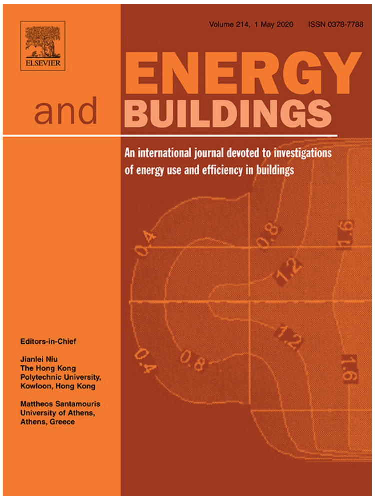

Are the dwellings of historic Mediterranean cities cold in winter? A field assessment on their indoor environment and energy performance

Rosana Caro, Juan José Sendra

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Tittle page

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Authors:

Rosana Caro[a], corresponding author. E-mail address: rocamar8570@gmail.com

Juan José Sendra[a], co-author. E-mail address: jsendra@us.es

[a] Instituto Universitario de Arquitectura y Ciencias de la Construcción, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla.

Av. de Reina Mercedes 2, Seville (41012), Spain.

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Contents

Abstract

Although European heritage buildings are excluded from energy efficiency targets, it would be beneficial to include the largest group, that of listed housing, in energy retrofit plans, in order to encourage its occupation and contributing to the sustainable maintenance of historic cities. This requires reliable experimental studies, which have been rare so far, in order to establish energy rehabilitation plans that do not jeopardize the conservation of their values. This paper aims to contribute to addressing this gap. It evaluates the energy performance and indoor environmental quality of dwellings within listed buildings of the conservation area of Seville, Spain, in the Mediterranean climate zone, under actual winter use and occupation conditions. An experimental campaign was conducted, generating energy models and measuring rates of indoor air temperature to validate them. The findings highlight important health and environmental issues: despite the mild winters of southern Spain, intensive use of the heating system is needed to maintain thermal comfort indoors, increasing polluting emissions; CO_2 concentration in bedrooms is usually excessive overnight and, regularly, indoor relative humidity remains too high; heat losses depend entirely on the physical condition of the constructive elements (walls, roofs, air leakage and glazing) which occupants cannot easily improve.

Keywords

Mediterranean city; City decarbonisation; Historic city; Historic buildings; Residential heritage; Indoor Air Quality; Thermal comfort; Energy efficiency; Occupant behaviour; Cold indoors.

Highlights

- Listed dwellings of southern Spain were monitored in winter to evaluate IEQ and EP.
- Lengthy high rates of IRH were observed.
- High levels of CO_2 concentration were recorded in bedrooms at night.
- Thermal comfort is only achieved through a constant use of the heating systems.
- Heat losses are entirely building-driven.

Abbreviations

AEMET: Spanish state meteorological agency.

Br: Bedroom.

CTE DB HE: Spanish energy code.

EP: energy performance

IRH: Indoor relative humidity (%).

IEQ: Indoor environmental quality.

IAQ: Indoor air quality.

IAT: Indoor air temperature (℃).

Lr: Living room.

NV: Natural ventilation.

NZEB: Nearly zero energy building.

n50: air change rate at 50 Pa (h^{-1}).

OAT: Outdoor air temperature (℃).

ORH: Outdoor relative humidity (%).

T_{op}: Optimal indoor operative temperature (℃).

T_o: Outdoor reference temperature (℃).

TBB: Thermal bridge break.

U: Thermal transmittance (W/ m^2K).

1. Introduction.

Until recently, the improvement of the energy efficiency and indoor environmental quality (IEQ) of homes was only linked to economic and environmental issues. However, over the last decade there has been growing interest in the study of its relationship to health [1–4]. Energy retrofits usually have a favourable impact on residents' health, although some could worsen indoor air quality (IAQ), leading to adverse health effects [1].

According to a 2016 EEA report [5], on a local scale the effects of global climate change have resulted in a reduction in energy demand for space heating and an increase in demand for space cooling between 1951 and 2014. According to projections, temperatures in Europe will continue to increase, causing hotter and more frequent heat extremes, especially in the South, a trend which is likely to accelerate. Therefore, in southern Europe, the seasonal effect of hot summers on the energy use, energy performance (EP) and IEQ of buildings is a well-developed field of research, with many studies analysing buildings located in European Mediterranean cities under summer conditions [6–8]. In contrast, and with some exceptions [9,10], due to the overconfidence in the thermal capacities of building envelopes to maintain warmth indoors less attention has been paid to the impact of cold weather on buildings and their residents in the Mediterranean region, where the winters are mild. Nevertheless, as reported by Healy [11], "higher mortality rates are generally found in less severe, milder winter climates where, all else equal, there should be less potential for cold strain and cold related mortality. Housing standards have been linked as a potential, causative factor behind this paradox". Healy named this phenomenon the "paradox of winter mortality". According to further analysis by Fowler

2015 [12], Excess Winter Deaths Index (EWDI, which is the ratio of deaths in the winter period compared with deaths in the non-winter period) for Malta, Portugal, Spain, Cyprus, and Belgium was significantly higher in statistical terms than the average EWDI for the other 30 European countries. When studying the short-term effects of cold weather on mortality in 15 European cities, Analitis et al. [13] established that the effect of cold weather was found to be greater in warmer (southern) cities. Improving protection from cold indoors has been found to be one of the measures with the greatest impact on reducing the high seasonal mortality reported in southern and western Europe [14].

Purposeful and consistent policies and targets on energy efficiency for existing buildings could alleviate poor domestic thermal conditions. Although its main motivation was initially not health-driven, but rather linked to environmental and economic issues, in Europe, the application of minimum requirements to the EP of existing buildings subject to major renovation was included in the Directive 2012/27/EU on energy efficiency, and a specific rate per year was set. However, this Directive allows the legally protected buildings to be excluded from complying with the energy efficiency requirements and, as a result, a significant portion of the existing building stock is not covered by these objectives and a large section of the European population, resident in historic districts, was left in a position of increased vulnerability to both health, economic and climate change-related risks. The residential building stock is particularly significant on the health front, given the high number of hours that people, especially the most vulnerable groups, spend in them. Furthermore, as they account for the vast majority of the total stock, in environmental terms the success or failure of decarbonisation policies hinges on them.

23% (on average 27 EU Member States) of the total European housing stock predates 1945 [15,16]. These buildings are usually considered “historic” in terms of legal protection or are located in conservation areas where specials rules apply. Since they constitute the biggest proportion of the historic building stock of European cities and define their identity, the potential environmental risks and the unexpected socio-economic consequences deriving from the legal exemption mentioned earlier should be thoughtfully considered. The failure to apply energy efficiency targets to the pre-1945 residential stock, underestimating its potential for CO_2 emissions reduction, may prevent the objectives set in the EU *2050 long-term strategy*, aiming to improve the energy efficiency of domestic buildings by 27%, from being reached [17]. Moreover, entire urban areas could be condemned to energy waste or obsolescence in terms of thermal comfort, in turn increasing health risks. In this scenario, high energy costs and low levels of well-being would discourage the use and occupation of historic neighbourhoods, which would further accelerate the ongoing commodification process, now globally recognized as a cause of unsustainable metropolitan unevenness.

On the other hand, including the large historic building stocks on the EU energy efficiency targets while ensuring the conservation of its protected values, is a complex task that may make energy retrofit projects extremely challenging. In fact, their heterogeneous geometry, constructive systems, materials, and conservation strategies are worse suited to standardized values and procedures, which are based on industrially manufactured materials of different hygrothermal properties. The variety of protected elements, façades, details, and indoor finishes can complicate retrofits, and some authors usually find these buildings, especially those from before 1919, less energy-effective compared to buildings constructed from 1945 [16]. These factors, coupled with the aforementioned absence of legal obligation, may have further hindered the scientific breakthrough in this particular field of research that some authors have pointed out [18]. Other reasons are:

- The widespread assumption that the contribution of historic buildings to the reduction of emissions is not significant, as they are in a minority. This belief may have been partially brought about by the lack of statistical data or the lack of coordination between databases, which have only recently begun to be resolved thanks to specific tasks and targets set in EU strategies [19].
- The widely assumed bioclimatic qualities of the historic buildings, though to help to maintain thermal comfort without mechanical systems and to perform energetically better than new ones. These exceptional qualities assumed have often been overestimated and extrapolated to all cases without sufficient scientific evidence.
- The assumption that the energy retrofit of historic buildings requires intrusive physical transformations following modern standards and would therefore be in conflict with the rules of protection.

In addition, the principle of conservation, to which only historic buildings are subject, has traditionally been the dominant, and practically the sole, criterion examined in the study of their EP [20]. This has led to excessive focus on the technical issues relating to the physical properties of the building envelope and construction materials in most of the existing research [18,20,21], disregarding some other key aspects of the EP of buildings in general, especially socio-economic, demographic and physiological factors, corresponding to different *Decision Making Models* ill-suited to deterministic analysis [22]. One of the most important non-technical aspects is occupant behaviour, which is becoming increasingly relevant in research on the EP of buildings, as overly simplified user profiles have been shown to lead to significant discrepancy between simulated and actual measured results [23], [24].

In view of this diagnosis, this study focuses on the numerous officially protected buildings for residential use. Its main objective is to evaluate the winter indoor environmental quality (IEQ) and EP of dwellings within listed buildings of a Mediterranean historic district, taking occupants' behaviour into account. Our results will also establish the extent to which the quality of the indoor conditions is due to the physical characteristics of the building or to the use that people make of its construction elements and installations. The case studies selected are four dwellings within listed buildings of the *Conservation Area* of Seville, Andalusia, in southern Spain. Three of these had previously been analysed by the authors under the severe hot summer conditions characteristic of the region [25], using the same method as in this work, based on monitoring, compiling qualitative information, in-situ inspections and tests, and dynamic simulation. This study aims to extend this summer analysis to the winter season of the same year, so that the results can contribute to the design of retrofit strategies based on real performance data. The mild winters of the city of Seville have generally caused winter-related energy retrofit actions to be disregarded or ruled out. The most commonly used energy source is the electricity from the public grid [26]. As a result, the vast majority of the existing housing, historic or not, is highly pollutant and out of compliance with the current national regulation about CO_2 emissions. Under normal weather conditions, Spanish dwellings located in the Mediterranean region require mechanical air conditioning and 86 % of them are equipped with mechanical heating systems [26]. However, both in summer and winter, the dwellings are usually conditioned only locally and partially, room by room, and air conditioning tends to be installed in only some rooms. In the case of low-income housing, these systems are not often encountered or are simply not used. Extensive research currently focuses on this energy poverty related problem [27], especially on winter conditions in southern Europe: Cyprus [10], Greece [9], Italy [28], Portugal [29,30] and Spain: [31], [32]. Since these studies examine social housing stock under different constructive and socio-economic conditions, their conclusions cannot be extrapolated to the heterogeneous historic residential building stock.

