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Evaluation of Thermal Comfort Conditions in Retrofitted Facades Using Test Cells and Considering Overheating Scenarios in a Mediterranean Climate

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Abstract: Energy retrofitting of the housing stock is a priority in current regulatory standards as a means of reducing energy consumption. The strategies used in retrofitting housing stock ought to respond both to regulatory conditions and to two challenges: specific climate conditions and the improvement of comfort conditions. These issues are especially important in the warmer regions of the Mediterranean, and will be even more so in the future due to climate change. The aim of this paper is to assess the influence that the improvement of facade insulation and the use of ventilation have on the existing housing stock. To do so, an energy evaluation is conducted using on-site monitoring of free-running conditions in test cells reproducing a residential room, both in current condition and with the retrofitted proposal, in Seville (Spain). The results obtained show limited improvement of the facade insulation when outdoor temperatures are high, as well as the influence of ventilation, mainly nocturnal, depending on the ventilation rate and the minimum outdoor temperatures.

Keywords: test cell; monitoring; housing stock; energy retrofitting; thermal comfort; ventilation system; Mediterranean climate; heatwave periods

1. Introduction

Nowadays, a large part of housing stock presents obsolete energy conditions, far removed from current energy legislation. This leads to deficiencies in indoor thermal conditions and situations of energy poverty. In Europe, a common regulatory ground has been established to promote measures for the improvement of energy efficiency in existing buildings to meet the intended requirements of H2020 [1] and subsequent legislation [2].

Numerous studies have analysed the energy characterization and retrofitting of existing housing stock, mostly in climate areas of central and northern Europe, where one of the main objectives is the significant reduction in energy consumption in winter. Previous research has mainly focused on verifying the energy standards in energy consumption [3]; measuring consumption in real use conditions [4]; and verifying real consumption against estimated consumption. These factors result in a considerable gap in performance [5] and a rebound effect [6], mostly due to occupants' behaviour. The key strategies for intervention in cold climates focus on the improvement of building envelopes using thermal insulation and double-glazing systems [7].

Energy performance of housing stock in the Mediterranean is especially conditioned by climate conditions and sociocultural characteristics [8]. Studies carried out in this area have evaluated the influence of orientation, window size and thermal insulation thickness [9]. It is also worth noting the importance attached to efforts to correct and increase the regulatory capacities of facades as the principal surface for exchange with the outside [10], along with other passive approaches such as ventilation [11] and solar control [12]. In fact, the retrofitting of the vertical envelope is one of the most commonly used strategies in the energy retrofitting of buildings, and has been widely researched [13,14], focusing particularly on double-skin facades [15–17]. Most research focuses on the improvement of comfort conditions as low energy consumption [18] and limited economic resources bring about fuel poverty [19] which has increased with the economic crisis [20].

In southern Spain, Escandón et al. [21] quantified thermal comfort in social housing using a specific protocol based on in-use monitoring in winter conditions. However, summer climate conditions, with major solar radiation and high outdoor temperatures, require precise analysis to reduce overheating problems. In Seville, for practically 100% of summer days in 2017 (from June to September), outdoor temperatures reached 30 °C, and on average 46% of the daily hours were above that value (Figure 1). Moreover, in almost 40% of summer days (June to September), outdoor temperatures were above 40 °C, the cut-off point for activating heatwave protocols. In other words, at least 10% of the periods examined registered maximum peaks above 96% of maximum daily temperatures for at least three consecutive days [22]. Five heatwave periods were recorded in 2017, with minimum outdoor temperatures rarely below 20 °C and maximum temperatures up to 47.4 °C.

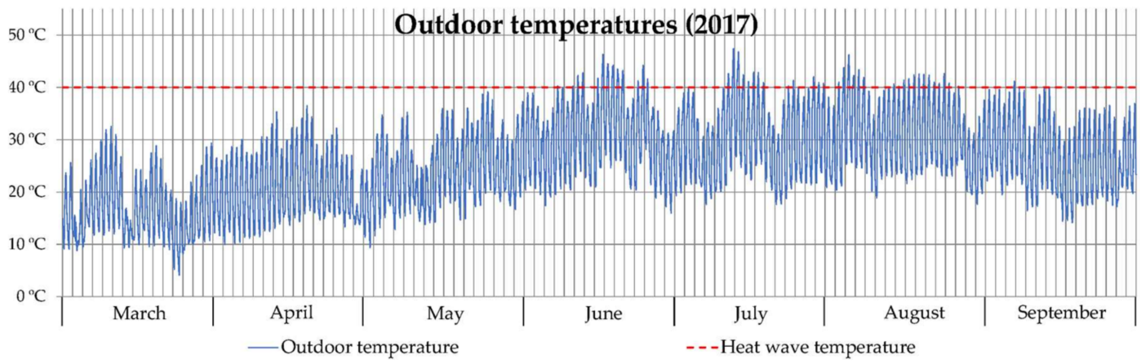


Figure 1. Outdoor temperatures from March to September in Seville, registered by the weather station placed above the test cells.

The effects of high temperatures on the reduction of ambient interior air quality and comfort conditions [23] are many. There is a subsequent increase in energy consumption due to lower temperatures [24,25], especially in social housing with deficient energy conditions. Given that these deficient energy conditions are responsible for increasing health problems and mortality rates [26,27], it becomes vital to adapt existing housing stock to these climate conditions, also taking into consideration climate change [28].

Prior to implementing retrofitting solutions in residential buildings [29], it is crucial to understand their energy performance in current conditions and to quantify their overall energy improvement, taking into account possible intervention proposals. Energy characterization can be carried out through in-use monitoring of representative case studies [30], extrapolating results using previously validated energy simulation models [31].

Although in this case conditions are reproduced in a steady-state regime, the effect of users can be removed from results using an alternative based on laboratory test studies. The use of on-site testing to assess real performance, using scale models [32] or real-scale test cells, is considered the best option. Test cells allow different elements of the thermal envelope to be evaluated [33], providing reliable results in real outdoor conditions, with a level of instrumentation that guarantees more accurate results than those of in-use monitoring [34].

Based on the most representative facade type of the pre-energy regulation period of housing stock in the warm Mediterranean area, this paper aims to assess thermal performance and comfort conditions through a strategy for the improvement of the facade, incorporating thermal insulation—specifically an External Thermal Insulation Composite System (ETICS)—combined with ventilation actions. For this, an energy evaluation was carried out through on-site monitoring of test cells in free-running conditions, reproducing a housing space, and supplemented by simulation models.

2. Methodology

Methodology developed in this research (Figure 2) combines an empirical method and experimental data from test cells, with energy model simulations applied to Seville (Spain), a city with a typically warm Mediterranean climate.

