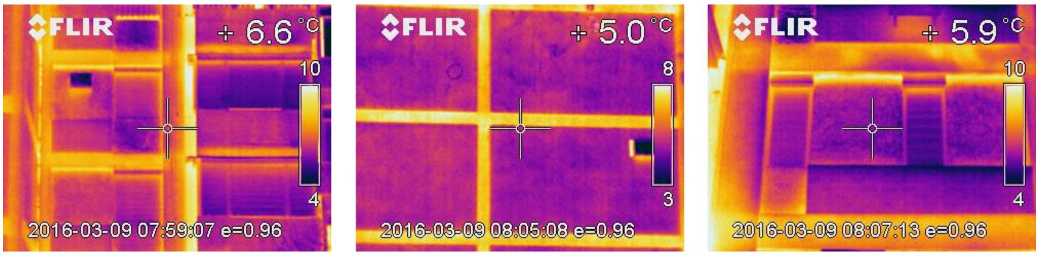
Case 3 (figure 2c), located in Huelva, is a dwelling with an area of 58 m^2 inhabited by an elderly retired couple who spend long periods away from home visiting their children. The main façades of the dwelling face Southwest (living room and main bedrooms) and Northeast (kitchen and secondary bedroom), with little exposure to the sun due to shade from the surrounding buildings. However, the dwelling is very exposed because it is on the top floor of the building, immediately under the roof. Case 3 has a reversible heat pump in the living room and another one in the main bedroom. The users often keep the doors of all the rooms open all day and close them at night.

The depressurisation tests carried out on the three case studies (table 3) show that in all cases the air permeability is medium, according to the categories established by EN-ISO 137900 [45]. Although these dwellings are old, in all of them the original window frames have been replaced with more modern sliding aluminium ones (partially in cases 1 and 3 and completely in case 2). In case 2 there are casement windows in the living room and secondary living room, with greater airtightness. Thus, the value of air change rate at 50 Pa (n50) obtained in case 2 is 5.6 h^{-1}, very close to the average values of retrofitted dwellings or those built after 1979 in southern Europe, between 5 h^{-1} (dwellings built after 2001 in Italy) and 7 h^{-1} (dwellings built after 1979 in Spain) [46].

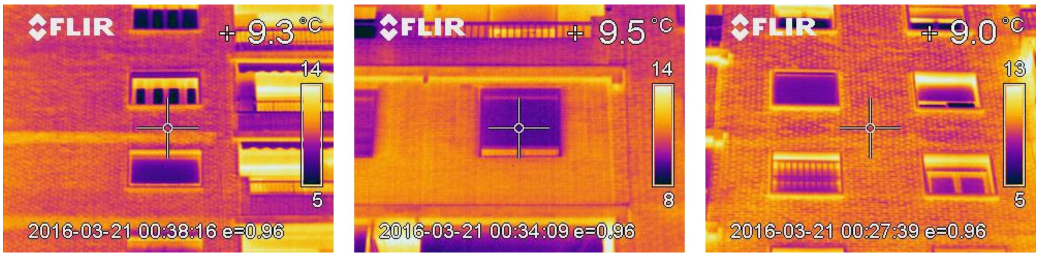
In addition, images of the façade were captured with a thermographic camera, in order to establish thermal behaviour patterns. In case 1 (figure 3a), significant heat loss was observed through pillars, floor slab edges, shutter boxes and façade surfaces with lower thermal transmittance (1-leaf façade). In case 2 (figure 3b), there was also important heat loss in floor slab edges, window edges and façade areas with lower thermal transmittance (brick joints). Finally, in case 3 (figure 3c), there was significant heat loss in pillars, floor slab edges, shutter boxes and façade surfaces with lower thermal transmittance (1-leaf façade).

Table 3. Air permeability test results.

Air permeability	**Case 1 (Seville)**	**Case 2 (Malaga)**	**Case 3 (Huelva)**
Air leakage rate at 50 Pa: V50 (m^3/h)	1053	1287	1258
Air change rate at 50 Pa: n50 (h^{-1})	9.4	5.6	8.4



(a)



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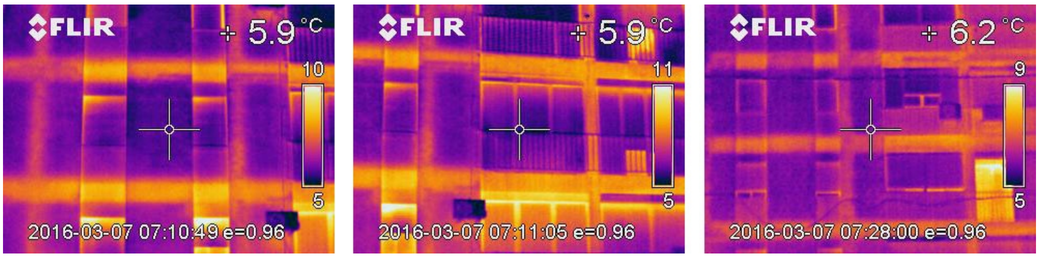