With few recent exceptions [33], little research has been produced combining the winter conditions and the particularities of the residential listed buildings under a no-fuel-poverty scenario. Energy analyses of historic housing that take occupant behaviour into account, like the one presented here, are almost inexistent. More extensive reliable empirical data on the indoor conditions of historic housing should be produced in order to design retrofit strategies which do not jeopardize the conservation of large urban areas rich in residential heritage. This study is intended to help meet this need.

3. Materials and methods.

The method used for this research is of general application for the evaluation of energy performance and indoor environments of buildings. While for many historic buildings, with exceptionally high spaces and/or large indoor air volumes, this method should be adapted, it is well suited to historic housing with common geometric and constructive features, as those presented here. It consists of:

1. Selection of case studies dwellings, data collection and user pattern analysis.
2. IEQ assessment.
3. Generation, simulation, and adjustment of the energy model of each dwelling.
4. EP analysis.

Despite its previous widespread application to social housing in the same Mediterranean climate region [32–34], its use in studies on historic housing has been very limited thus far. This is due to the fact that the research field of energy retrofit of heritage buildings has traditionally been restricted to materials and technical measures, while other user-driven energy parameters, included in this methodology, have often been neglected.

3.1. Selection of case studies.

As the method for selecting the dwellings has been fully described recently [25], only a brief summary is presented here.

The chosen city, Seville, in the south of Spain within the Mediterranean climate area, is one of the richest European cities in terms of built heritage, mostly composed of residential buildings. This makes it a suitable city for the purpose of this research. Since 2005 a Special Protection Plan has protected the historic buildings within its *Conservation Area*, regulating their transformations. It classifies the listed stock in four grades of protection (A, B, C and D). Grades A and B are made up of catalogued monuments of outstanding value protected by very strict rules. C-grade applies to buildings of typological interest while D-grade to those with no recognisable typological values but which contribute to preserve the historic landscape, maintaining the urban identity. C-listed buildings are typologically classified in several groups, of which three types, “Casa de pisos” (PI) (meaning block of flats), “Casa patio” (PA) and “Corral de vecinos” (CV) together account for the majority of total listed stock. C and D listed buildings are the most abundant and correspond mainly to housing. Specifically, D-listed buildings are those for which the room for transformation is greatest.

The local protection policy for the *Conservation Area* of Seville allows specific types of transformations depending on the listing grade of each building, as long as the physical integrity of a series of elements is preserved. A summary of types of work allowed and which elements are protected for C and D listed buildings is presented in Table 1. According to it, the façades cannot be thermally insulated on the outside. The protection of carpentries hinders the substitution of the originals for new more efficient ones, although for the majority of cases, where those are not of outstanding value, in practice, this substitution is often allowed by the local authorities. Apart from these rules, protecting the buildings themselves, other restrictions related to the landscape protection (visual pollution) also apply: the Andalusian regional law on heritage conservation [35] compels the municipalities with heritage assets registered in the *General Catalogue of Andalusian Historic*

Heritage (as is the case of the *Conservation Area* of Seville) to enforce control measures regarding "permanent or temporary installations whose high, volume or distance may disturb the perception of the asset" and specifically "installations related to the energy supply, generation and consumption". Thus, although it is not explicitly prohibited, the installation of solar renewable energy sources or some other high-efficiency systems in buildings (listed or not) of the historic centre of Seville, is complicated.

Table 1
Local protection policy in *Conservation Area* of Seville for buildings listed under C and D grades.

Allowed interventions	Listing grade
Conservation	C, D
Enlargement works respecting all alignments	C, D
Coplanar enlargement works according to height regulation	D
Elements protected	
Main spatial configuration	C, D
Façade and façade bay	C, D
Roof typology	C, D
Spatial configuration of the group: entrance-stairs-patio	C
Plan configuration of patios	C
Main beams span	C
Original façade colour and materials	C, D
Ornamental façade elements	C, D
Cornices (form and position)	C, D
Size and form of façade openings	C, D
Mouldings of windows and doors	C, D
Carpentry	C, D
Locksmith's crafts	C, D

Four dwellings within listed buildings were selected as representative of the *Conservation Area* of Seville based on the threefold criteria of listing grade, typology, and user pattern diversity. These criteria were considered relevant because of their direct impact on the energy performance of buildings: listing grades can restrict the type of intervention when buildings are renovated; typology is related to geometry, compactness and use; and occupants' behaviour is widely recognized as one of more influential factors in the energy performance of buildings. Their general suitability for the project objectives and residents' willingness to cooperate were also taken into consideration in the selection process.

Three out of the four dwellings presented here (Cases 1, 2 and 3) were analysed under summer conditions, as mentioned in the Introduction [25]. Case 1 is a first floor apartment in a C-listed building, typologically classified as PI. Case 2 is a duplex located in the top floor of a D-listed building, classified as PI. Case 3 is a top floor apartment in a C-listed building, classified as CV. A fourth case study (Case 4), also catalogued under the most common typology (PI) and grade of protection (C), has been added to this research in order to provide greater diversity to the sample as regards household composition, given its major influence on the energy requirements of homes [24]: unlike Cases 1, 2 and 3, with no children, Case 4 is an apartment occupied by a couple and a 7-year-old child. The main characteristics of the selected dwellings are summarized in Table 4 of Section 4.1.

3.2. Data collection.

The energy-related parameters of buildings can be grouped into five categories: climate, form, fabric, equipment, and program. *Climate* refers to weather conditions of the specific location; *form* to geometric factors; *fabric* to the constructive characteristics of the building elements and their state of repair; *equipment* to technical characteristics of mechanical systems and appliances and their operating conditions; and *program* is related to occupant behaviour. Of the monitored variables, climate data (OAT, ORH, average wind speed and direction) was used as input of the energy models. The IAT data was used to adjust the energy models (see Section 3.5) and to analyse thermal comfort. CO_2 concentration and IRH data, in combination with IAT, were used to evaluate the indoor air quality of each dwelling. Figure 1 includes additional information (methods, equipment, ranges and applications).

	Method/period	Equipment	Data	Range /Accuracy	Application	
CLIMATE	Continuous monitoring / 2017	AEMET Weather station [35], 1-minute intervals	OAT (°C)	-30 °C to 70 °C / ±0,1 °C	Energy model simulation	
			ORH (%)	0-100% / ±3%		
			Average wind speed (km/h) and direction (º)	0-50 m/s / ±1 m/s a <5 m/s, 360º		
	Various one-off measurements next the buildings / 2017	Thermohygrometer PCE-444	OAT (°C)	-20 °C to 70°C / ±1°C		
			ORH (%)	0-100% / ±3,0 % (45-75%), ±4,5 % (<45%, >75%)		
FORM	Cadastre open data base [36] On-site drawings /2017		Plots map, buildings plans. Usable surfaces, ceiling heights, opening location and size.		Energy model simulation	
FABRIC	In-situ examinations and measurements. Consultation of scientific and regulatory literature /2017		Thermal transmittance (U) of the envelope elements: walls, roofs, windows (W/m^{2}K)		Energy model simulation	
	In-situ inspections of rooms / 2017		State of repair of roofs, walls, floors, plumbing... Operation conditions of windows, blinds and vents.			
	Depressurization and pressurization tests / Autum and spring 2017	Blower Door in compliance with EN-13829 [41].	Air change rate at 50 Pa (h^{-1})	1% or 0,5 Pa / -1,25 to 1,25 Pa		
EQUIPMENT	In-situ inspections / 2017		Technical characteristics of air-conditioning systems and appliances: type, make and model, input electrical power, efficiency coefficients EER and COP.		Energy model simulation	
PROGRAM	Mixed-mode / (1) July-August and December 2017, January 2018 / (2) Throughout year 2017	(1) WOHLER CDL 210 data-logger (2 per dwelling, Lr and Br) measuring at 30-minutes intervals	Indoor CO$_2$ concentration (ppm)	0-9000 ppm / 50 ppm	Deduction of presence hours, NV cycles, IAQ evaluation	Definition of user profile to be introduced in the energy model
			IRH (%)	5% to 95% / ±5%	Deduction of NV cycles, IAQ evaluation	
			IAT (°C)	-10 °C to 60 °C / ±0.6 °C	Deduction of NV and heating operation cycles, thermal comfort evaluation, energy model adjustment.	
		(2) Interviews, questionnaire.	Presence (occupancy density and duration)			
			NV habits			
			Heating operation			
			Use of rooms			
			Cooking habits			
			Personal preferences on thermal comfort.			
			Electricity bills for 2017 and the two years preceding.			

Fig. 1. Data collection summary: variables, methods, equipment, outputs obtained and their application.

The Blower Door tests were carried out in compliance with EN13829 [36]. They were executed keeping all the internal doors of the dwellings open and mounting the power fan into the frame of the entrance door, before extracting air (depressurization) and introducing air (pressurization). It was controlled from within (Fig. 2). All the windows remained closed and the ventilation ducts were sealed. For the constructive characterization of walls and roofs, the existing scientific literature on the constructive features of Seville residential buildings dating from the 18th, 19th and early 20th centuries [37] was consulted and contrasted with the in-situ inspections and measurements. With the information gathered, the Thermal Transmittance (U) of the constructive elements was calculated in W/m^{2}K following the Spanish energy code (CTE DB HE) method [38] which is based on the characterization for materials in UNE EN ISO 6946.

Fig. 2. Blower Door test development in Case 4 dwelling. The photograph is taken from the inside.

3.3. User pattern analysis.

As factors related to occupant behaviour decisively affect real energy use and IAQ and contribute to uncertainty of building EP [39], especially when it comes to residential buildings where is a greater, almost infinite, variety of use patterns and each may have random variations over time [40], compiling detailed data on occupant behaviour profiles of the dwellings was deemed vital. This research obtained this knowledge using a Mixed Mode approach [41] which integrates qualitative and quantitative data. Qualitative information was gathered through interviews and a structured written questionnaire was also handed out to all residents by specialized personnel, as shown in Fig. 1. It touched upon aspects such as number, age and average daily presence hours (weekdays and weekends) of residents, daily routines in the use of rooms and preferred level of clothing indoors, NV habits, usage profile of the existing appliances and technical systems (preferred schedule, average hours of daily use, usual set-points temperature). Quantitative data, obtained empirically by monitoring the environmental parameters mentioned above, was used to check that subjective information: measured indoor CO_2 concentration rates were studied to establish actual presence hours; and analysed in combination with OAT, IAT and IRH rates to deduce NV periods; sharp changes in measured IAT were considered to infer heating operation. In order to define the four occupant behaviour profiles to be introduced into the energy models, all this qualitative and quantitative information was contrasted for each dwelling. A sample weekday was chosen for a more detailed description of hourly practices in occupancy, NV and heating operation, based on the monitoring data (see Section 4.1.5.)