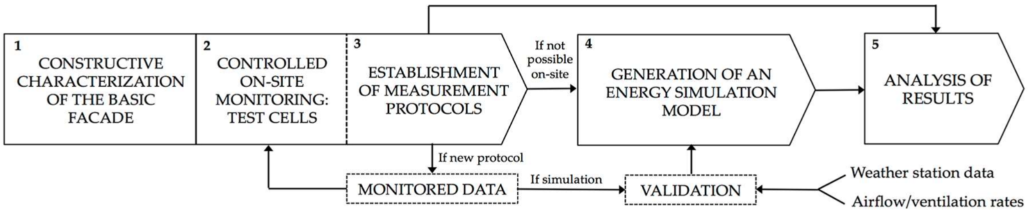


Figure 2. Methodological scheme.

2.1. Phase 1. Constructive Characterization of the Basic Facade

A comprehensive analysis was conducted using source documents, construction projects, fieldwork and statistical studies relating to the predominant constructive characterization of the housing stock built in Seville between 1939 and 1979 [35], when Spanish cities experienced the highest growth and transformation. Until the implementation of NBE-CT-79 [36]—the first Spanish legislation to establish limited measurements for energy demand in buildings—there were no requirements relating to energy consumption or thermal comfort for residential buildings.

The aim of this study is to identify the constructive solution of the facade most commonly used in the period studied (Table 1), for its implementation as a basic facade in the test cells. During the 1940s and 1950s, facade solutions consisted of a single brick enclosure with rendering layers: solid walls (types F1 and F2). In contrast, during the 1960s, cavity and double layer walls began to be used: for cavity walls (F3 and F4), solution F4 is the most commonly used in the period studied.

Table 1. Classification of the facade solutions of the housing stock by period.

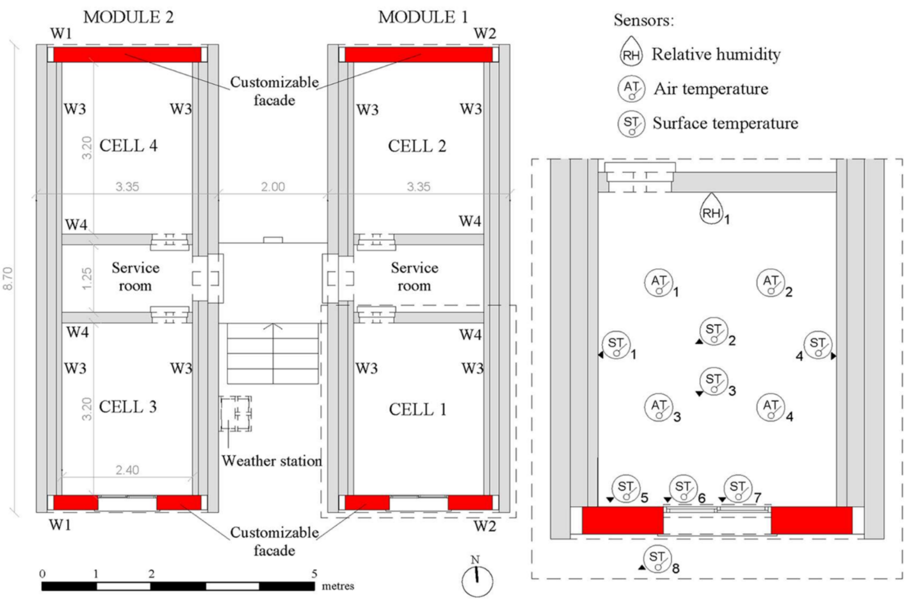
Facade Solutions		U (W/m²K)	% of Total Constructive Area				
			1940s	1950s	1960s	1970s	Total
F1	Ceramic brick (solid or perforated) e > 24.5 cm Cavityless No insulation	1.68–1.97	100	70	22	-	29
F2	Concrete block construction (hollow) Cavityless No insulation	2.17	-	-	-	45	6
F3	Ceramic brick (solid or perforated) e > 24.5 cm Air Cavity No insulation Inner ceramic construction (hollow)	1.28	-	20	9	-	5
F4	Ceramic brick (solid or perforated) e ≈ 11.5 cm Air Cavity No insulation Inner ceramic construction (hollow)	1.43	-	6	65	38	45
F5	Others	0.72–4.32	-	4	4	17	15

In general, windows used until the 1970s had metal frames and single glazing, with U-values around 5.70 W/m^{2}K. Although the opaque parts of these facades have not changed, most of the openings have now been replaced with double glazing systems. Low energy performances can be appreciated in these types of facades, with U-values almost three times the reference limit values stipulated in Spanish legislation CTE DB HE1 [37].

2.2. Phase 2. Controlled Monitoring of Indoor Ambient Conditions in Test Cells

To carry out an energy evaluation of the facade solution, two symmetrical modules with a north–south orientation were placed in an outdoor area of the University of Seville, which was free from obstacles.

Each module consists of two experimental test cells, each with a customizable facade, reproducing a housing space (Figure 3a). The distribution of the cell in pairs allows the simultaneous comparison and assessment of two different facade solutions, calculating interior variables for both solutions with equal outdoor conditions. This research has assessed the facade identified in Phase 1 as one of the constructive solutions most frequently used in social housing (F4) and a retrofitted facade with an external thermal insulation system (ETICS) (Table 2 and Figure 4). The ETICS solution chosen is usually used in retrofitting interventions as it is cheaper, has no negative impact on the useful area of buildings and there is no need to displace tenants as it can be fitted from the exterior.



(**a**) (**b**)

Figure 3. (**a**) Floor plan of the test cells: ETICS facades (W2) in Cells 1 and 2, and basic facades (W1) in Cells 3 and 4; and (**b**) location of the sensors within each test cell.

A set of sensors was installed inside the test cells to monitor ambient conditions (Figure 3b)—air temperature, relative humidity and superficial temperature of the envelope—every 5 min. Likewise, outdoor parameters were recorded using a weather station above one of the modules, obtaining data for air temperature, relative humidity and solar radiation. Other relevant information can be found in León et al. [38] along with the constructive characteristics of test cells (Table 2).

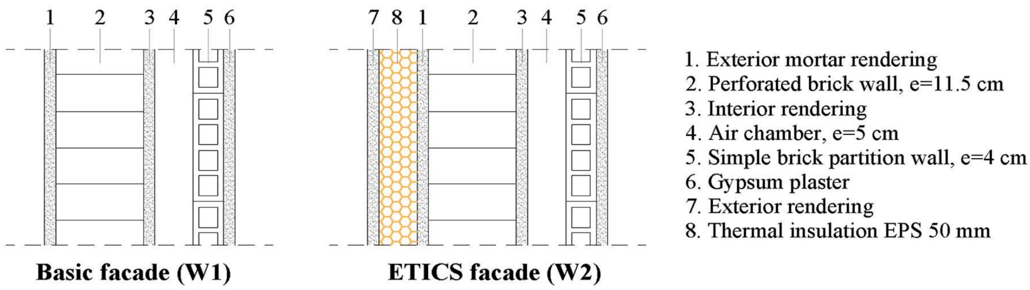


Figure 4. Constructive characterization of the basic facade (W1) and the ETICS facade (W2).