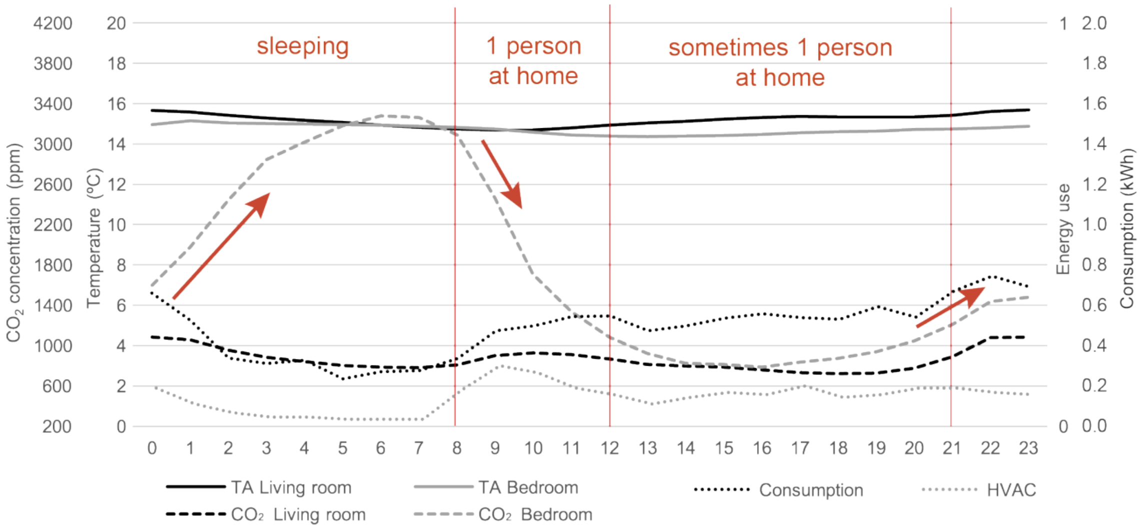
(c)

Case study	(a)	(b)	(c)
Outdoor temperature (ºC)	7.0	10.0	7.5
Indoor temperature (ºC)	16.2	19.7	14.4

Figure 3. Infra-red thermography and environmental conditions: (a) case 1 - Seville, (b) case 2 - Malaga, (c) case 3 - Huelva.

3.3. User patterns

Following the mixed methodology described in section 2.1.4., the user patterns of the three case studies have been defined based on the qualitative data of the user surveys and the quantitative measured data (temperature, CO_2 concentration and electricity consumption). Figure 4a shows the occupation pattern of case 1 (Seville), extracted essentially from the measured CO_2 levels and energy consumption. Surveys (table 4) confirm that in the early morning one of the users is at home and it is not until night-time that the dwelling is completely occupied. Both the measured temperature and the operation of the heating systems (figure 4a) show that they are used very sporadically. In surveys, users confirm that they do not use local heating systems frequently, but occasionally used them in the bedroom in the early hours of the morning.



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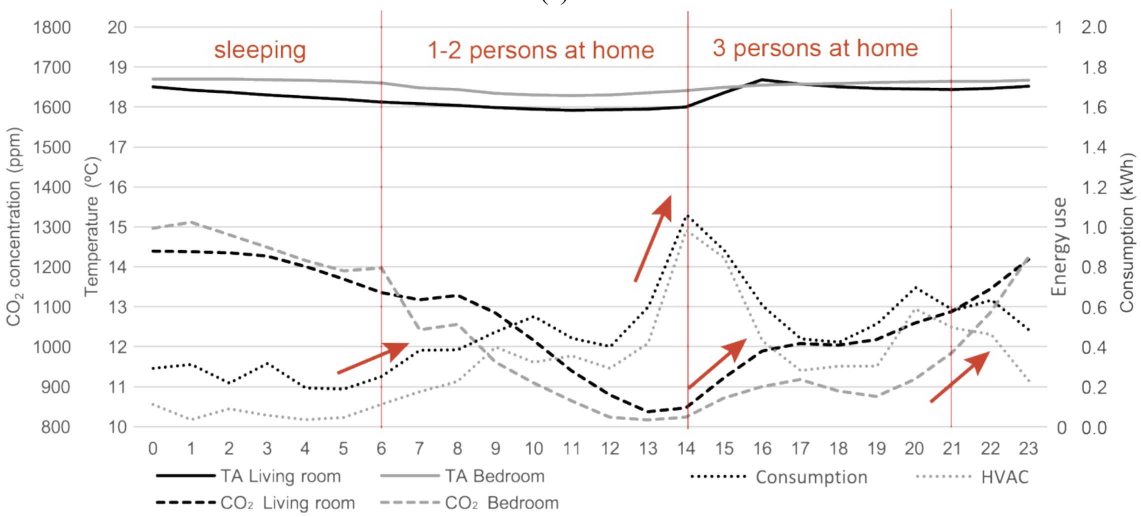


(b)

(c)

Figure 4. User pattern (winter weekday), based on the evaluation of the average hourly values of temperature (ºC), CO_2 concentration (ppm), local heating 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.

Table 4. Surveys: user pattern (winter 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)	■	■	■	■	■	■	■	■													■	■	■	■
Natural ventilation								■	■															
Local heating									■	■														
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 (son 1)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■						■	■	■	■
Occupancy (son 2)	■	■	■	■	■	■	■							■	■	■	■	■	■	■	■	■	■	■
Natural ventilation							■	■	■	■	■	■	■											
Local heating														■	■					■	■			
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)	■	■	■	■	■	■	■	■					■	■	■	■	■	■	■	■	■	■	■	■
Natural ventilation								■	■	■	■													
Local heating																					■	■	■	

Figure 4b shows the occupation pattern of case 2 (Malaga) confirmed by the surveys (table 4), establishing that in the early morning there are one or two users at home, while around 14.00 h there are three users and the house is not completely occupied until night-time. Both the measured temperature and the operation of the heating systems (figure 4b) show very sporadic use, except for more repeated use in the living room around 14.00 h and 20.00 h.

Figure 4c shows the user pattern of case 3 (Huelva) confirmed by the surveys (table 4). It establishes that one of the couple usually leaves home in the morning and returns around 13.00 h, when the dwelling is completely occupied. Both the measured temperature and the operation of the heating systems (figure 4c) show very sporadic use, more frequent between 21.00 h and 23.00 h, as confirmed by the surveys. The graph also shows a decrease in the interior temperature of the bedroom between 8.00 h and 11.00 h, coinciding with the natural ventilation schedule noted in the survey.