3.4. IEQ assessment.

The evolution of the internal environmental conditions of the four dwellings was analysed in three stages: first, for the complete period of about 30 days (December 2017); second, for an 11-day-long period, which includes weekdays and weekends (264 hours); and third, for a sample weekday. The complete period was used to establish an overview of the general trends of the monitored parameters and the interactions between them. The 11-day-long period, representative of those analysed general trends, was used to calculate average, maximum, and minimum values of the main environmental parameters, summarized in Table 8 of Section 4.1.3, and to assess IAQ and thermal comfort. IAQ evaluations were carried out based on data measured for two parameters: indoor CO_2 concentration and IRH. Admissible rates of indoor CO_2 concentration have been adopted from the “Finnish Classification of Indoor Environment. Target values, design guidance and product requirements” [42] which considers three indoor environment categories: S1 (Best), S2 (Good) and S3 (Acceptable). The monitoring values for IRH were compared to the limit values of two different standards: the European EN 15251 [43] and the Spanish energy code [44]. The first establishes four categories of buildings based on the level of expectation: I (high, for buildings with special requirements), II (normal for new buildings and renovations), III (acceptable, generally used for existing buildings), and IV (limited, only accepted for a limited part of the year). For each category an IRH range is established. The Spanish energy code establishes a single range of admissible values for the general case, applicable to dwellings, where occupants develop a sedentary metabolic activity of 1.2 met, with clothing levels of 0.5 clo in summer and 1 clo in winter, and PPD between 10 and 15 %. IAQ admissible conditions according to these standards are summarized in Table 2.

Table 2
IAQ admissible conditions

CO_2 concentration		**IRH**	
Categories		EN 15251 Categories	
S1	<750 ppm	I	50-30%
S2	<900 ppm	II	60-25%
S3	<1200 ppm	III	70-20%
		IV	>70%, <20%
		CTE DB HE2 (winter)	40-50%

The thermal comfort evaluations were carried out considering the measured IAT rates for the Lr and Br of each dwelling. Adaptive thermal comfort models were considered suitable for application in this research given that the occupants interact freely with the building elements and systems, and that according to the monitoring data, dwellings are heated intermittently. Given the differences observed between the existing models [45], two different ones have been applied to calculate optimal indoor operative temperature (T_{op}) and its upper and lower limit values: the European standard EN 15251 from the CEN/TC 156 [43] and the American Standard 55 from ASHRAE [46]. Both standards were applied under low-demand acceptability ranges, for the protection rules applicable to listed buildings might restrict the range of retrofit measures. Using meteorological data from AEMET [47], the daily evolution of T_{op} lower and upper limits of each model for December 2017 were obtained and compared (see Table 3), showing that the difference between daily T_{op} lower limits is about 1 °C on average, a small difference which nonetheless causes significant disparities in the thermal comfort results, as described in Section 4.3.

Table 3
Adaptive thermal comfort models. Ranges and T_{op} values for December 2017

	Range			T_{op} values for December 2017		
	Applicable T_o	Acceptability	T_{op} Interval	Average T_{op}	Maximum T_{op}	Minimum T_{op}
Standard 55	10-33,5 °C	80% satisfied occupants	±3,5 °C	21,6 °C	23,5 °C	21,1 °C
EN 15251	10-30 °C	Category III (moderate level of expectation)	±4 °C	22,8 °C	24,9 °C	22,3 °C

Based on the two series of lower limits of daily T_{op} for December 2017 two comfort indexes were calculated for the Lr and Br of the four dwellings:

(a) Percentage of occupied hours of discomfort (%). It measures the number of occupied hours in which the IATs measured are below the lower comfort limit and thus heating would be needed. Occupancy hours was considered under two different profiles: the first is a night-day profile which contemplates a night-time occupancy for the Br (24-7 h, with no occupancy in the Lr) and a day-time occupancy for the Lr (7–23 h, with no occupancy in the Br), both adjusted to the specifics occupant behaviour profiles defined with the Mixed Mode approach previously described. No distinction between weekdays and weekends was considered. The second profile (24 h profile) was that established by CTE DB HE [48] which considers a continuous thermal load in all the rooms.

(b) Average deviation of the measured IATs in relation to the daily T_{op} (℃). This quantifies the magnitude of the discomfort, identifying how far, on average, the actual IATs deviates from the lower comfort limit during the period analysed.

The thermal condition of the dwellings was also represented in *temperature clouds*, plotting the hourly IAT and the simultaneous OAT measured against each other "to illustrate how the indoor temperature of the particular room responds to the local climate through the physics of the construction of the building itself, the behaviours of its occupants, and their use of mechanical services and passive systems" [49].

3.5. Generation, simulation and adjustment of energy models.

The dynamic simulation tool used for this research was Design Builder (v.4.7.0.027), which employs the calculation engine Energy Plus [50] recognized by the US Department of Energy. The input data required for the simulation was obtained according to the method described in Section 3.2. Once the energy models were generated, they were adjusted to ensure their precision. There are no common criteria on how to adjust energy models [51], [52]: this can be done manually, in an iterative process of fine-tuning model inputs and recomposing the results to measure data, a procedure employed in this investigation; or through automated procedures. The output of several parameters can be used for model adjustment, although the most commonly used are energy consumption (kWh), IAT (℃), and IHR (%). Since this research focuses on thermal comfort and EP of dwellings with an occasional use of mechanical conditioning systems, the output considered for calibration was the IATs of the rooms monitored. The first comparison was graphic: for the 11-day-long period, simulated and measured IAT rates were matched iteratively by manually adjusting the variables with the highest degree of uncertainty, such as occupants' metabolic rates, window shutter operation, and air changes per hour during NV cycles. A measurement error of ±0.6 ℃ was considered. This was followed by the statistical comparison following the U.S. Department of Energy M&V Guidelines [53] which uses two indices for the quantification of the error, Mean Bias Error (MBE) and Coefficient of variation of the Root Mean Square Error (CvRMSE):

$$\text{MBE (\%)} = \frac{\sum_{i=1}^{Ni}(Mi - Si)}{\sum_{i=1}^{Ni} Mi} \times 100 \tag{1}$$

$$\text{CvRMSE (\%)} = \frac{RMSE}{\frac{1}{Ni}\sum_{i=1}^{Ni} Mi} \times 100 \tag{2}$$

$$\text{RMSE}=\sqrt{\sum_{i=1}^{Ni}\frac{(Mi-Si)^2}{Ni}} \qquad (3)$$

where: M_i is the measured data at instance n, S_i is the simulated data at instance n, N_i is the number of records used in the calibration, and RMSE is the Root Mean Square Error. The model is considered to be calibrated when MBE hourly values fall within ±10% and CvRMSE falls below 30%.

3.6. EP analysis.

Once the energy models were adjusted, the outputs on thermal loads were organized in two groups: user-driven and building-driven, in order to quantify the occupant's contribution to the overall energy balance and to organize and prioritize intervention strategies. User-driven thermal loads are those strictly dependant on actions carried out by the resident: presence, use of electrical appliances and devices, lighting, heating, NV, and window shading. Building-driven thermal loads are those that are dependent only on the physical condition of the envelope elements, such as air leakage, walls, glazing, roofs and slabs. Since protection rules restrict the room for improvement of some of these elements, the contribution to the overall heat losses was calculated for each of them. This was made using the Design Builder simulation tool, which can measure the heat flow at surface boundaries and attribute a thermal load to the space derived from each constructive element: walls (including air leakage), glazing, roofs and internal partitions. In addition, we analysed the dynamic interaction of these envelope elements with IEQ factors (thermal comfort, CO_2 concentration and IRH) as they have a direct impact on the residents' health and on the proper conservation of the buildings (Sections 4.4. and 5.4.).

4. Results.

4.1. Results of the data collection and the user pattern analysis.

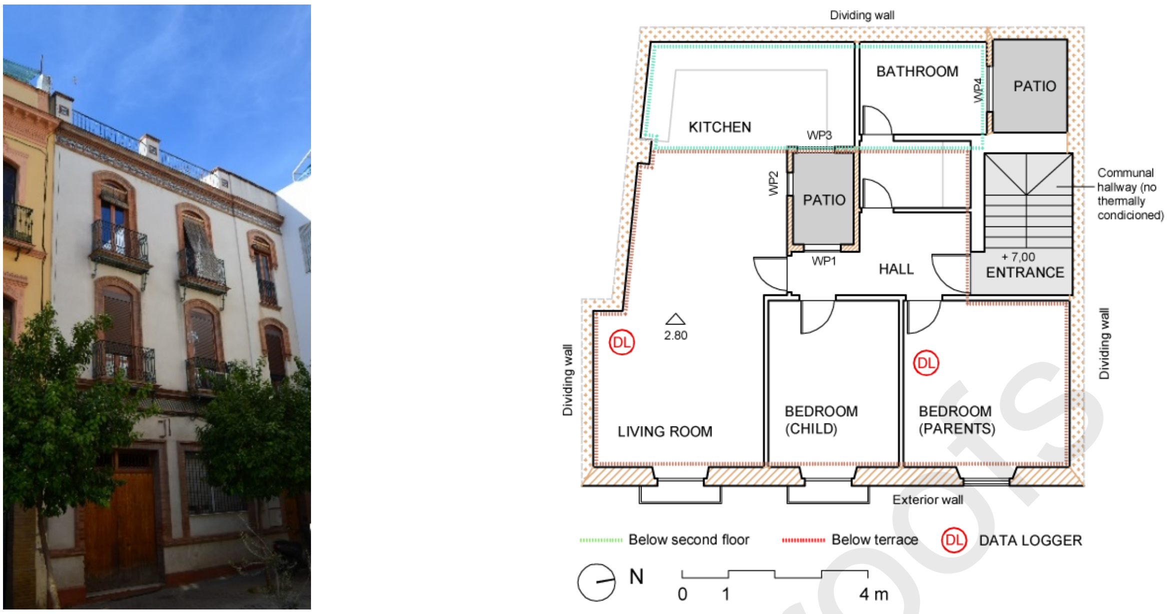
4.1.1. Description of case studies.

Cases 1, 2 and 3 were described in detail in a publication by the same authors [25], mentioned previously, and are also summarized here in Table 4, where the general characteristics of the four case studies are shown. Exterior views of Cases 1, 2 and 3 are also included here in Fig. 3.

Fig. 3. Exterior views of Case 1 (a), Case 2 (b) and Case 3 (c). Communal patio of Case 3 (d).

Case 4 is a duplex apartment facing east within a “Casa de Pisos” building dating from the late 19th century. Its second floor, containing a studio and a private terrace, is located at the top of the building. The first floor has a usable surface of 73 m^2, including Lr and kitchen in the same space, as well as a bathroom and two Brs. Two small patios facilitate natural cross ventilation. The apartment was renovated recently. The old windows in the façade were replaced by new aluminium and wood joinery ones, with thermal break, and double glazing with solar control. The traditional external rolling shutters were preserved. The sliding single-glazed aluminium windows to the patio, with no thermal break, were not replaced or improved and none of them have shading systems. Thermal insulation of extruded polystyrene (80 mm sheets) was placed in the roof above the whole dwelling surface, except for the child’s bedroom area. Exterior view of Case 4 building is shown in Fig. 4a) and drawing plan of the apartment in Fig. 4b).