Table 2. Thermal envelope definition, U-values.

Nomenclature	Building Envelope	U (W/m^{2}K)
W1	Basic facade: exterior mortar rendering, perforated brick wall, interior rendering, 5 cm air chamber, brick partition wall and gypsum plaster	U_{W1} = 1.43
W2	ETICS facade: W1 + thermal insulation EPS 50 mm with exterior rendering	U_{W2} = 0.47
W3	200 mm sandwich panel, thermal insulation MW 80 + 80, 100 mm sandwich panel	U_{W3} = 0.05
Floors		U_F = 0.05
Roof		U_R = 0.05
W4	100 mm sandwich panel	U_{W4} = 0.17
Opening	4/8/4 double-glazing, Metal frame (no thermal bridge break)	U_O = 3.30

2.3. Phase 3. Establishment of Analysis Protocols and Conditions

The evaluation of ambient and energy conditions was carried out over several months, establishing different measurement protocols to assess the influence of various factors and their combinations including the use of a controlled mechanical ventilation system.

This paper is a preliminary study analysing the results of test cell performance in free-running conditions (without air-conditioning systems and with the blind aperture set at 50%). Outdoor conditions are analysed during different months of the year. This is also the case of the implementation and schedule of ventilation, considering a ventilation rate of 1.75 ACH (Air changes per hour), the rate established in the Spanish Technical Building Code CTE DB-HS3 [39] for a bedroom (Table 3).

Table 3. Characteristics of protocols analysed in free-running conditions.

Protocol	Cell	Date Time	Ventilation	Window Blinds (% Aperture)
March	C1, C3 C2, C4	14/03/2017–20/03/2017	On (continuous), 1.75 ACH	50% No window
April	C1, C3 C2, C4	03/04/2017–11/04/2017	Off	50% No window
July	C1, C3 C2, C4	03/07/2017–10/07/2017	Off	50% No window
September	C1, C3 C2, C4	13/09/2017–21/09/2017	On (22:00–8:00), 1.75 ACH	50% No window
December	C1, C3 C2, C4	01/12/2017–08/12/2017	Off	50% No window
January	C1, C3 C2, C4	17/01/2018–24/01/2018	On (continuous), 1.75 ACH	50% No window

Note: Shaded lines indicate ventilation system is on.

The six protocols shown in Table 3 are grouped into three distinct periods. The March and April protocols correspond to a mid-season or "soft summer" period with maximum outdoor temperatures below 30 °C and varying minimum temperatures around 10 °C. The July and September protocols are characterized by maximum outdoor temperatures close to the heatwave limit of 40 °C and with minimum temperatures of 15–20 °C, characteristic of a "severe summer". Finally, two winter periods have been evaluated in December and January, with outdoor temperatures usually fluctuating between 5 and 20 °C. The protocols selected provide a global vision of the particularities of the Seville climate during several seasons in the year.

In soft summer and winter protocols, the influence of continuous minimum ventilation of 1.75 ACH is considered. In severe summer, due to high outdoor temperatures and the current Spanish regulation CTE DB HE1 [37], it was decided to assess nocturnal ventilation from 22:00 to 8:00, with an airflow rate equal to that mentioned above.

A comfort analysis was presented to evaluate indoor conditions, determining the comfort band following ISO 7730:2005 [40]. Thus, values of thermal comfort were established at 18.5–24.5 °C for soft summer and winter, and 22.8–26.8 °C for severe summer, with relative humidity of 50%, an interior Predicted Percentage of Dissatisfied (PPD) of 15%, a metabolic rate of 1.2 met and a thermal resistance of 1 clo in winter and 0.5 clo in soft and severe summers. Moreover, the influence of use patterns was not considered, since the objective is to create a controlled indoor environment which allows accurate energy results to be obtained.

2.4. Phase 4. Generation and Validation of an Energy Simulation Model

Dynamic analysis was conducted through simulation models of the energy performance of the test cells to develop variations in the night ventilation variable. This variable is a passive mechanism for reducing indoor overheating mainly during the severe summer [41], unlike that obtained in the protocols analysed.

Energy simulation software DesignBuilder (v.4.7.0.027), recognized by the US DOE [42] and EnergyPlus [43] were used to generate energy models reproducing the test cell performance, entering current weather data (air temperature, relative humidity and solar radiation) recorded by the weather station, into the climate file in the program. To reduce model uncertainty (see Section 3.4), current airtightness was determined through a Blower Door Test [38]. This provides a characterization of envelope permeability for the simulation model. On-site measurements allow an accurate calibration of the model. For this, the September protocol was selected, given the higher temperatures registered, making this the most demanding situation for severe summer.

2.5. Phase 5. Analysis of Results

For the discussion and interpretation of results, the operative temperature of each test cell was calculated following ISO 7726:2002 [44]. This variable was obtained through indoor air temperature values registered by 4 sensors hanging from the false ceiling of each cell (16 in total), and with radiant interior temperatures, derived from the surface temperature values of the envelope collected by 8 thermocouples in each cell (32 in total) (Figure 2). These operative temperatures were subsequently evaluated for the establishment of the percentage of hours of comfort for each protocol and cell. A statistical analysis based on the study of centralization, position and dispersion parameters was carried out to evaluate the representativeness of results obtained.

3. Analysis of Results

This section assesses the results obtained in the different on-site measurement and simulation protocols carried out in the cells with basic facades and retrofitted facades (ETICS).

For the sake of greater clarity, the results have been structured into four sections: on-site measurements, both with and without the influence of ventilation systems; thermal comfort analysis for each constructive system; and, finally, the influence of ventilation rates in indoor conditions.

3.1. Result Assessment in Protocols without Ventilation

Figures 5–7 represent operative temperatures in the protocols without ventilation (April, July and December, respectively). For all three periods, higher thermal oscillations can be clearly observed in non-retrofitted C3 and C4, in contrast to the retrofitted facades.

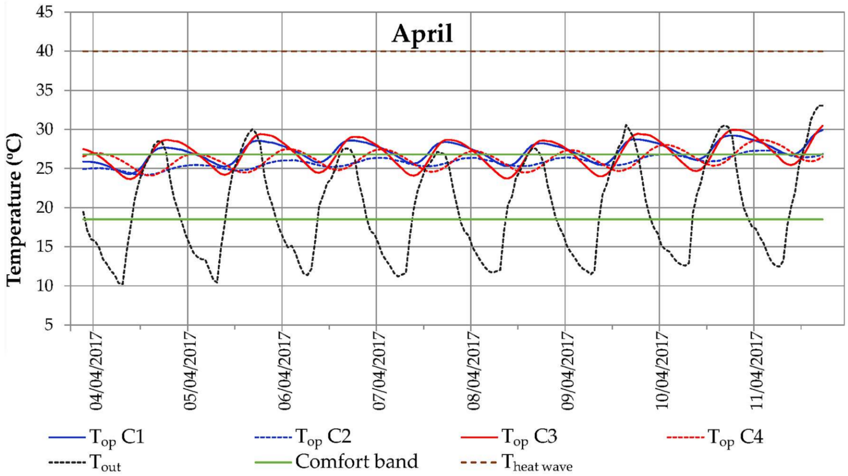


Figure 5. April protocol (no ventilation): Daily evolution of operative temperatures in each cell compared to outdoor temperatures (see Supplementary Materials Figure S1a).