4. Results

4.1. Evolution of internal environmental conditions

The data monitored during the winter in the three case studies were analysed, focusing the study on the hourly temperature, relative humidity and CO_2 concentration evolution during the coldest month of the winter period. In the temperature graphs an adaptive comfort band has been included following standard EN-15251. The CO_2 graphs also included a reference limit below which indoor air quality is considered good (1200 ppm), following the FSIAQ (Finnish Classification of indoor climate 2000 [47]) standard for category S3 (a less demanding category which may be associated with existing buildings).

In case 1 (Seville), during the winter period monitored (December 2014 - February 2015) the coldest month was January. During this period (figure 5), with mild outdoor temperatures ranging from 5 ºC to 18 °C, inside the dwelling the temperatures were always around 14-15 °C, and so always below the lower limit set by adaptive thermal comfort standard EN-15251 (around 18 °C). In particular, the average January interior temperature was 15 °C in the living room and 14.2 °C in the main bedroom. The behaviour of the two monitored rooms was very similar, with the exception of some times of night when a local heating system was used in the bedroom. As it is a very shaded dwelling, there is not much solar gain during the day repeatedly making indoor temperatures fall below outdoor ones.

Analysing other environmental variables (figure 6), an internal relative humidity between 60 % and 80 % was found, compared to an external one varying from 40 % to 90 %. The interior CO_2 concentration shows two very different ways of use of the rooms monitored. While the living room is routinely kept below 1250 ppm (with the exception of high occupancy periods) due to sporadic use, the bedroom reaches 5000 ppm for a high percentage of nights because of more continued use.

In case 2 (Malaga), during the winter period monitored (December 2015 - February 2016) the coldest month was February. In this month (figure 7), with warm outdoor temperatures ranging from 10 ºC to 20 ºC, the temperatures inside the dwelling were always around 18-19 ºC, and almost always below the lower limit set by the adaptive thermal comfort standard EN-15251 (around 20 °C in this case). The average interior temperature for February was 18.1 ºC in the main living room and 18.8 ºC in the main bedroom. The behaviour of the two monitored rooms was very similar, with the exception of some periods where a local heating system was used in the main living room. This dwelling maintains a very stable temperature throughout the whole day.

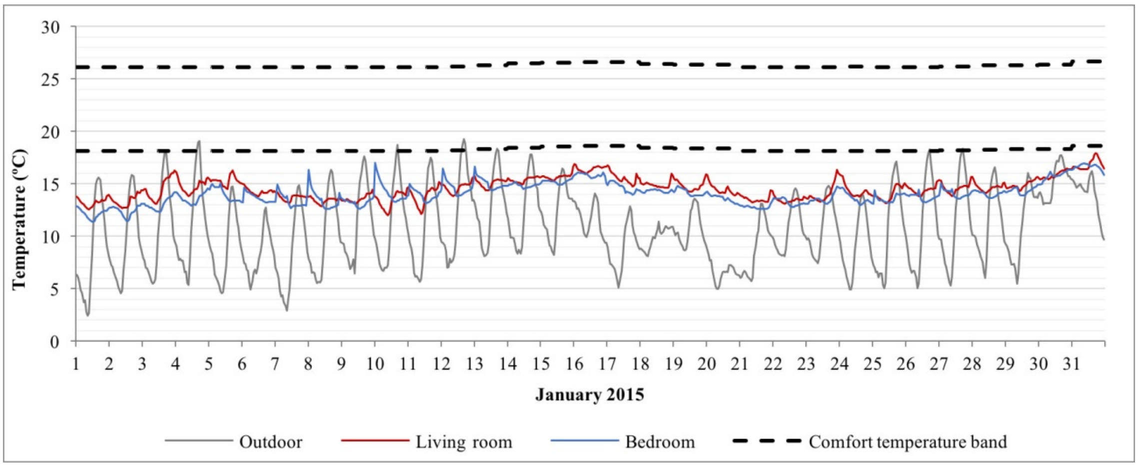


Figure 5. Case 1 - Seville: hourly temperature evolution during January.

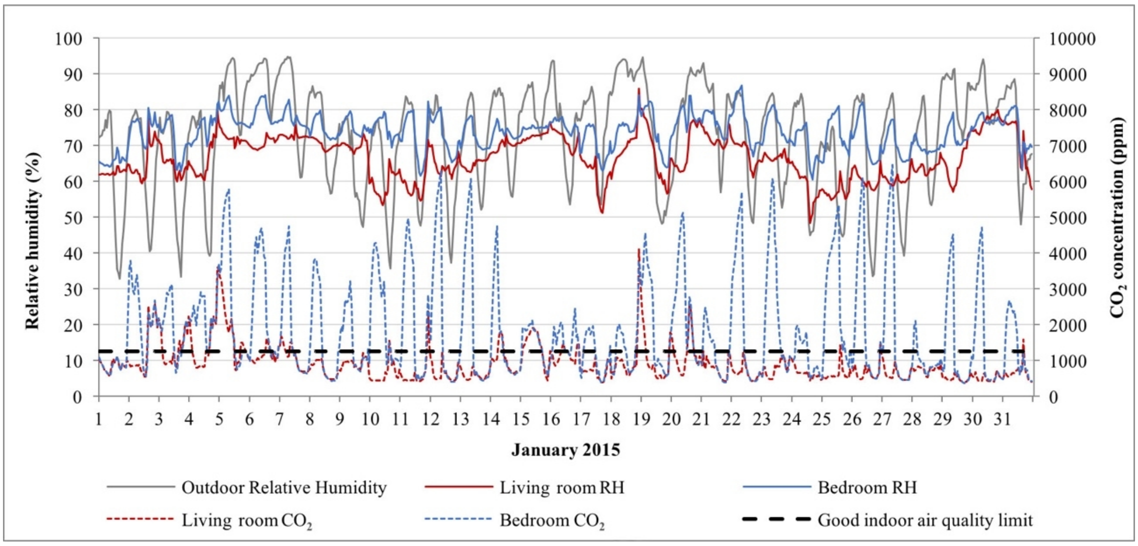


Figure 6. Case 1 - Seville: hourly relative humidity and CO_2 concentration evolution during January.