The constructive and thermal characteristics of the four building envelopes are summarized in Table 5. Table 6 shows the technical systems existing in the four dwellings: all were equipped with mechanical vents located in bathroom ceilings. However, these did not work properly in any of the cases, and in Cases 2 and 3 the ducts had been blinded. Kitchen smoke extraction systems were only installed and working well in Cases 1 and 3. Annual non-renewable primary energy consumption in kWh/m^2 was calculated for the four dwellings, based on the collected electricity bills, and then compared to the current CTE DB HE upper limit, showing that all the cases fall short of compliance (Fig. 5).



a) b)

Fig. 4. Case 4: street view of the building (a) and floor plan (b), with the position of the data loggers during the monitoring campaign marked in red.

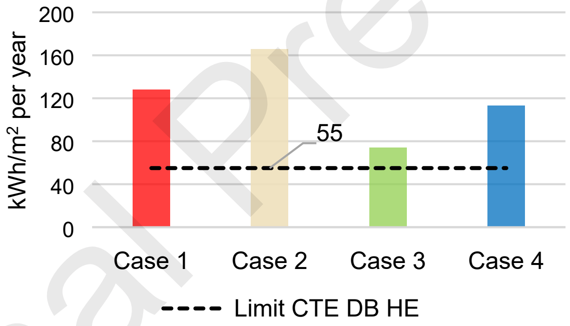


Fig. 5. Annual non-renewable primary energy consumption of the four dwellings compared to the current limit.

Table 4
Case studies general characteristics

		Case 1	**Case 2**	**Case 3**	**Case 4**
Selection criteria	Historic typology	PI	PI	CV	PI
	Listing grade	C	D	C	C
	User pattern	Retired single (UP1)	Two working adults without kids (UP2)	Single working adult (UP3)	Two working adults with 1 or 2 kids (UP4)
Age	Construction date	1923	1940	XVIII century	XVIII century
	Refurbishment dates	1967, 2004	1960	1992	2010
Geometry	Number of storeys of the building (*)	GF+4+A	GF+3+A	2+A	3+A
	Level position in the building	1	3	A	3
	Façade solar orientation	South	East	South	East
	Usable floor area (m^2)	41	65	35	73
	Compactness (m^3/m^2) (**)	3,8	3,3	1,3	1,7
Energy	Energy supply source	Public electricity grid			
	Average annual electricity consumption (kWh)	2452	5375	1327	4044
	Percentage of average annual electricity consumption produced in the winter months (Nov-Feb)	32%	54%	35%	40%

(*) GF: ground floor (comercial), A: Attic
(**) Total volume to outer surface ratio

Table 5
Case studies' envelope constructive and thermal characteristics.

	Case 1	**Case 2**	**Case 3**	**Case 4**
Walls. Façades.				
Thickness (cm)/ U (W/m^2K)	60/0,60	40/1,56	27/2,26	40/1,40
Composition (outer-inner)	Facing solid brick (24 cm) Air chamber (5 cm) Solid brick (24 cm) Plaster and paint (2cm) XPS (3 cm) and insulating gypsum plaster (1,5 cm)	Facing solid brick (24 cm) Air chamber (2 cm) Solid brick (12 cm) Plaster and paint (2cm)	Plaster and paint (2 cm) Solid brick (12 cm) Air chamber (3 cm) Perforated brick (8 cm) Plaster and paint (2 cm)	Plaster and paint (2 cm) Solid brick (24 cm) Solid brick (12 cm) Plaster and paint (2 cm)
Walls. Patios				
Thickness (cm)/ U (W/m^2K)	27/1,14	-	14/2,26	14/2,87
Windows				
U windows (Façade/Patio) (W/m^2K)(*)	2,96/5,80	3,76/5,80	6,96/5,80	2,56/5,80
U glazing (W/m^2K) (Façade/Patio)	3,23/5,78	3,23/5,78	5,78/5,78	1,40/5,78
U joinery (W/m^2K) (Façade/Patio)	1,90/5,88	5,88/5,88	1,90/5,88	1,8/5,88
Joinery type. Façades (all folding) (**)	Wood. No TBB	Aluminium. No TBB	Wood. No TBB	Aluminium. TBB
Glazing type. Façades	Double clear 3/6/3 mm (air)	Double clear 3/6/3 mm (air)	Single clear 6 mm	Double 4+4SC/12/6+6SC (air)
Glazing type. Patios	Single clear 6 mm	Single clear 6 mm	Single clear 6 mm	Single clear 4 mm
Window shading (Façade/Patio)	Interior opaque wooden shutters / Aluminium rolling shutters	Interior opaque aluminium shutters/-	Interior opaque wooden shutters/-	Exterior wooden blinds, interior opaque curtains/-
Roofs				
U (W/m^2K)	-	3,1/2,63	3,10	0,37/2,60 (***)
Type of roof (building)	Rooftop terrace	Rooftop terrace/ arabic-tile gable roof	Flat roof	Rooftop terrace
Roof composition (outer-inner)	Tiles (double leaf with mortar) Mortar Asphalt sheet Slab	Arabic tiles Mortar Asphalt sheet Mortar Roof structure	Tiles (double leaf with mortar) Mortar Asphalt sheet Slab	Tiles (double leaf with mortar) Mortar (4 cm) Extruded polystyrene (8 cm) Mortar (2 cm) Asphalt double sheet Mortar (1 cm) Aerated concrete (5 cm) + vapour barrier Slab
Air leakage rate at 50 Pa: n50 (h^{-1})	15,71	7,14	7,71	3,76

(*) Combined joinery and glazing
(**) All joineries of the patio openings are sliding and made of aluminium without TBB.
(***) Part of the flat roof with thermal insulation/ without thermal insulation

Table 6
Technical systems.

	Case 1	**Case 2**	**Case 3**	**Case 4**
Ventilation	Natural through windows			
	Kitchen: smoke extractor	Kitchen: none	Kitchen: smoke extractor	Kitchen: none
	Bathroom: vent in ceiling (blinded or not working)			
Domestic hot water	Electric hot water boiler			
Heating	Centralized COP= 2.70 (outlets to Lr and Br)	Convection heater in first-floor Br	Heat pump in Lr (COP = 2.50)	Centralized COP = 4.0 (outlets to Lr, child Br)
	Portable electric oil-radiator (1800 W, usually in Lr)		Portable electric oil-radiator (2000 W usually in Br)	Portable electric oil-radiator (2000 W, in kitchen or parent's Br)

4.1.2. Climatic data

Seville (Latitude: 37° 25' 0'' N, Longitude: 5° 52' 45'' W, Altitude: 34 m), included in zone B4 of the Spanish climatic zoning [48], has a warm temperate climate with hot and dry summers and rainy mild winters. According to the historic data from AEMET [47], the coldest months are January and December, with average monthly temperatures of 11 ℃ and 12 ℃ and average minimum daily temperatures of 6 ℃ and 7 ℃ respectively. During December 2017, when the monitoring campaign was conducted, the average monthly outdoor temperature was within the normal range (11.5 °C) while the average minimum daily temperature was unusually low (3.3 ℃). Historic climate characteristics of Seville are summarized in Table 7.

Table 7
Annual average climate values for Seville (1981-2010)

Daily temperature (°C)	19,2
Maximum daily temperature (°C)	25,4
Minimum daily temperature (°C)	13
Daily precipitation (mm)	539
Relative humidity (%)	59
Hours of sunlight	243
Direct solar radiation (kWh/m^2)	153

4.1.3. Hygrothermal conditions.

The monitoring results in Table 8, referred to the 11-day-long period, indicate that average IATs of Case 1 and 4 are in the comfort range, above the lower limits of adaptive models Standard 55 and EN 1521 (for December 2017 they are 17.6 ℃ and 18.3 ℃ respectively). In both cases temperature fluctuations are between 3 and 4 ℃, indicating a regular use of the heating system. In contrast, the average IATs for Cases 2 and 3 are too low, showing that heating operation is not as frequent and continuous as stated in the surveys or that the capacity of the mechanical systems is insufficient to maintain comfort conditions. Case 3 appears to respond to the first hypothesis, as the minimums are extremely low, while Case 2 seems to fit the second, as the thermal oscillations are greater with maximums above the comfort level and minimums well below. This is graphically represented in Fig. 6, depicting hourly evolution of OAT and IAT for the Lr and Br of the four dwellings during the typical period. These graphs show the large differences in heating operation patterns that were deduced from Table 8 calculations: from the total lack of use in Case 3, to the extended use in Case 4, leading to extremely dissimilar thermal environments. In addition, the thermal stability of Case 1 is remarkable, with heating patterns similar to those of Case 2, where on average IATs remain 2 ℃ lower.

Table 8
Measured rates of the environmental parameters for the four case studies during the 11-day-long period.

Outdoor	**Case 1**		**Case 2**		**Case 3**		**Case 4**	
Max OAT (ºC)	19		20		19		19	
Min OAT (ºC)	4		5		4		4	
Max RH (%)	95		94		94		94	
Min RH (%)	38		46		35		35	
Indoor	Lr	Br	Lr	Br	Lr	Br	Lr	Br
Temperature (ºC)								
Average	19	19	17	17	14	15	20	20
Maximum	22	22	23	22	16	17	24	23
Minimum	18	18	14	16	13	13	17	17
CO_2 concentration (ppm)								
Average	655	669	743	777	649	715	702	782
Maximum	1123	1123	2075	2107	1916	2082	1389	2271
Minimum	419	430	475	519	404	408	397	402
Relative humidity (%)								
Average	48	51	59	60	57	58	53	53
Maximum	61	63	69	77	90	92	63	64
Minimum	38	37	47	48	36	38	42	36
% occupied hours of heating use	57%		40%		0%		83%	

Table 8 also show that average CO_2 concentration is slightly high for the four dwellings, probably due to the short duration of the NV cycles which is commonly adopted in winter to avoid heat losses. The significant differences between maximums and minimums for this parameter, common to all cases, proves the alternating use of the rooms, frequent in these small low-occupancy dwellings. Regarding IRH, Cases 2 and 3 show excessively high average rates and fluctuations in Case 3 dwelling are remarkable, as it seems to run in parallel to the outdoor ones.