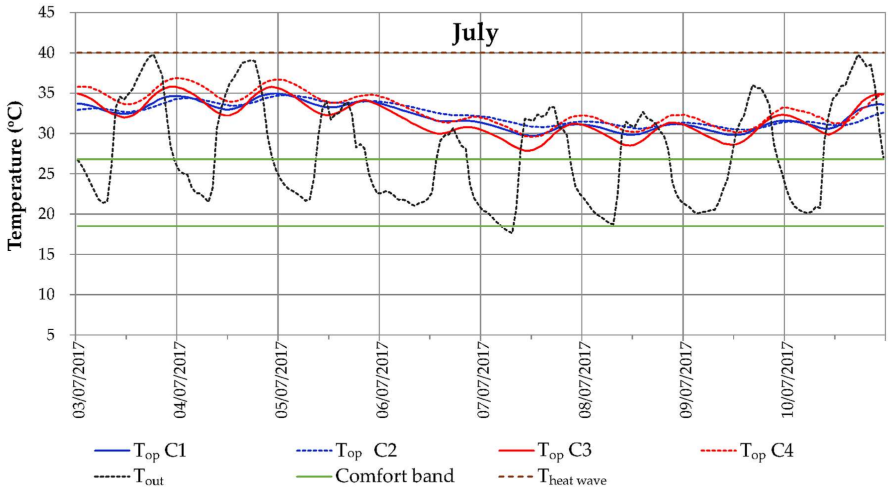


Figure 6. July protocol (no ventilation): Daily evolution of operative temperatures in each cell compared to outdoor temperatures (see Supplementary Materials Figure S1b).

When the outdoor temperature is above 35–40 °C, an ETICS facade presents lower operative temperatures than a non-retrofitted facade. However, during the night and early hours of the morning, when minimum outdoor values registered are 10–20 °C, the non-insulated cells have less overheating, while thermal inertia in the ETICS facade is much greater, giving rise to lower thermal oscillations. Nevertheless, in a Mediterranean climate with a temperature range of 10 to 30 °C in soft summers and 20–40 °C in severe summers, thermal dissipation problems occur. Increasing thermal insulation thus enables maximum peak indoor temperatures to be minimized but still causes overheating since minimum night-time values rise. This is particularly noticeable in the south, due to direct solar radiation.

In December, with maximum outdoor temperatures of 15–20 °C, thermal performance of the ETICS and basic facades are quite similar, as was the case for soft summer. Maximum indoor temperatures remain in the comfort band (21–23 °C) for both solutions. However, at night minimum outdoor temperatures of 2–5 °C reflect better thermal performance in the ETICS cells, with indoor temperatures 3 °C higher than in cells with basic facades (lower nocturnal heat losses). In both solutions, operative temperatures are slightly lower than minimum comfort values. The influence of the window negatively affects the performance of the insulation layer, with higher thermal oscillations in C1 than C2. At midday, heat gain due to solar radiation leads to higher maximum temperatures in cells with windows (C1 and C3).

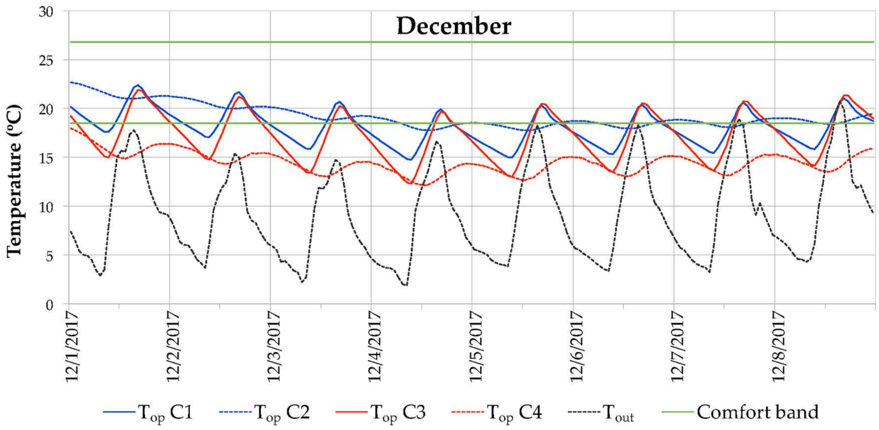


Figure 7. December protocol (no ventilation): Daily evolution of operative temperatures in each cell compared to outdoor temperatures (see Supplementary Materials Figure S1c).

3.2. Result Assessment in Protocols with Ventilation

Figures 8–10 below show operative indoor temperatures registered during the months of March, September and January, when the ventilation system was active, on a continuous schedule (24 h) or at night (from 22:00 to 8:00). In all three protocols, the ventilation rate was 1.75 ACH.

As with the protocols (without ventilation) in general, indoor thermal oscillation is higher in cells with basic facades (C3 and C4) than in retrofitted ones. In these cases, a slight improvement is observed in indoor temperatures, although insufficient in certain periods.

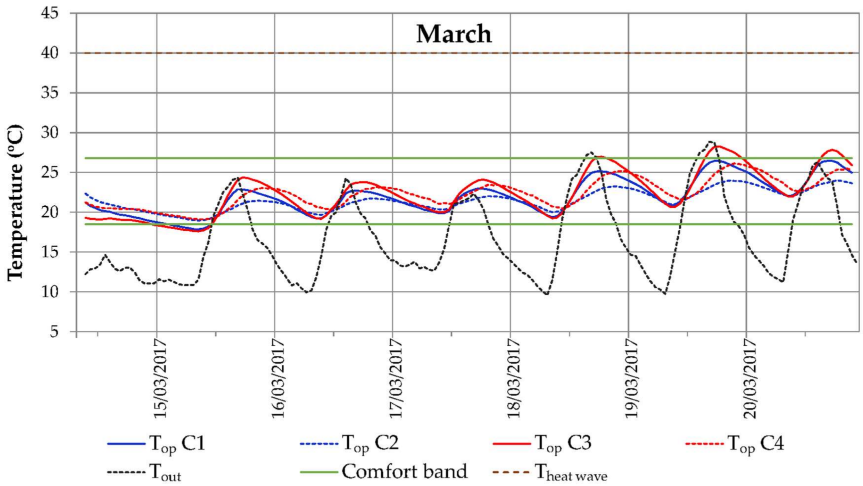


Figure 8. March protocol (continuous ventilation, 24 h): Daily evolution of operative temperatures in each cell compared to outdoor temperatures (see Supplementary Materials Figure S1d).