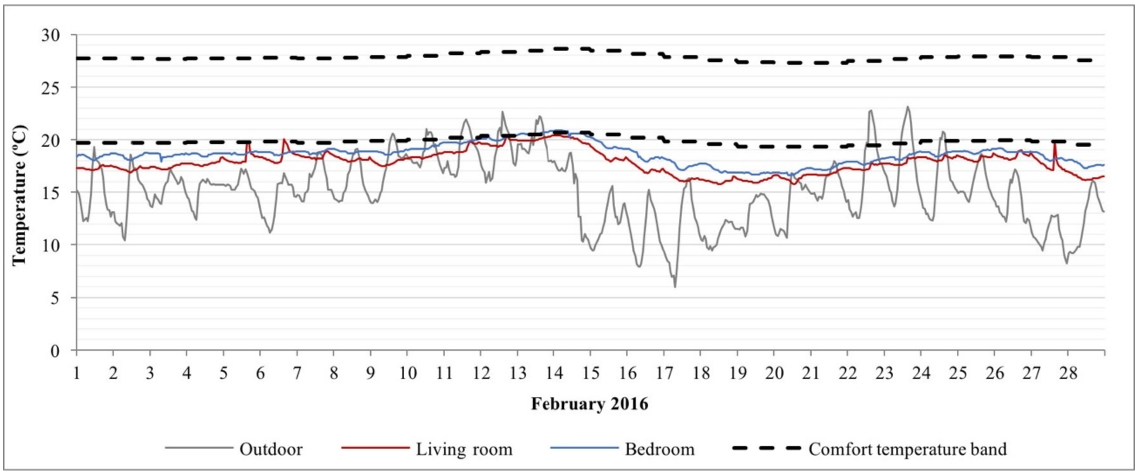


Figure 7. Case 2 - Malaga: hourly temperature evolution during February.

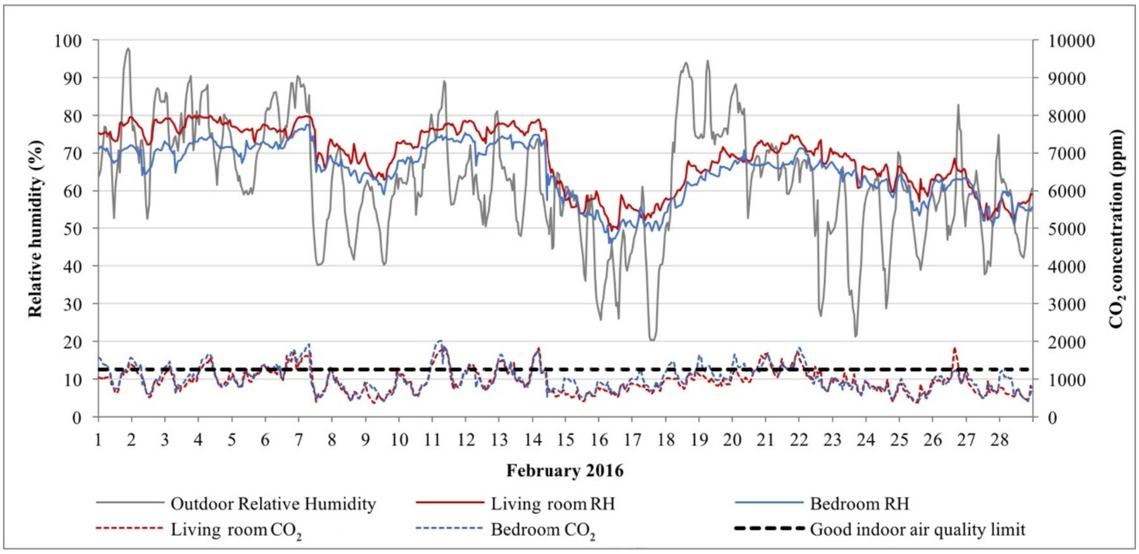


Figure 8. Case 2 - Malaga: hourly relative humidity and CO_2 concentration evolution during February.

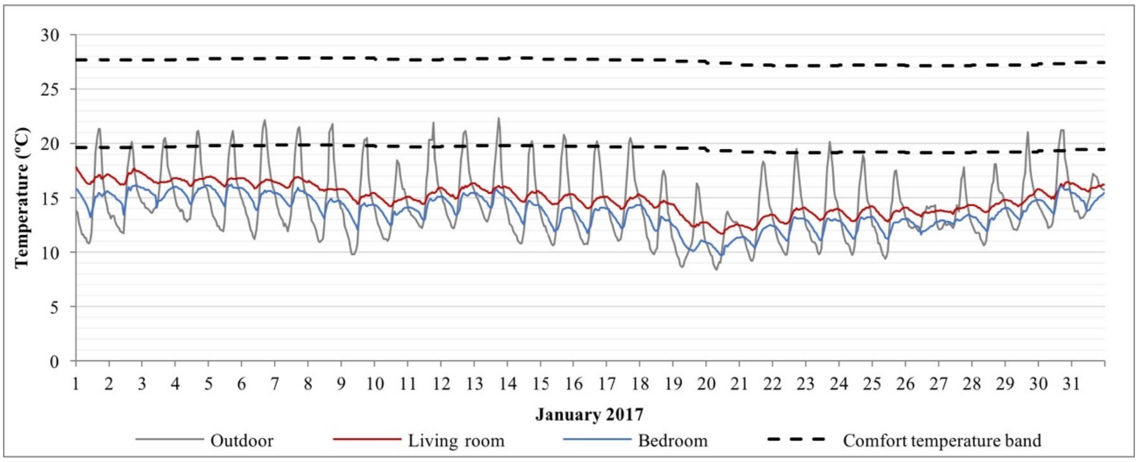


Figure 9. Case 3 - Huelva: hourly temperature evolution during January.