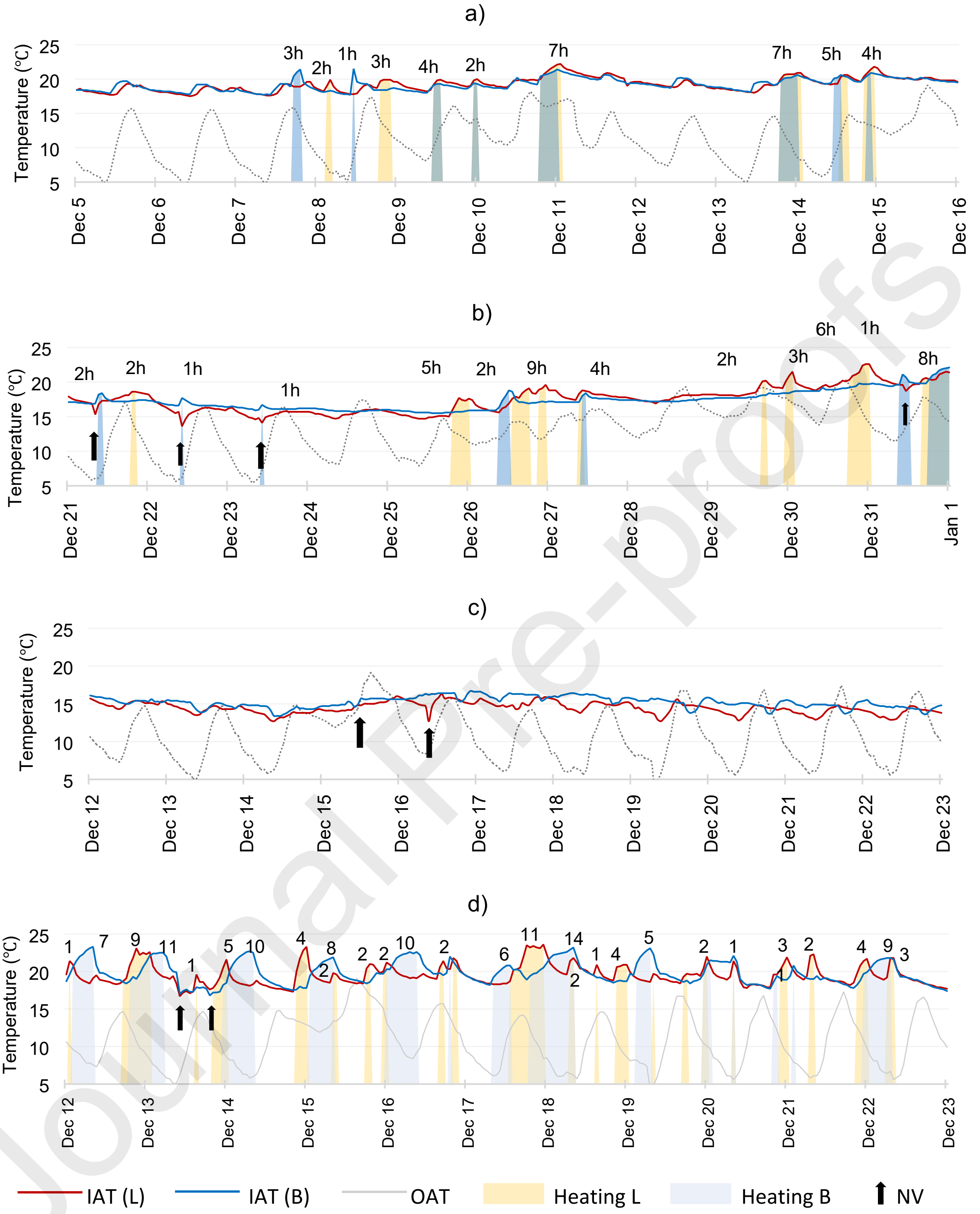


Fig. 6. Hourly IAT evolution in the typical time period for the four case studies: (a) Case 1, (b) Case 2, (c) Case 3, and (d) Case 4. Heating cycles are coloured and duration is indicated in black digits. The NV cycles are highlighted using black arrows.

4.1.4. Airtightness test.

The results of the Airtightness Test for each case study were included in Table 5 of Section 4.1.1. and are also shown in Table 9. It should be noted that the results of the Blower Door Tests were very different for Case 1 (15.71 h^{-1}) and Case 4 (3.76 h^{-1}), while both Cases 2 and 3 are in the average for southern Europe [54]. Significant dispersion of airtightness values has been experimentally proven by Fernández-Agüera et al. [54] in Andalusia building stock. The divergences are particularly noticeable in the older buildings because of the variety of construction habits and the state of conservation and repair. In order to establish the extent to which the four dwellings are in compliance with the current regulation CTE DB HE, regarding air permeability of the envelope, the values measured were benchmarked against its upper limits. They were also compared to data obtained in two field tests carried out in the same climatic conditions [54], [55]. As shown in Table 9, despite its low Compactness Index (CI=1.7) Case 4 is a remarkably airtight dwelling, 1.6 times over the current regulation upper limit. This could be due to the recent replacement of the original wooden window frames of the façade with new aluminium ones. Case 1 is the least airtight dwelling, despite being very compact (CI=3.8). This may be explained by the existence of some unnoticed hole or crack likely hidden by the plaster ceiling which was not identified clearly in the monitoring campaign. Cases 2 and 3 are in line with the average of the experimentally measured sample of social housing constructed between 1950-2010 (field test b) in the same climatic zone by J. Fernández-Agüera et al. [54].

Table 9
Air tightness of the envelope. Comparison between measured, normative and experimetal values.

			Case 1	**Case 2**	**Case 3**	**Case 4**
		Compactness (m^3/m^2)	3,8	3,3	1,3	1,7
		Measured air leakage rate at 50 Pa: n50 (h^{-1})	15,71	7,14	7,71	3,76
		Upper limit CTE DB HE 1 (h^{-1})	2,84	2,45	6	6
Contrast sample	(a) Open gallery buildings constructed between 2004-2011 in Andalusia (45 units) REF 31	Highest	8,7	8,7	8,7	8,7
		Lowest	3,2	3,2	3,2	3,2
		Mean	5,7	5,7	5,7	5,7
	(b) Social housing constructed 1950-2010 in Andalusia (159 units) REF 30	Highest	15,6	15,6	15,6	15,6
		Lowest	2,8	2,8	2,8	2,8
		Mean	7	7	7	7

4.1.5. User pattern.

This section presents descriptions and analyses of the four user practices and routines during winter. According to the qualitative information gathered in the monitoring campaign, Case 1 dwelling is occupied by a single retired person who reported long periods of time of use of the portable electric radiator and a more sporadic use of the central system, below set-point temperatures of about 21-22 ºC. Fig. 7a shows a typical Case 1 weekday: two heating cycles (using the ducted system) were recorded: 11-16 h and 20- 24 h, which managed to raise the IAT to a maximum of 22 ºC. Case 1 dwelling consumed 2452 kW h/year, almost three times less than the average Spanish multi-storey building in the Mediterranean Climate, which is 6386.105 kW h/year per dwelling [26]. Case 2 dwelling is inhabited by two professionals. One works outside the home from 8 to 21 h, while the other works from home with her computer. Based on measured data, a sample weekday for Case 2 is shown in Fig. 7b: Lr remains unoccupied until 15 h, when the heating is switched on for a period of three hours, which managed to raise the IAT to 20 ºC. Case 2 annual electricity consumption is the highest of the four case studies: 5375 kWh/year, just 15% below the national average [26]. Case 3 dwelling is inhabited by a single professional whose work schedule is 8-18h. Her practices of a sample day are shown in Fig. 7c: maximum IATs do not exceed 15 ºC. The scarce heating of the dwelling could explain the extremely low power consumption for Case 3, 1327 kWh/year, which is about half that of Case 1 and six times less than that of Case 2. Case 4 apartment is occupied by a family of three, two working adults and a seven-year-old child. The work schedule of both adults is 9-19 h. Daily routine of Case 4 sample weekday is depicted in Fig. 7d: two heating cycles were recorded: 7-9 h and 21- 24 h, which raised the IAT to maximum of 23℃. The electricity consumption of Case 4 is 4044 kWh/year, and is only surpassed by Case 2. During the four cold months the electricity consumption was 1600 kWh, twice that of Case 1 and more than three times that of Case 3. As shown in Fig. 7, on the sample weekdays, CO_2 concentration rates were almost always below the upper limit of good quality air for both rooms of Cases 1 and 2. In contrast, they were less favourable for Cases 3 and 4, especially during night-time at the bedrooms.

When comparing the qualitative information with the quantitative one (the last referred only to the monitoring data of the 264 hours of the 11 day-long period) some divergences appear (see Fig. 8). Regarding occupancy, the number of hours declared and deduced through monitoring are practically the same for cases 1, 3 and 4, but for Case 2 the registered presence hours are 37% less than those asserted in the survey. Regarding heating operation, significant differences were found between reported and monitored information for Cases 2, 3 and 4, while for Case 1 they almost coincide.