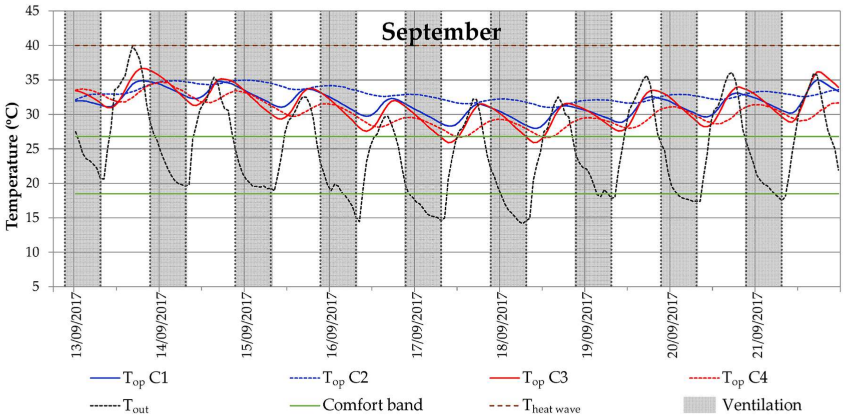


Figure 9. September protocol (night-time ventilation, from 22:00 to 8:00): Daily evolution of operative temperatures in each cell compared to outdoor temperatures (see Supplementary Materials Figure S1e).

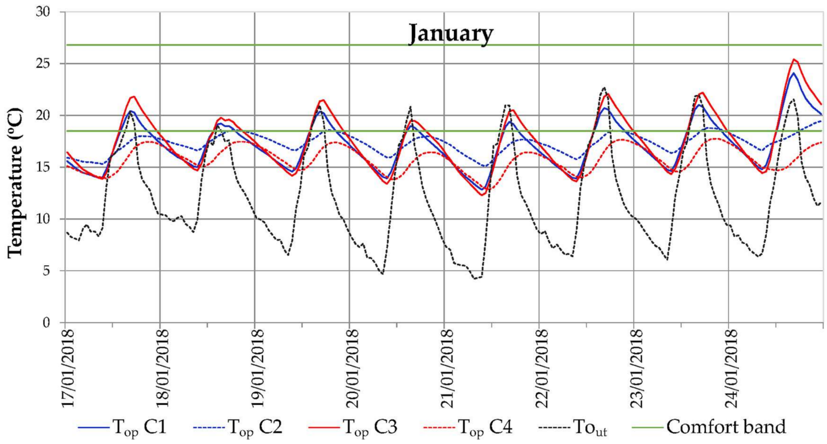


Figure 10. January protocol (continuous ventilation, 24 h): Daily evolution of operative temperatures in each cell compared to outdoor temperatures (see Supplementary Materials Figure S1f).

In March (similar to soft summer), outside temperatures are similar to those registered in April and there is an overall variation from 10 °C to 30 °C. However, unlike the month of April, when ventilation systems are active 24 h (continuous ventilation), cells with retrofitted facades (C1 and C2) present indoor operative temperatures lower than cells with basic facades (C3 and C4). This situation is registered throughout the whole day, with maximum and minimum outdoor temperatures.

In September (severe summer), the cell with basic facade C3 again presented higher maximum temperatures than C1 (ETICS) when outdoor temperatures rose to around 40 °C, but with more significant differences, especially after night-time ventilation periods. Thus, the heat dissipation effect produced by the ventilation slightly improved performance in south-facing cells with the retrofitted solution. In the north-facing cells, overall improvements due to ventilation were substantially better.

Thus, the analysis of the minimum operative indoor temperatures is key in evaluating possible improvement in retrofitted solutions with ETICS, bearing in mind the influence of different ventilation rates such as passive cooling techniques. However, with outdoor temperatures between 30 and 40 °C, the use of ventilation during midday hours for passive cooling is unsuitable, as outdoor temperatures are much higher than the comfort band, leading to a shift to a night-time ventilation scheme, improving thermal dissipation, despite minimum heatwave temperatures close to 20 °C.

Considering continuous ventilation (1.75 ACH), with minimum outdoor temperatures of 5–10 °C, the south ETICS facade reaches minimum indoor temperatures similar to those of the basic facades (north and south), occasionally decreasing to below 15 °C. The effect of the 24 h ventilation is more significant in the ETICS solution, with maximum indoor operative temperatures up to 2 °C lower than in the non-retrofitted cell. However, retrofitted C2 (north) maintains a more balanced situation with intermediate indoor temperatures.

3.3. Thermal Comfort Assessment

For the discussion and comparison of results, temperature ranges (indoor and outdoor temperatures) were analysed for each protocol.

For the thermal comfort analysis, a dispersion diagram is represented for each cell, orientation and protocol studied. The point cloud corresponds to measured hourly values for the comfort band (maximum and minimum values), as established in ISO 7730, and the indoor/outdoor temperature difference (ΔT) and outdoor temperature (T_{out}) (Figures 11–13).

In March (Figure 11a,b), with a continuous ventilation system, the percentage of comfort hours (157 h analysed) is 100% in north-facing cells (C2 and C4), 95% in C1 and approximately 83% in C3. Average deviation of operative temperatures in discomfort is about 0.5 °C, which is almost twice that of C3 (basic), when compared to C1 (ETICS). Although average indoor temperatures in C3 are within the comfort band, values above comfort limits present higher dispersion.

Throughout April (Figure 11c,d), the percentage of hours in discomfort is higher than in March, because the ventilation system is off, despite similar outdoor temperatures. In this case, slightly better results are reached in north-facing cells (C2 and C4), with a difference of almost 3 °C in the operative temperature. Average deviation of the non-retrofitted cells compared to the comfort band is approximately 1.3 times more significant in south cells and 2.5 higher in north cells, resulting in higher thermal oscillations in the non-retrofitted solution.