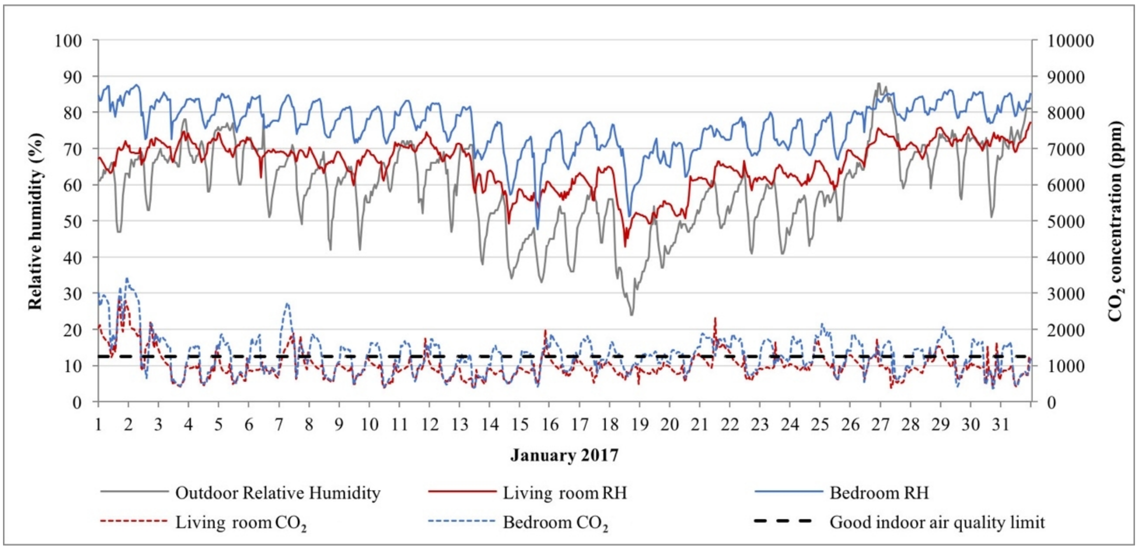


Figure 10. Case 3 - Huelva: hourly relative humidity and CO_2 concentration evolution during January.

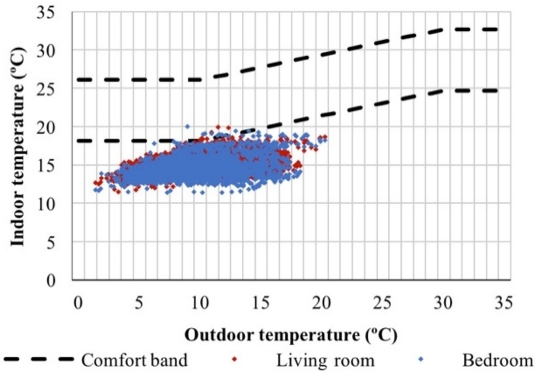
An internal relative humidity between 50 % and 80 % was found (figure 8), compared to an external one ranging from 30 % to 95 %. The interior CO_2 concentration shows a very similar way of use for the two rooms monitored, probably because the doors of all the rooms are always open linking them. Both are routinely kept below 1250 ppm due to low occupancy of these rooms. Another key aspect for the good quality of the interior air in this case study is the continuous operation of the natural ventilation system. This system keeps a low continuous ventilation rate through the kitchen window and extracted by the vents in the bathrooms.

In case study 3 (Huelva), during the monitored winter period (December 2016 - February 2017) the coldest month was January. During this month (figure 9) the external temperatures were warm, between 10 ºC and 20 °C, while inside the dwelling the temperatures were measured at around 13-14 °C, far below the lower limit set by adaptive thermal comfort standard EN-15251 (around 20 °C in this case). In particular, the January average interior temperature was 14.7 °C in the living room and 13 °C in the main bedroom. The two monitored rooms exhibit almost parallel behaviour, with the exception of night-time, when the temperature decrease in the bedroom is greater.

Analysing other environmental variables (figure 10), an internal relative humidity between 50 % and 85 % was found, compared to an external one varying from 30 % to 70 %. The interior CO_2 concentration shows two slightly different ways of using the monitored rooms. During the day the doors of all rooms are kept open which homogenizes the quality of the air. However, at night the bedroom reaches higher CO_2 concentrations, up to 2000 ppm, while the living room stays below 1250 ppm. In general, the interior air maintains good quality due to the fact that the users ventilate the dwelling naturally every morning (from 8.00 to 11.00 h, as seen from the survey).

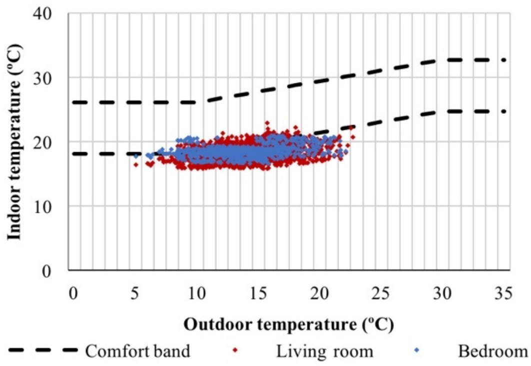
4.2. Comfort analysis

The thermal comfort level in the three case studies during the winter period has been analysed according to the adaptive model established by standard EN-15251 [26]. In addition, the percentage of hours of discomfort and the average deviation of the interior temperatures with respect to the comfort band have been contrasted with the percentage of hours of use of the local heating systems in each dwelling.