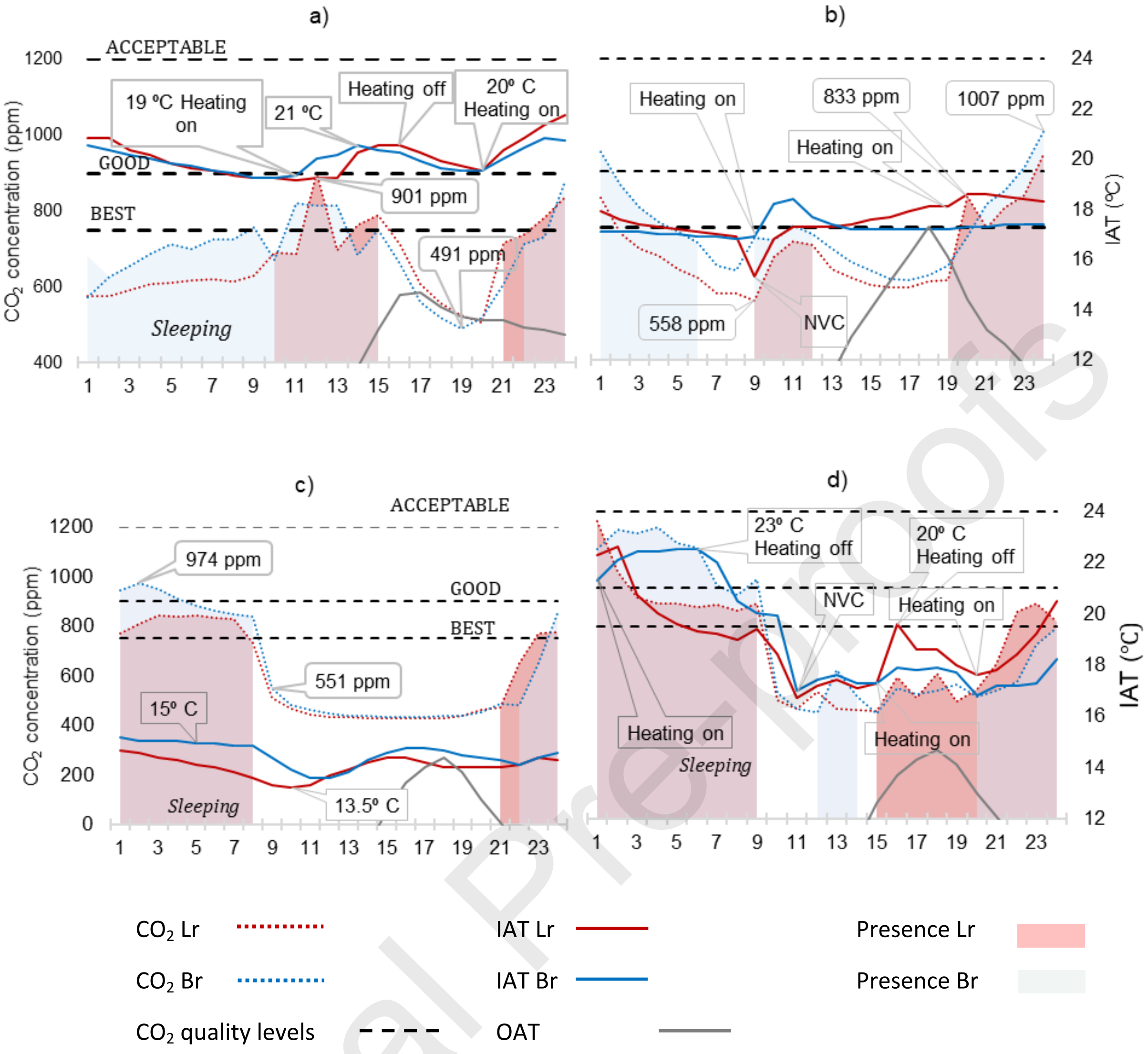


Fig. 7. User pattern on the winter sample day of Case 1 (a), Case 2 (b), Case 3 (c) and Case 4 (d). The occupancy periods are shown in light red (Lr) and light blue (Br). Indoor CO_2 concentration, OAT and IAT evolution throughout the day are shown. Recommended levels of CO_2 concentration are indicated by black dashed lines. NV cycles in Lr and Br are indicated.

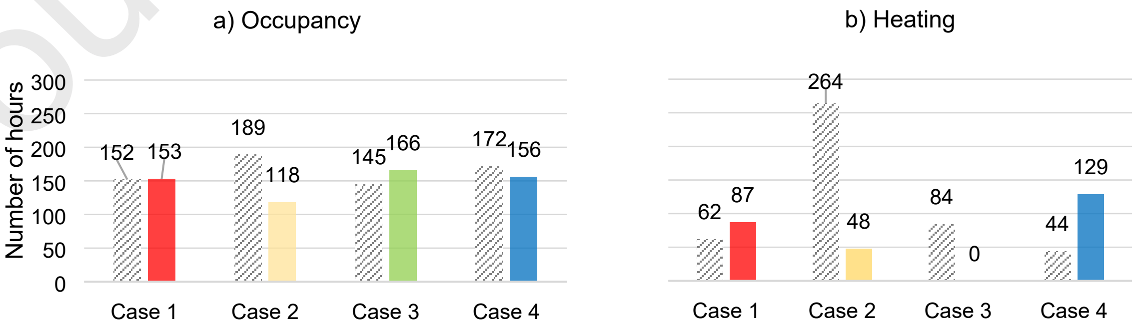


Fig. 8. Divergence between qualitative information obtained in surveys (grey dashed) and objective data deduced through monitoring (bright colours), in hours, during the 11 day-long period. Occupancy is shown on the left (a) and heating operation on the right (b).

4.2. Results of IAQ evaluation.

Only in Case 1 the levels of CO_2 concentration remain within the acceptable range (up to 1200 ppm [42]) for both rooms. Although in Lrs of Cases 2, 3 and 4 the upper limit of 1200 ppm is exceeded only occasionally, their CO_2 concentration in Brs is not as favourable. In view of these results, its distribution during sleeping time were compared to the recommended thresholds. The results are shown in Fig. 9a: the Br of Case 1 performs best while the Br of Case 4 performs worst. The air tightness of the envelopes of Cases 1 and 4 may partially explain both results, since its value for Case 1 is the lowest and for Case 4 is the highest, suggesting that the more permeable the envelope (higher values of n50) the lower the CO_2 concentration in Brs. A similar conclusion was reached in recent studies in the same climate area [56].

The measured rates of IRH in Lr and Br of the four case studies have been compared to the limit values for EN15251 [43] (25%-60% for Category II) and to CTE DB HE2 [44] (40%-50% in winter) (see Table 2). The histogram in Fig. 9b shows the percentage of hours over the typical 11-day-long period in which the IRH (average of Lr and Br) reaches certain levels in each dwelling.

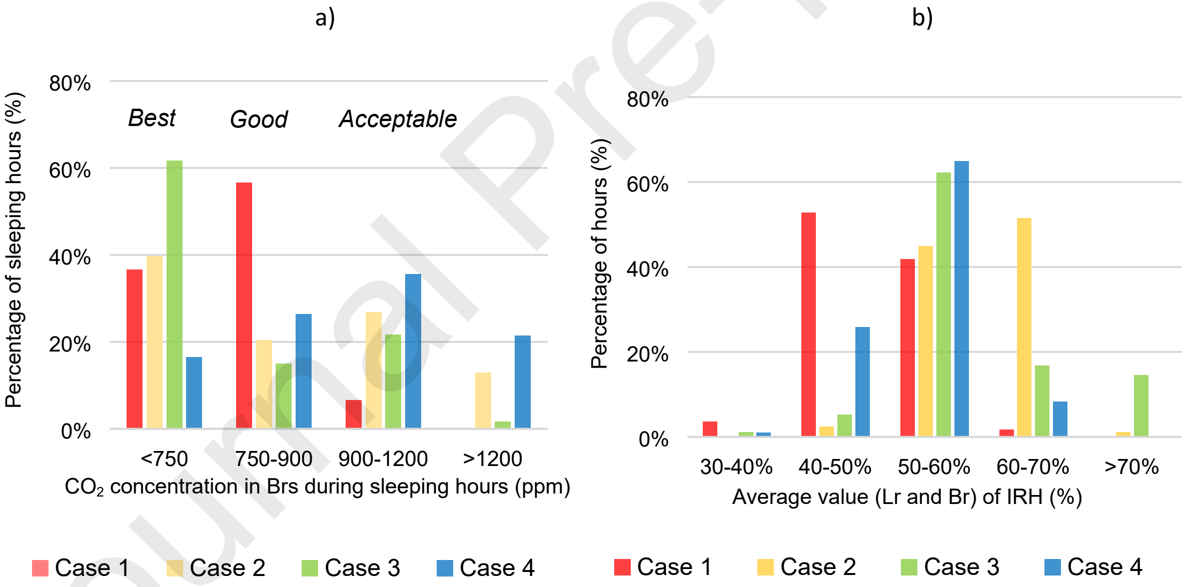


Fig. 9. Comparison of the four case studies over the 11-day-long period. On the left (a), it is shown the percentage of sleeping hours at Brs distributed according to their CO_2 concentration level. On the right (b), it is shown the IRH rates (average of Lr and Br).

4.3. Results of thermal comfort evaluation.

The thermal conditions of the four case studies for the 11 day-long period are graphically represented in *temperature clouds* in Fig. 10. In the same graph, two other pairs of temperature rates have been drawn using black lines: upper and lower T_{op} limits versus OAT, in order to compare the thermal state of the rooms with the comfort limits proposed by the two adaptive models used.

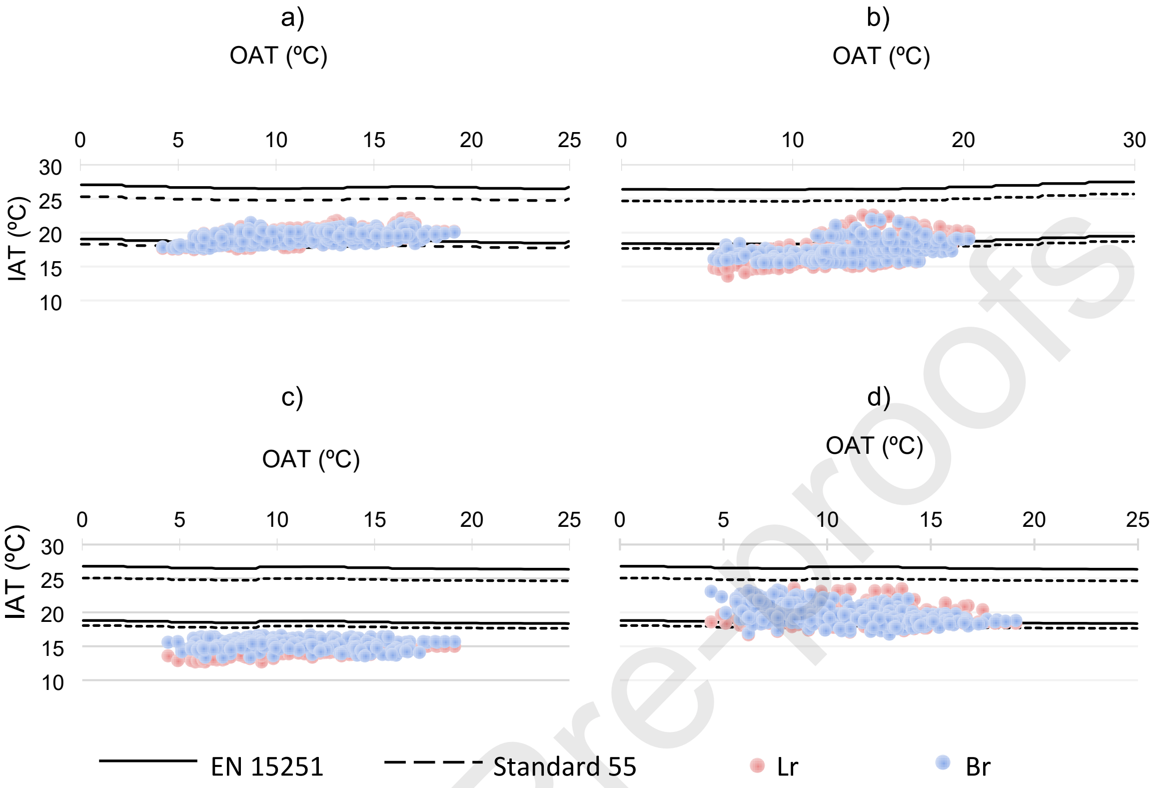


Fig. 10. Comfort-based assessment of monitoring results during the sample period for Lr and Br of all four case studies: (a) Case 1, (b) Case 2, (c) Case 3, and (d) Case 4. Comparison of two adaptive models: EN 15251 and Standard 55.