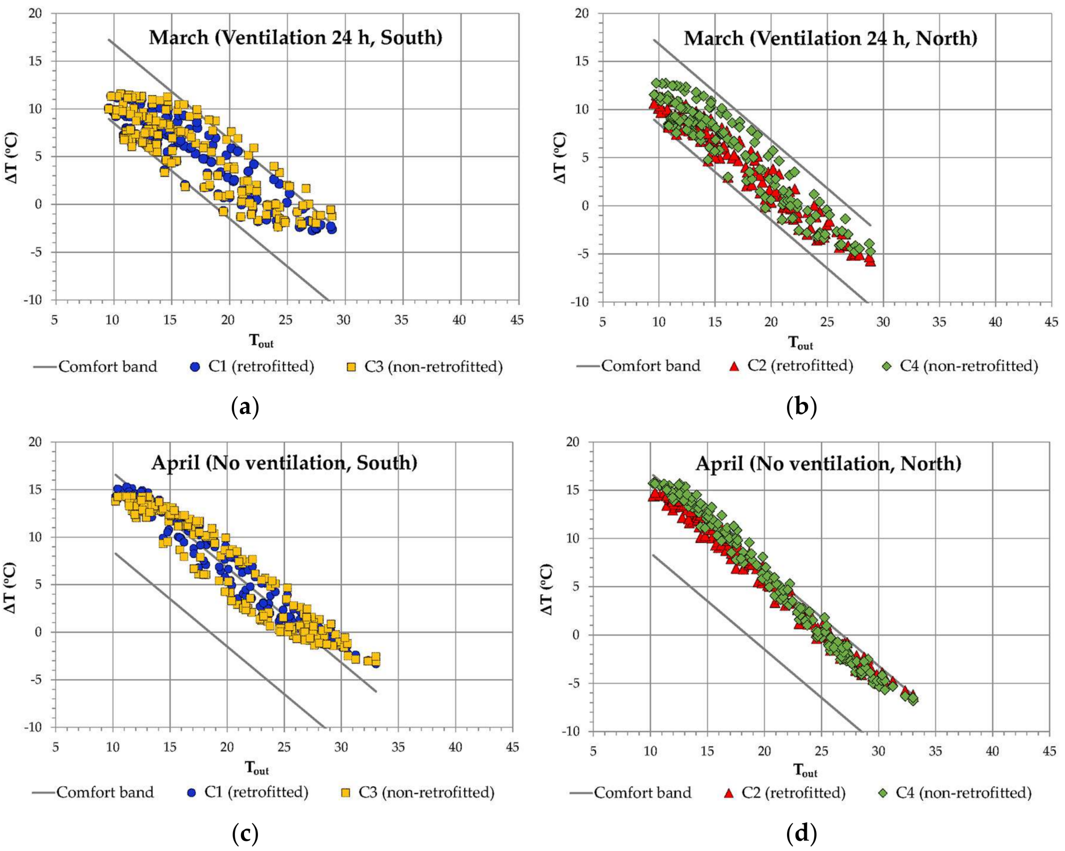


Figure 11. Dispersion diagrams. March protocol: (**a**) south cells; and (**b**) north cells. April protocol: (**c**) south cells; and (**d**) north cells.

In July, with the ventilation system off (Figure 12a,b) for 100% of the 192 h studied, indoor temperatures are in discomfort, exceeding the upper limit. The average deviation of operative temperatures from comfort is 5 °C in the retrofitted cells (C1 and C2) and up to 6 °C in non-retrofitted ones (C3 and C4).

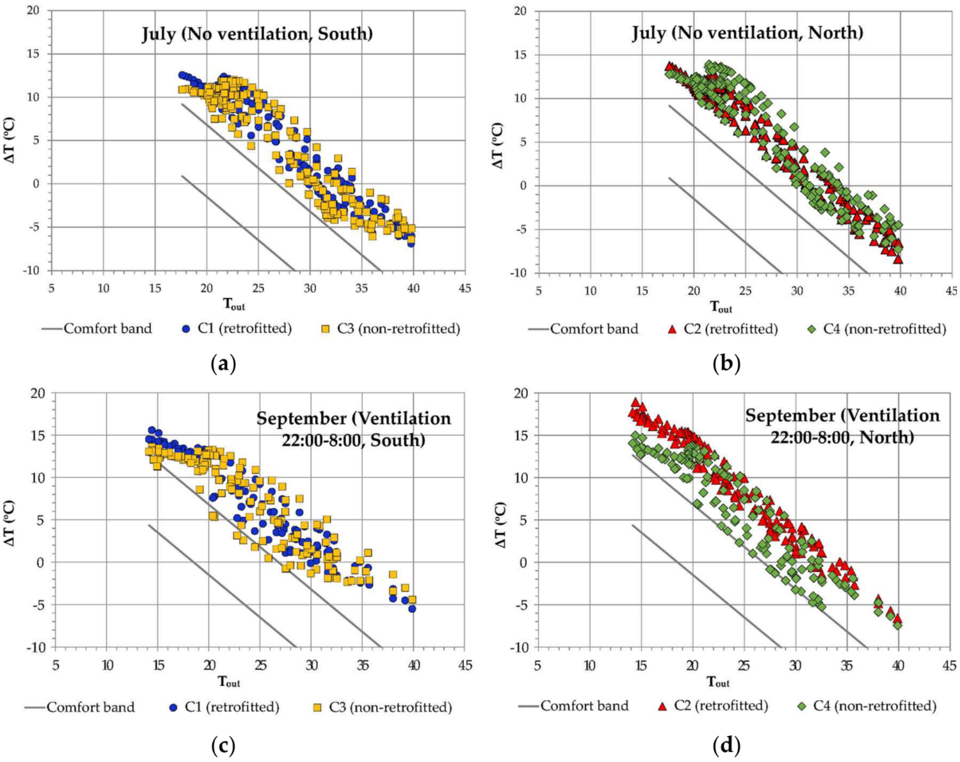


Figure 12. Dispersion diagrams. July protocol: (**a**) south cells; and (**b**) north cells. September protocol: (**c**) south cells; and (**d**) north cells.

During September (Figure 12c,d), with very high outdoor temperatures and the night-time ventilation system on (22:00 to 8:00), indoor operative temperatures are again in discomfort for almost all the hours. Only retrofitted cells (C1 and C2) meet the comfort requirements for a 5% (south cell) and 2% (north cell) of 216 h analysed. Average deviation of temperatures from comfort is approximately 5–6 °C for ETICS facades (C1 and C2), while 4–4.5 °C in basic facades (C3 and C4).

During December with the ventilation system off (Figure 13a,b), only 42% of the hours in C1 (ETICS) and 35% in C3 (basic) are in comfort. Without window (C2), the additional layer of insulation adds stability to indoor conditions and lowers extreme values. In north-facing C4 (basic), indoor temperatures drop below the lower limit for 100% of the hours. The deviation of the average in indoor operative temperatures is 1.5 times higher in C3 (basic) than in C1 (ETICS), with a deviation of the operative temperature 1.12 °C higher in the basic facade.

Finally, in January (Figure 13c,d), the percentage of comfort hours varies noticeably compared to December as the ventilation system is active 24 h a day. In retrofitted C1 (south) and C2 (north), comfort hours are reduced to 28% and 9%, respectively. In contrast, discomfort hours in non-retrofitted C3 (south) and C4 (north), slightly improve, decreasing the differences between retrofitted (C1 and C2) and non-retrofitted cells (C3 and C4), with fewer hours of discomfort in C3 than in retrofitted C1. Deviation of average indoor temperatures barely differs ±0.12 from C1 (ETICS) to C3 (basic).