Period	December 2014	January 2015	February 2015	Winter 2014/15
% hours of discomfort				
Living room	99.7	100	100	99.9
Bedroom 1	100	100	99.5	99.9
Average deviation Indoor temperature – Comfort band (ºC)				
Living room	-3.4	-3.7	-2.7	-3.3
Bedroom 1	-3.9	-4.2	-3.9	-3.8
% hours of use of local heating systems				
Portable air heater	5.4	4.4	3.3	4.4
Bedroom 2 heat pump	9.6	14.7	4.6	9.9

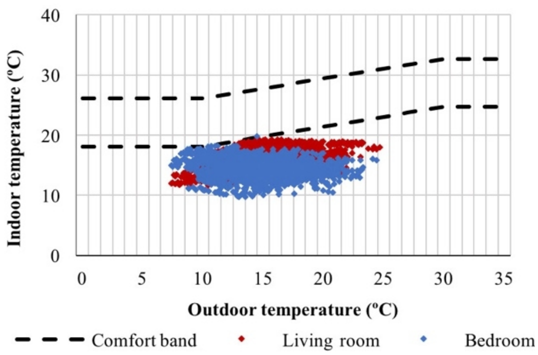
(a)



Period	December 2015	January 2016	February 2016	Winter 2015/16
% hours of discomfort				
Living room 1	92.5	87.5	99.4	92.9
Bedroom 1	*	100	95.4	96.1
Average deviation Indoor temperature – Comfort band (ºC)				
Living room 1	-1.3	-1.6	-2.0	-1.6
Bedroom 1	*	-1.3	-1.3	-1.3
% hours of use of local heating systems				
Living room 1 heat pump	12.9	15.2	18.2	15.3
Living room 2 heat pump	13.6	17.7	20.8	17.3

* Loss of monitoring data due to equipment failure.

(b)



Period	December 2016	January 2017	February 2017	Winter 2016/17
% hours of discomfort				
Living room	100	100	100	100
Bedroom 1	98.7	100	100	99.5
Average deviation Indoor temperature – Comfort band (ºC)				
Living room	-3.6	-4.6	-3.0	-3.8
Bedroom 1	-4.8	-5.8	-4.2	-5.0
% hours of use of local heating systems				
Living room heat pump	7.1	22	2.8	10.9
Bedroom 1 heat pump	0.1	0.3	0.1	0.2

(c)

Figure 11. Evaluation of thermal comfort and use of heating systems during the winter period: (a) case 1 - Seville, (b) case 2 - Malaga, (c) case 3 - Huelva.

In cases 1 and 3 (Seville and Huelva), a high percentage of hours of discomfort was detected throughout the winter period in the two rooms monitored, around 100 % (figure 11a, 11c). In case 3, despite having higher external temperatures than in case 1, interior temperatures even further removed from the comfort band are observed. This is mainly due to heat losses of case 3 through the roof, as it is on the top floor. In both cases, in spite of being in a clear situation of discomfort, the percentage of hours of use of local heating systems is very low. During the coldest period (January) this percentage is less than 15 % in

Seville and 22 % in Huelva. In case 3 the use of the local heating system in the main bedroom is almost zero although this is the room furthest away from the comfort band.

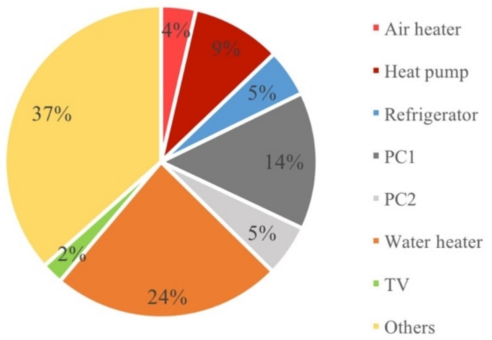
In case 2 (Malaga), as the climate is milder than in case 1 (but similar to case 3), the percentage of hours of discomfort is slightly lower than in the other cases but it is still high. This percentage was above 90 % during the whole winter period in the two rooms monitored (figure 11b). Although the percentage of hours of discomfort does not differ much from the other cases, the graph shows that the average deviation of the interior temperature with respect to the comfort band is much lower in case 2 (-1.6 ºC in the living room and -1.3 °C in the bedroom) than in cases 1 (-3.3 °C in the living room and -3.8 °C in the bedroom) and 3 (-3.8 °C in the living room and -5.0 °C in the bedroom). However, in this case the percentage of hours of use of local heating systems is higher than in case 1 and similar to the case 3 living room during the colder periods, reaching 20 % in February. In spite of this, the percentage of hours of use of the heating systems does not nearly cover the percentage of hours of discomfort.

4.3. Energy consumptions

The electricity consumption of the three case studies has been analysed comprehensively and in detail during the winter period, focusing on the consumption of the local heating systems. In order to evaluate the heating consumption, the addition of the consumption of all local heating systems (kWh) has been divided by the heated area, which in this case is the total area of the dwelling except for the kitchen and bathrooms (the doors of the rooms are always kept open). In the three case studies, very low levels of total consumption and no significant percentages of the use of local heating systems were detected.