Both comfort indexes, the percentage of hours of discomfort and the average deviation of IATs in relation to the daily T_{op}, present more unfavourable results under EN 15251 than under Standard 55. Regarding the first index, huge variations between case-studies are recorded, as shown in Fig. 11: Case 3 is always in discomfort while Case 4 is almost always in comfort conditions. It should be noted that despite regular heating in the Br of Case 1, it presents 49% occupied hours of discomfort in the night-time. Case 2 is worse: its Br is uncomfortable for 75% of night-time occupied hours. Regarding the second index measuring the magnitude of the discomfort, IATs deviate from T_{op} 8 ℃ in Lr of Case 3, 5 ℃ in Lr of Case 2 and about 3 ℃ in Lr of Cases 1 and 4 under standard EN15251. Under Standard 55, IATs deviate 7 ℃ in Lr of Case 3, 4 ℃ in Lr of Case 2 and about 2 ℃ in Lr of Cases 1 and 4 (see Supplementary Material SM_2).

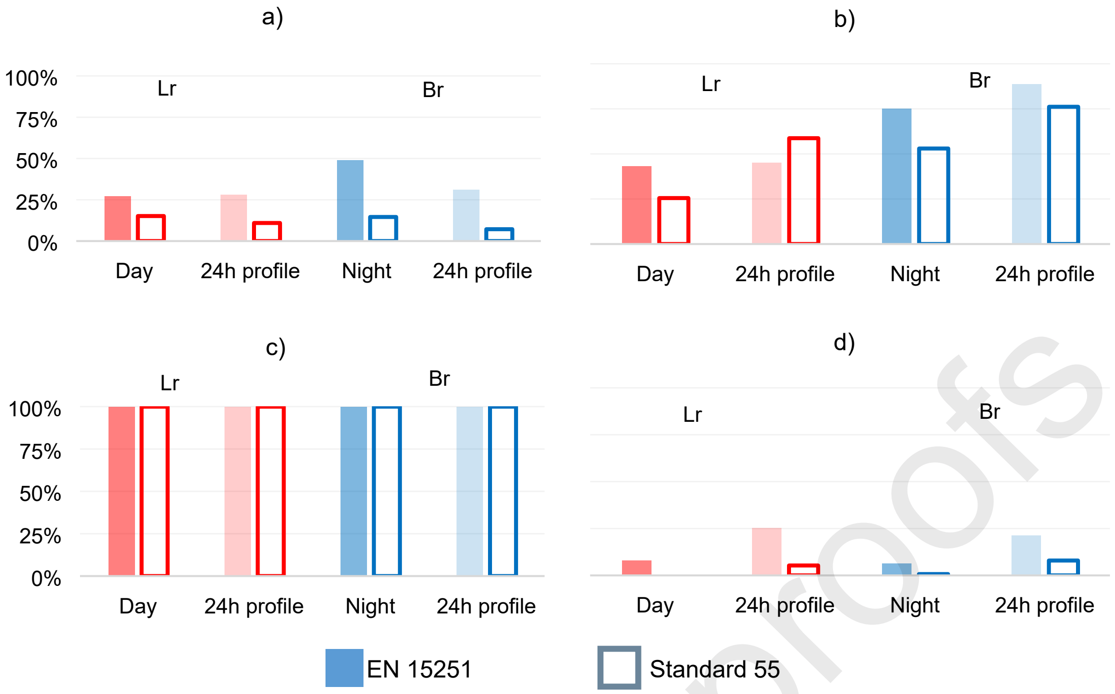


Fig. 11. Percentage of hours of discomfort for Lr and Br of Case 1 (a), Case 2 (b), Case 3 (c) and Case 4 (d), during the typical winter period. Results of applying the two adaptive models and the two occupancy profiles.

4.4. Results of EP analysis.

The simulation results of the adjusted energy models are presented in this section. According to the method described in Section 3.5., a graphical adjustment of the simulated and measured IAT hourly rates were firstly carried out and then, once the graphs met approximately, both series were compared statistically, according to the criteria adopted by M & V Guidelines of U.S. Department of Energy [53]. Results are summarized in Table 10, showing the precise adjustment achieved.

Table 10
Statistical validation of the EMs for winter
(temperatures measured in degrees Celsius).

	MBE		**CvRMSE**	
	Lr	*Br*	*Lr*	*Br*
Case 1	0,2%	0,3%	2,0%	1,9%
Case 2	0,6%	-0,6%	3,5%	2,2%
Case 3	-0,2%	-0,4%	0,1%	2,7%
Case 4	0,3%	0,0%	1,6%	3,4%
Limit [53]	<10%		<30%	

The energy models outputs referred to thermal loads (average of Lr and Br) per surface area during the 11-day-long period are depicted in bar charts in Fig. 12. They have been grouped in user-driven and building-driven loads. The percentage of losses that each constructive element represents of the total was calculated for the four cases (see Section 3.6) and depicted in bar charts in Fig. 13.

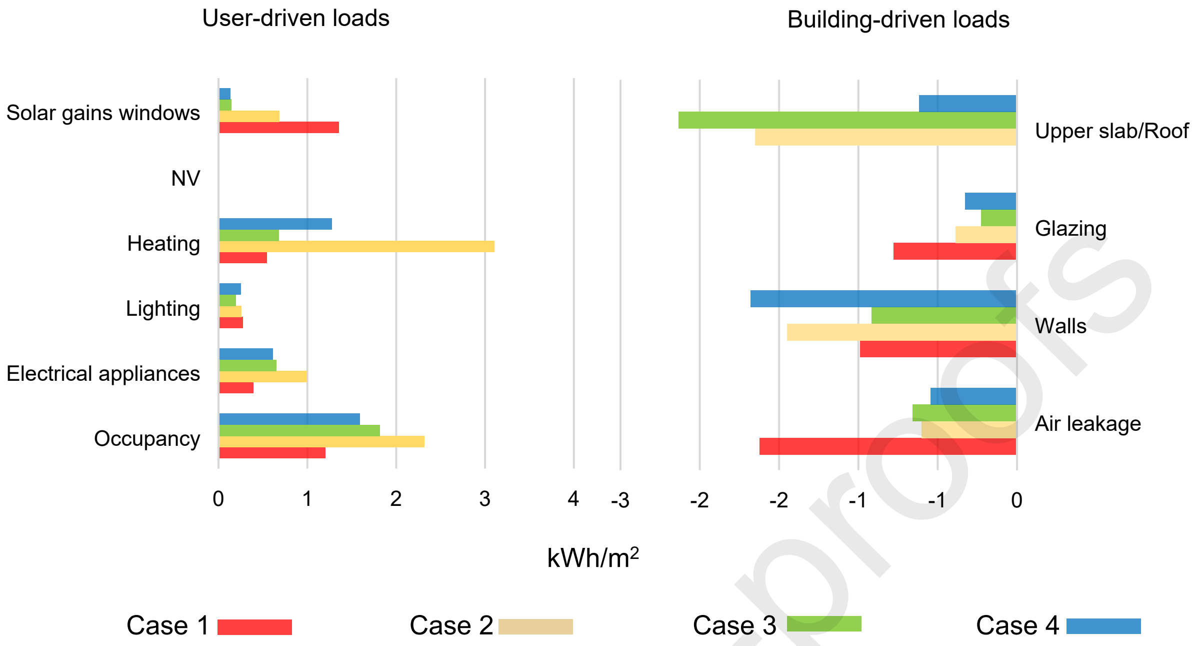


Fig. 12. Heat gains and losses (average of Lr and Br) during the typical winter period, referring to usable surface for the four case studies.

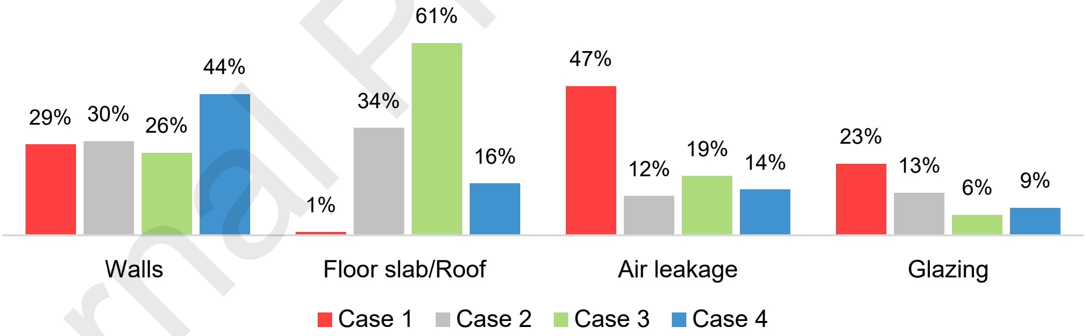


Fig. 13. Distribution of heat losses according to building element for the four case studies. Walls refers to the façades and all other external walls of patios.

5. Discussion.

This study aimed to evaluate the indoor environment and energy performance of dwellings in listed buildings of Mediterranean historic town centres, using Seville, Spain, as a case study. Special attention was paid to the selection of case-study dwellings, in order to enable extrapolation of results to a greater number of cases. Both evaluations were carried out following a procedure that included the actual data collection on the physical parameters most influential in the energy performance of buildings, the Mixed-Mode analysis of the occupant behaviour and the generation and validation of energy models.

5.1. Methods and application.

Although the method proposed here is of general application to common residential buildings, historic or not, as mentioned in Section 3, the diversity of cases, typical of historic cities requires a more painstaking description of constructive and morphological characteristics, as well as of the maintenance and conservation state in which the elements and systems are found. This forces us to inspect the dwellings one by one, recording as much data as possible: mechanical ventilations systems which are not working, window frames, glazing, and blinds which are replaced or repaired only partially, as in Cases 2 and 4, to rather different quality standards, or mechanical heating systems, whose type, capacity, quality, and state of conservation differ significantly from one case to another or even from one room to another. In Case 2, for instance, the poor quality and state of repair of the patio covering was visible in-situ and helped to explain the wide temperature fluctuations in a such a compact dwelling. The in-situ tests, inspections, interviews and monitoring of indoor environmental variables entail an invasion of the privacy of the occupants, who must be willing to collaborate, for about 2 to 4 months a year. Their commitment to the project is crucial to collecting diverse relevant information about their habits and the way they use the systems available. For this research, the Mixed Method approach allowed us to deduce reliable user profiles to be introduced in the energy models, as considerable divergences have been found, mostly between the declared and the actual heating operation, as shown in Fig. 8 of Section 4.1.5. Other numerous user-driven factors, such as accurate use profiles of household appliances, window shading, lighting and NV rates, not analysed in depth in this research, should be further investigated.

To experimentally determine the actual airtightness of the envelope, instead of using standard or statistical values, it was considered essential to reduce the uncertainty of this parameter in the energy models, given the wide variety of unforeseeable circumstances, mostly linked to undocumented interventions on envelopes, which can affect the n50 value of historic buildings.