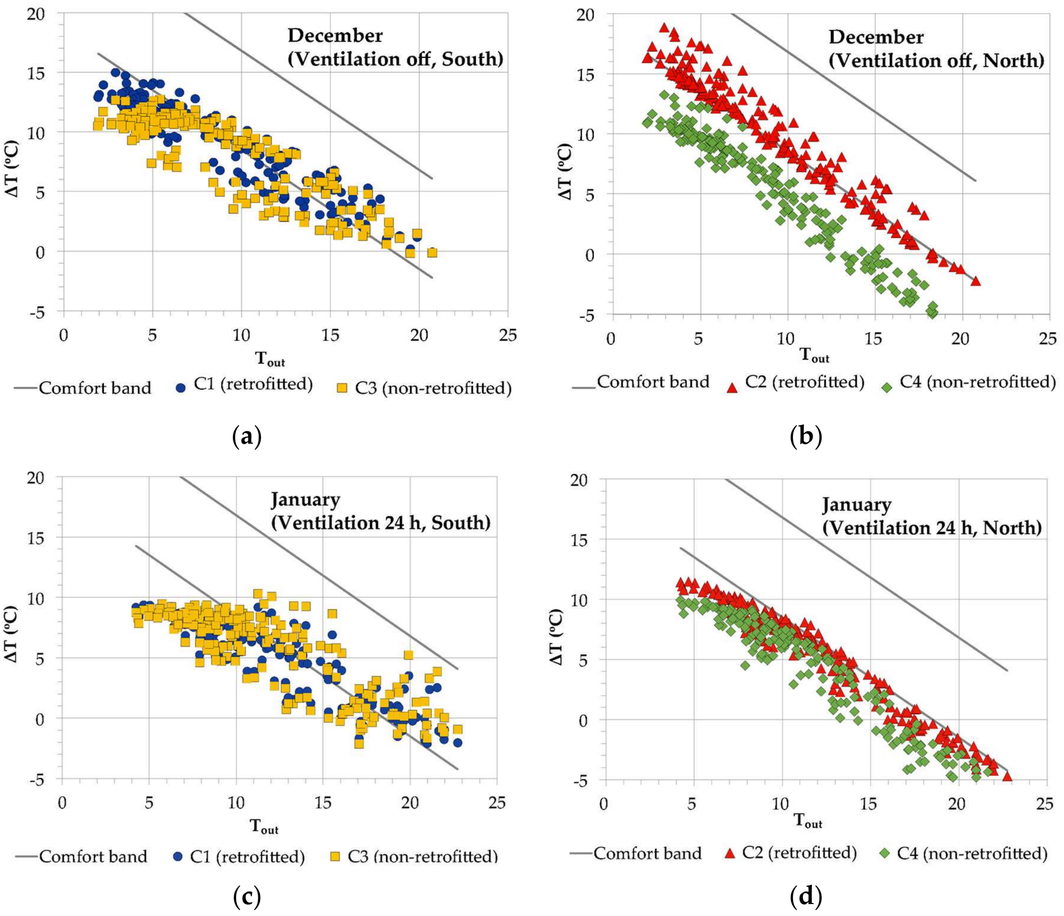


Figure 13. Dispersion diagrams. December protocol: (**a**) south cells; and (**b**) north cells. January protocol: (**c**) south cells; and (**d**) north cells.

Moreover, Table 4 shows the percentages of hours when operative temperatures are outside the comfort band for each cell and protocol, as well as those where temperatures exceed the lower and upper comfort limits.

Table 4. Percentage of hours in discomfort for each cell and protocol analysed.

Protocol	Discomfort (% Hours)				Operative $T_{i\text{-}dis}$ > 26.8 °C (% Hours)				Operative $T_{i\text{-}dis}$ < 18.5 °C (% Hours)			
	C1	**C2**	**C3**	**C4**	**C1**	**C2**	**C3**	**C4**	**C1**	**C2**	**C3**	**C4**
March	5.7	0.0	16.5	0.0	0.0	0.0	8.9	0.0	5.7	0.0	7.6	0.0
April	61.9	9.0	54.5	32.2	61.9	9.0	54.5	32.2	0.0	0.0	0.0	0.0
July	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.0	0.0	0.0	0.0
September	100.0	100.0	95.4	97.9	100.0	100.0	95.5	97.9	0.0	0.0	0.0	0.0
December	58.8	32.2	65.6	100.0	0.0	0.0	0.0	0.0	58.8	32.2	65.6	100.0
January	72.4	90.6	64.5	100.0	0.0	0.0	0.0	0.0	72.4	90.6	64.5	100.0

Note: Shaded lines indicate ventilation system is on.

Table 5 shows the percentage of hours in which heat gain and loss are registered. Finally, Table 6 presents the average operative temperatures of values outside the comfort band ($T_{i\text{-}dis}$), determining their standard deviation (σ). The average deviation of temperatures in discomfort was included, calculating the upper limit of this parameter for temperatures as above 26.8 °C, while temperatures lower than 18.5 °C were determined based on the lower limit ($A_v T_{i\text{-}dis} - CB$).

Table 5. Percentage of hours with positive or negative ΔT.

Protocol	% Hours ΔT < 0 (Heat Gain)				% Hours ΔT > 0 (Heat Loss)			
	C1	C2	C3	C4	C1	C2	C3	C4
March	82.8	76.4	84.7	80.2	17.2	23.6	15.3	19.8
April	87.8	73.5	86.2	71.9	12.1	26.5	13.8	28.0
July	67.7	69.2	65.6	70.3	32.3	30.7	34.4	29.7
September	80.7	82.3	77.8	70.9	19.3	17.6	22.1	29.1
December	99.4	96.3	98.7	79.2	0.5	3.6	1.0	20.8
January	88.5	80.7	92.7	73.4	11.5	19.3	7.3	26.6

Note: Shaded lines indicate ventilation system is on.

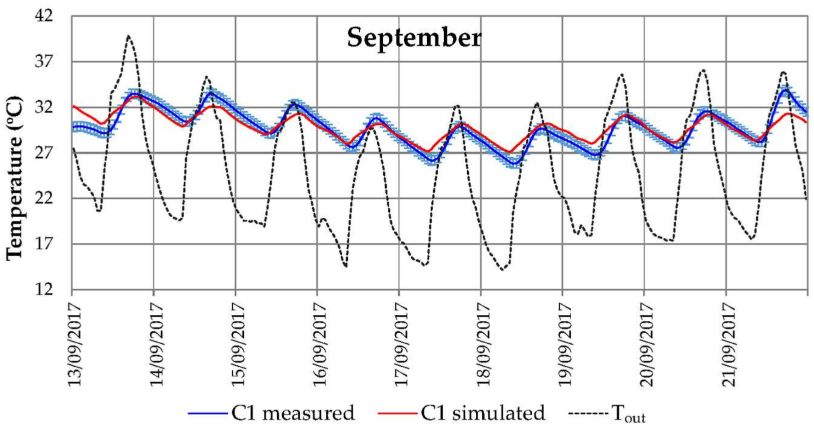
Table 6. Statistical temperature values (T_i).