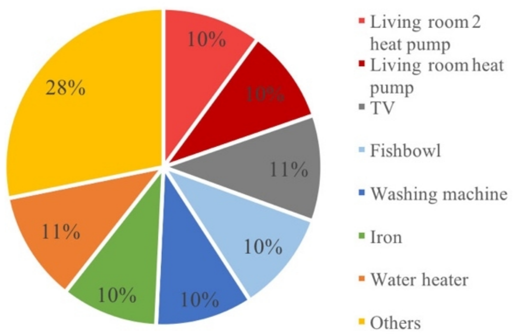
In cases 1 and 2, it is worth noting that the Hot Water production system is electric. In case 1 (Seville) specifically the water heater shows very significant consumption (figure 12a), around 24 %, well above heating consumption, around 13 %. Also in this case, the high consumption of two computers, around 19 %, is significant since the users usually work at home. In case 2 (Malaga) (figure 12b), a balanced distribution of consumption can be observed, in which heating accounts for around 20 % of total consumption. In case 3 (Huelva) (figure 12c), the living room heating system consumption is notable as it accounts for 29 % of the total consumption of the dwelling. In this case, the global consumption of all devices without individual meters (‘others’ in figure 12) represents a more significant percentage than in the other cases (52 %), due to the fact that it has less electric equipment (Hot Water is heated by gas) and the consumption from lighting and cooking acquires greater relevance.

Looking at the total consumption data, it is apparent that case 1 (occupied by a young couple who work at home) consumes the same as case 2 (occupied by a family of 4 members) and almost double that of case 3 (occupied by a retired couple). The economic level of the users of case 1 is slightly higher than the others. When analysing the heating consumption, case 2 consumes the highest amount in relation to the space heated, as well as taking up the highest percentage of use of the heating systems (figure 11).



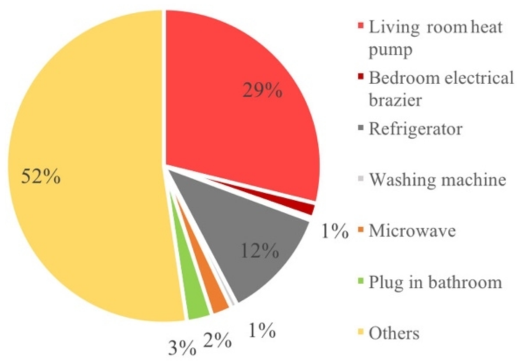
Period	Total consumption (kWh)	Heating consumption (kWh/m² heated)
December 2014	355.89	1.12
January 2015	394.80	1.15
February 2015	305.84	0.47
Winter 2014/15	1056.53	2.75

(a)



Period	Total consumption (kWh)	Heating consumption (kWh/m² heated)
December 2015	268.01	1.46
January 2016	327.23	1.57
February 2016	410.44	1.42
Winter 2015/16	1005.68	4.45

(b)



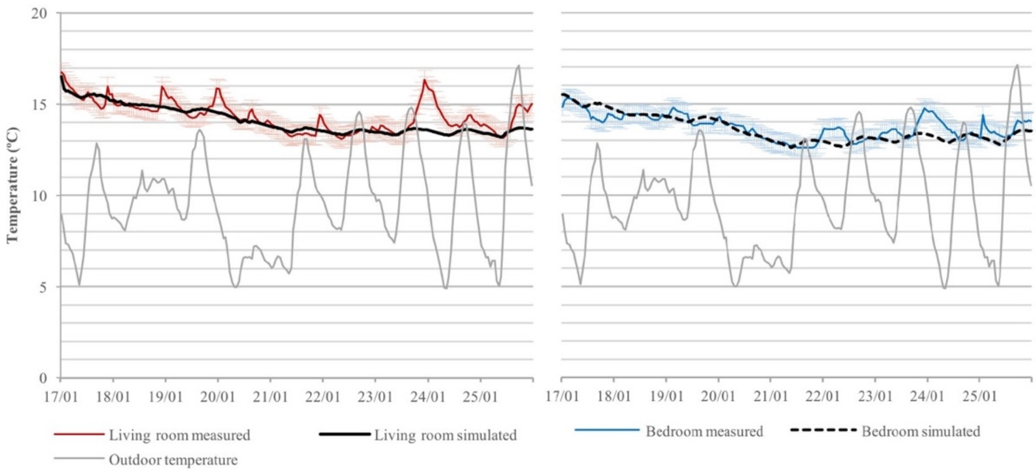
Period	Total consumption (kWh)	Heating consumption (kWh/m² heated)
December 2016	165.87	0.77
January 2017	206.46	1.76
February 2017	133.68	0.38
Winter 2016/17	506.01	2.91

(c)

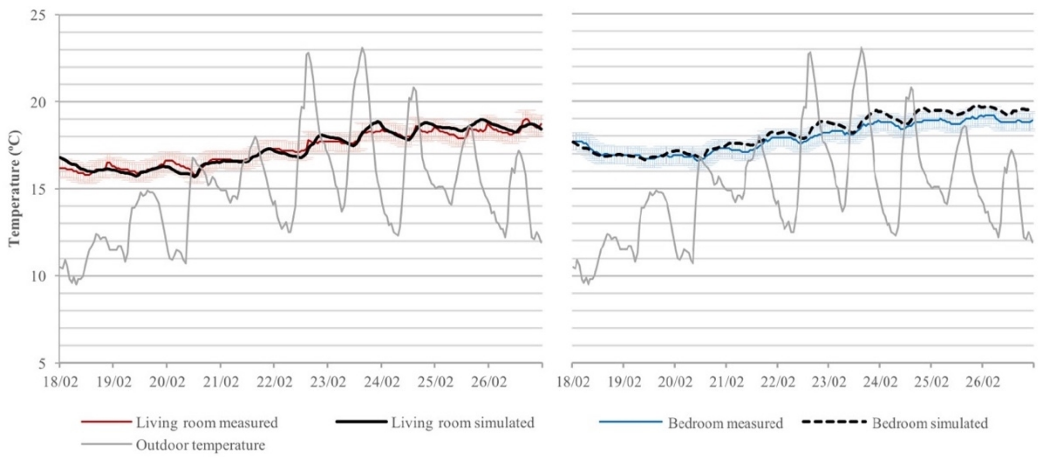
Figure 12. Evaluation of electric consumption during the winter period: (a) case 1 - Seville, (b) case 2 - Malaga, (c) case 3 - Huelva.