Despite the existence of reliable predictive models, recent research findings for the Mediterranean region [57] have established that unintentional air entries through hidden cracks or holes, very common in older buildings, can lead to erroneous data assumptions. This has been proven in Case 1 dwelling, where the airtightness test, performed twice in different seasons with the same result, allowed us to deduce some hidden, unnoticed air leakage causing a high n50 value which would never have been assumed or predicted given the favourable compactness and good state of repair of this dwelling. The thermal stability displayed by Case 1 nevertheless led to the assumption that air entry is not from the outside, but from some enclosure inside the building, as already detected in other campaigns carried out in the same region [54]. Therefore, the heat loss outcome delivered by the energy model of Case 1 should be cautiously considered.

If examining envelope characterization, the accuracy of the standards U-value adopted for walls and façades remains uncertain, since it might differ to varying degrees from the actual value which was not measured in the campaign. Some researchers have found significant differences between the measured and the standard U values of historic walls [58], [59], the latter of which was deduced by assuming thermal properties of the materials obtained in the laboratory and not in their real conditions (effects of deterioration, real thickness, type of stone/brick and mortar, etc…). It therefore remains to be investigated what influence the use of standard U-values has on the overall EP of the dwellings**.**

The comparison carried out in Section 4.1.1. (Fig. 5), between the annual non-renewable primary energy consumption of each dwelling and the current upper limit, reveals that, despite the low electricity consumption registered for all four case studies, far below the average, the dwellings are highly polluting as the only energy source is of fossil origin. Since energy rehabilitation policies have often focused on reducing consumption, this result, common to other research in the same climate region [32], [60], is determining for the design of future long-term renovation strategies pursuing the objective of net-zero GHG emissions.

5.2. Indoor Air Quality.

Since all dwellings lack mechanical ventilation, IAQ depends on NV (user-controlled only) and on unintentional air infiltration through the envelope (airtightness, which cannot be controlled by the user). Under winter conditions, in buildings which can only be naturally ventilated, poor airtightness of the envelope directly impacts on the EP of dwellings causing heat losses (adverse effect), but also impacts on the IAQ, as it contributes to maintaining low CO_2 concentrations in the air (positive effect). Just as other researchers have found on dwellings on the same climatic zone [32], [56], [60], our results show that, in winter, CO_2 concentration in Brs, continuously occupied and with windows and doors closed, is above the limit considered "good" during a considerable part of the nigh-time (see Section 4.2), especially in the most airtight dwellings, as Case 4. It prompts reflection on the convenience of the general substitution of old wooden window joineries for tighter new ones. In many cases, the installation of highly airtight carpentry should be associated to a forced air ventilation plan.

IRH rates regularly remain too high for the four case studies and none of them would be in compliance with national regulation CTE DB HE2 [44] which sets an admissible range of 40-50% for dwellings (Table 2 of Section 3.4). This happens even in the case of intense heating use, as with Cases 1, 2 and 4. Although the best rates are measured in Case 1, even there, 42% of the time IRH levels exceeded 50%. Case 2 displayed the worst rates as half the time IRH levels were above 60%. In Case 3, in free-running mode, presented 32% of hours with IRH rates above 60% and 15% of hours above 70%. Due to the adverse health effects and the constructive pathologies which lengthy rates of IRH can foster, further analysis should be carried out on this aspect.

5.3. Thermal comfort.

The *temperature clouds* of Fig. 10 graphically illustrate the high thermal stability of Cases 1 and 3. A greater dispersion is observed in Cases 2 and 4. According to the results presented in Section 4.1.3. and the data shown in Supplementary Material SM_2, only Cases 1 and 4, where residents make continuous use of the heating (see Table 8 in Section 4.1.3) present acceptable thermal comfort conditions. Even so, the average deviation of IATs in relation to the daily T_{op} is about -3 ℃ for both rooms of the two dwellings and the Br of Case 1 is thermally uncomfortable for 50% of the sleeping hours according to EN15251 standard. Cases 1 and 4 are the cases in which the dwellings are better-equipped technically: both have ducted heat pumps of COP=2.70 (Case 1) and COP=4 (Case 4). This confirms that the age-factor, the presence of children or elderly people at home, greatly influences energy use. The inadequacy of some of the systems used, such as Case 2, lead to a continuous situation of discomfort (75% of sleeping hours in Br and 43% of day hours in Lr, with an average deviation from T_{op} of -5 ℃ in both rooms, under EN15251 model), coupled with excessive electricity consumption, which also makes it the most polluting dwelling. Case 2 is an example of inadequate thermal-conditioning facilities in a dwelling renovated to poor quality standards. Case 3, in free-running regime, is always below comfort levels in the typical period and the average deviation IAT-T_{op} is around 8 ℃ in both rooms. It is the less polluting, since its resident barely uses the heating system.

Cases 2 and 3 support the finding of Healy [11]: despite having mild outside temperatures, with minimums rarely below 5℃, southern European homes have excessively cold indoor environment. As these results show, those can sometimes be attributed to personal motivations and cultural preferences, as may be the case of Case 3 resident; but also to the fact that the impact of users' voluntary action to counteract the heat losses is less in winter than in summer, as observed in the previous work [25] analysing the same dwellings. In winter, what actions are available to users to avoid heat loss and achieve thermal comfort in their dwelling? One is to switch on the heating system, should there be one. Another is to avoid ventilating the rooms frequently. The third action would be, in hours of sunshine and low cloudiness, to keep the blinds open in order to maximize the incidence of the solar radiation on the glazing of favourably exposed windows but not the rest. The first two strategies are the most commonly used. The effectiveness of the third strategy realistically depends on automatized mechanisms, which are not frequently found in historic buildings. The range of choices available to users to counteract heat losses is short and, in most cases, is limited to switching the heating on.

5.4. EP analysis.

As shown in Fig. 12 of Section 4.4, except for the negligible heat losses derived from NV, no thermal loss is associated with users' behaviour. All heat losses are related to the constructive elements of the envelope. **Walls** are responsible for the vast majority of heat losses, considering the four case studies. This category includes not only the thick façade walls, built with solid materials, but also the walls of internal patios, which are not as thick and are built with poorer-quality materials hardly ever improved and, therefore, of much higher U-values. This confirms that the exceptional thermal properties of this type of construction should not be so easily assumed and further reinforces the usefulness of measuring the U-value of walls experimentally. The **roof** is the second most unfavourable building-driven factor. In Case 3, with the higher proportion of exposed surface, 61% of heat loss is through the roof. This percentage is 36% for Case 2 and 16% for Case 4. **Air leakage** is the third heat-loss factor, causing between 13-19% of the total heat loss in 3 out of 4 cases. Even so, in view of the direct relation existing between airtightness of the envelope and CO_2 concentration described in Section 4.2, any intervention trying to generate excessively airtight rooms should be considered carefully if the ventilation system is not improved, in order to guarantee acceptable quality levels of the indoor environment. **External glazing** also accounts for a large proportion of the heat loss: from 23% in Case 1 to 16% in Case 3. Part of the heat lost through glazing is connected to the specific solar orientation and solar obstructions of each dwelling: heat loss in Case 1 is four times higher than in Case 3, also south-facing. This may be due to the fact that the façade windows of Case 1, located on the first floor of the building, remain sun-obstructed longer than those of Case 3, due to the shadow cast by the building opposite. Although many energy-related improvements were made recently in Case 4, they were irregular and focused only on the façade. Existing windows were replaced with new high quality ones, but no attention was paid to the poor thermal insulation capacity of the 14-cm-thick patio walls or the rest of the windows, in spite of the fact that the exterior surface of patio walls account for 44% of the total vertical exposed surface of the dwelling (see drawing in Fig. 4). This is an example of the wide range of cases and different situations occurring in dwellings of historic cities.

6. Conclusions.

Based on the results of this study, the generalized assumption of the intrinsic capacities of historic buildings, stemming from their particular constructive features, to maintain thermal comfort under acceptable conditions, is called into question: in all cases, regardless of the specific occupant behaviour profile, heat losses during winter are caused by walls, roofs, air leakage, and glazing, ranked in decreasing order. All these elements can only be modified by the occupant through refurbishment.

Despite Seville's mild winter of 2017, in two out of four cases analysed, the IATs recorded were regularly below the minimum comfort levels. Although due to climate change "low-temperature extremes (cold spells, frosty days) could become less frequent in Europe" [61], reducing heating loads in homes, our results confirm the need to introduce constructive and technical improvements, as envelopes of low thermal quality and deficient facilities have a greater impact on the low interior temperatures than climate severity in winter [11]. In addition to improvements in the envelope elements, efficient mechanical ventilation and heating systems should be introduced in the historic dwellings, in order to guarantee indoor environmental conditions during winter of identical or, at least similar, quality to those of newly constructed buildings so as not to discourage occupation, ensuring the long-term sustainability of the historic urban areas.

Heating inefficiency can lead to adverse effects such as excess of IRH or an increased tendency not to ventilate naturally, generating in turn an excessive CO_2 concentration. Special care should be taken in future energy retrofit strategies for the historic housing stock in relation to IRH since lengthy high rates, as the ones reported in this research for three out of four cases, cause most of building-driven adverse health effects by boosting the proliferation of bio-pollutants such as fungi, and foster important building pathologies, such as condensation and mould. When the only possible ventilation is natural through the windows, the widespread formula of increasing the envelope airtightness in order to avoid heat losses, may compromise air quality and lead to unhealthy indoor environments, especially in winter when occupants tend to ventilate less frequently, as Underhill et al. also point out [1]. The current Spanish energy code forces the dwellings within newly constructed or totally refurbished buildings to be equipped with a ventilation system, either hybrid or mechanical [62]. As listed buildings to be rehabilitated do not need to comply with this regulation this important health factor is commonly neglected.

Long-term renovation strategies of historic urban areas should consider the particularly heterogeneous nature of their residential building stocks which complicates the energy analysis forcing to be handled on a case-by-case basis. The energy analyses are effected by the user-patterns heterogeneity characteristic of all residential stocks, and also by the building-related heterogeneity connected, among other intrinsic factors, with the undocumented copious differences created by users over time, which undoubtedly affects the EP and IEQ.

The protection rules affecting the historic buildings may complicate the improvement in the performance of some envelope elements, forcing the deviation from standardised solutions. But, precisely because of this, this protection rules may as well lead to carry out a more thorough analysis of the fine balance between heritage preservation, energy efficiency, comfort and indoor air quality. Field studies like the one presented here, based on real monitoring data and in-situ inspections and tests and infrequent to date would enable the design of renovation plans which could result in less polluting, more comfortable, healthier buildings, while also protecting the physical materiality of the buildings and also their value in use.

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Credit authors statement

Rosana Caro: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing-original draft, Writing-review and editing.

Juan José Sendra.: Conceptualization, Methodology, Supervision, Validation, Resources, Writing-review and editing.