Table 5. Statistical validation of the energy models.

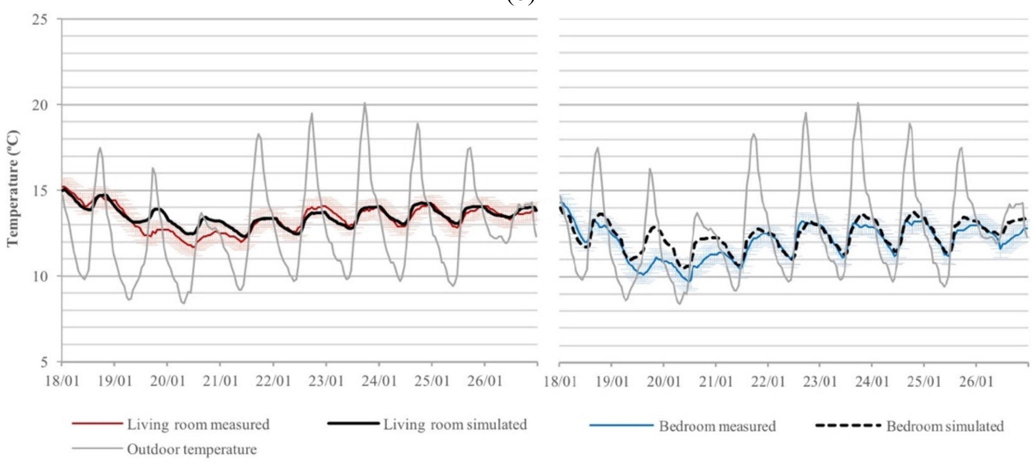
	MBE Living room	MBE Bedroom	CV Living room	CV Bedroom
Case 1 (Seville)	-5.33 %	-5.06 %	10.14 %	11.27 %
Case 2 (Malaga)	-0.23 %	-3.17 %	4.08 %	4.33 %
Case 3 (Huelva)	-4.78 %	-1.73 %	8.22 %	5.61 %
ASHRAE Standards	MBE < 10 %		CV(RMSE) < 30 %	



(a)



(b)



(c)

Figure 13. Graphic validation of the energy models: (a) case 1 - Seville, (b) case 2 - Malaga, (c) case 3 - Huelva.

4.4. Energy model adjustment

Following data collection for all case studies, the energy models were constructed and subsequently simulated to verify the adjustment to the measured data. First, the results of energy simulations and monitoring for a typical week were compared in graphs. According to the results obtained, the energy model achieves the adjustment of variables on which there is some degree of uncertainty (due to the impossibility of measurement), such as the natural ventilation rate through opening windows and the occupants' metabolic rate. The final result is an adequate graphic adjustment of the energy models (figure 13), which took into account the degree of error of the measurement equipment (+/- 0.5 ºC), represented in the graph by error bars.

In addition, the statistical validation of the energy models has been verified during the whole winter period, following the indicators established by the ASHRAE [35] (table 5). The adjustment between the energy models and the measured data shows that the monitoring of the buildings is essential to obtaining a valid adjustment, and so greatly reducing the number of uncertain variables. Therefore, for the energy evaluation of retrofitting measures it is essential to have a calibrated simulation model, even more so in case studies with a user pattern so far removed from the standards.

5. Conclusions

In southern Europe, there is extensive social housing stock with a notable need for retrofitting due to energy obsolescence. Energy simulation incorporating standardized user patterns cannot be used to ascertain the most appropriate measures for these particular dwellings to avoid the Prebound effect after retrofitting. Given that the case studies evaluated demonstrate a variety of user profiles, retrofitting decisions should not be simplified by using a single user profile. National regulations should define different user profiles, including the number and age of users, the intensity of use of the dwellings, and the climatic zone in which it is located (to consider the different criteria for thermal comfort).

After monitoring the environmental and energy behaviour of some case studies (during the winter period), the following results have been obtained:

- Despite the mild climate conditions during the harshest winter months, the average indoor temperatures measured are low, oscillating between 13 ºC (Huelva) and 18.8 ºC (Malaga).
- The low values of the interior temperature mean that for most of the time the dwellings are in discomfort conditions, and the percentage of hours outside the comfort band ranges from 92.9 % (Malaga) to 100 % (Huelva).
- In spite of these inadequate indoor thermal conditions, users generally reject the use of their local heating systems, mainly for financial reasons. The percentage of hours of use of the local heating systems ranges from 9.9 % (Seville) to 17.3 % (Malaga).

Despite the warm Mediterranean winters, the low energy performance of the pre-1980 social housing envelope (without any kind of thermal insulation) causes indoor thermal conditions far removed from comfort. This, added to the lack of global and efficient heating systems and to financial constraints of users, means that this housing stock is completely exposed to the risk of falling into a situation of fuel poverty. The current energy policies must take into account the environmental behaviour of social housing in southern Spain described in this research, and ensure that energy retrofitting grants focus on passive measures that entail the improvement of thermal comfort instead of energy savings.

This research also demonstrates that the monitoring of in-use dwellings permits enough information to be obtained to generate energy simulation models that minimize the 'performance gap' between real and estimated behaviour. This is essential if retrofitting decisions are to be based on the results of energy simulations.

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