Cell	Protocol	$T_{i\text{-}dis}$ (°C)		$A_vT_{i\text{-}dis}$ − CB (°C)	T_{op}	
		Average	Standard Deviation (σ)		(°C)	Frequency (%)
C1	March	18.10	±0.21	0.39	22.00	17.00
	April	27.94	±0.69	1.15	28.00	27.00
	July	32.06	±1.56	5.30	31.00	26.00
	September	31.36	±1.75	4.26	31.00	21.00
	December	16.87	±0.99	1.63	19.00	21.00
	January	16.00	±1.41	2.50	16.00	18.00
C2	March	-	-	-	21.00	30.00
	April	27.06	±0.20	0.26	26.00	40.00
	July	32.33	±1.32	5.55	31.00	41.00
	September	32.68	±1.28	5.46	33.00	32.00
	December	18.16	±0.23	0.34	19.00	52.00
	January	17.16	±0.86	1.33	18.00	42.00
C3	March	22.61	±4.89	0.65	22.50	28.00
	April	28.30	±0.88	1.52	29.00	17.00
	July	31.71	±2.13	4.98	31.00	19.00
	September	31.29	±2.30	4.21	30.00	16.00
	December	15.75	±1.57	2.75	19.00	15.00
	January	15.78	±1.53	2.72	15.00	15.00
C4	March	-	-	-	23.00	26.00
	April	27.46	±0.51	0.66	27.00	34.00
	July	32.92	±2.00	6.18	32.00	22.00
	September	30.49	±1.93	3.46	29.00	22.00
	December	14.43	±1.11	4.07	15.00	34.00
	January	15.74	±1.21	2.76	16.00	27.00

Note: $T_{i\text{-}dis}$: Indoor temperature during hours of discomfort; $A_vT_{i\text{-}dis}$ − CB: Average deviation of indoor temperatures from comfort band; Shaded lines indicate ventilation system is on.

3.4. Influence of the Ventilation Rate on Comfort Conditions

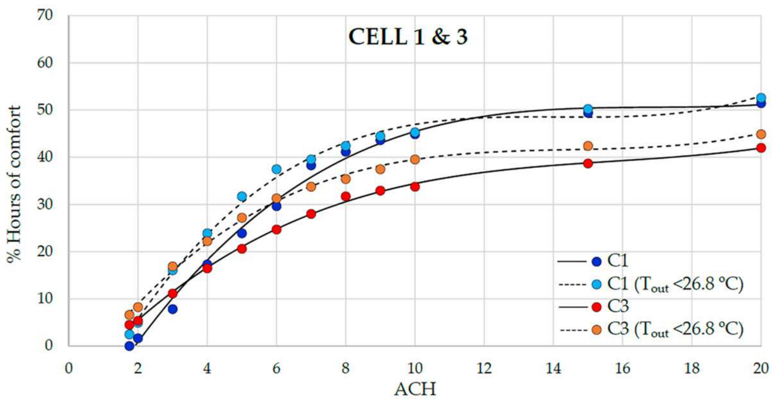
This section presents a sensitivity test relating to the influence and scope of the use of ventilation to improve indoor comfort. As mentioned in Section 2.4, an energy model was generated and validated to evaluate the influence of different air changes in relation to the percentage of hours in comfort for the period of September. For the statistical validation of the model (Figure 14), a Mean Bias Error (MBE) within ±10% and a Coefficient of Variation of the Root Mean Square Error (CVRMSE) below 30% were considered, following American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Guideline 14–2002 [45]. Under these conditions, an error range of the simulated model of ±0.5 °C in relation to the real monitoring values was obtained.



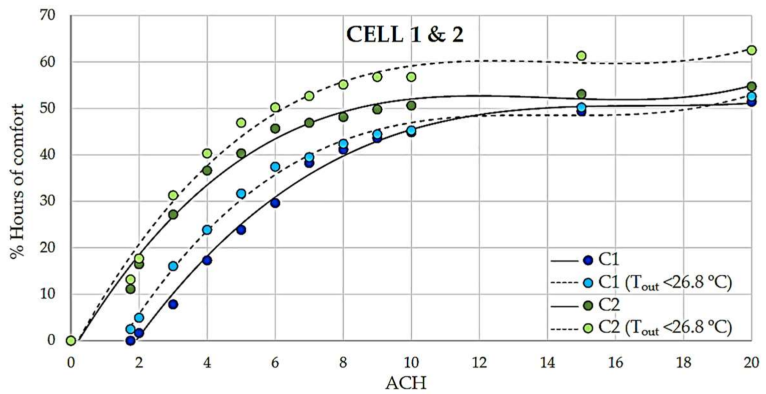
	NMBE (±10%)	CVRMSE (<30%)
C1	-0.34%	3.03%
C2	-0.60%	2.23%
C3	0.65%	4.00%
C4	-0.60%	2.60%

Figure 14. Validation of the energy simulation model. Mean Bias Error (MBE) and Coefficient of Variation of the Root Mean Square Error (CVRMSE) for each test cell.

The results of this test can be observed in Figure 15, which shows the correlation between air changes per hour (ACH) and the per cent of comfort hours, in both C1 and C3 (south), as well as in the retrofitted north-facing C2.



(**a**)



(**b**)

Figure 15. Influence of air changes per hour on the percentage of comfort hours in the September protocol (night-time ventilation): (**a**) retrofitted C1 and non-retrofitted C3; and (**b**) retrofitted south-facing C1 and north-facing C2.

For each cell, two curves are represented: the solid line shows the per cent of comfort hours, considering night-time ventilation from 22:00 to 8:00; the dashed line corresponds to ventilation cycles only in operation when outdoor temperatures are below the upper comfort limit of 26.8 °C.

In south-facing cells (Figure 15a), the influence of night-time ventilation is slightly more favourable in C3 (basic) than in C1 (ETICS), almost up to a ventilation rate of 4 ACH. More specifically, C3 reaches up to 4% more hours in comfort than C1. A progressive increase in ventilation rates leads to a notable improvement in comfort up to 10 ACH, when the percentage of improvement is stabilized. Ventilation cycles considering the control of outdoor temperatures present better results in C1 (ETICS) than in C3 (basic).

If ventilation cycles are only active during periods with outdoor temperatures below the upper comfort limit (26.8 °C), major improvement occurs (dashed curve lines). In this situation, a ventilation rate of 4–10 ACH in C1 entails improvements of approximately 7–8%, and of 5–6% considering 4–7 ACH in non-retrofitted C3.

In south- and north-facing retrofitted C1 and C2, respectively (Figure 15b), an improvement of 15–19% can be clearly observed when night-time ventilation is on (solid curve line). With ventilation rates from 2 to 10 ACH, a maximum of 50% of comfort hours can be reached. Restricting ventilation temperatures below 26.8 °C (dashed curve line) leads to an improvement of 6–8% in retrofitted C2 with values over 7 ACH, reaching up to 60% of comfort hours.

Figure 16 shows the detailed analysis of the thermal evolution of C1 (ETICS) over a 24-h period, in free-running conditions on the hottest day in September (13/09). This figure reflects the variation in indoor temperatures, modifying ventilation performance and rate. Without ventilation, temperatures remain far from comfort conditions (32–33 °C). With a night-time ventilation rate of 4 ACH (22:00 to 8:00), operative temperatures never reach the comfort band, considering outdoor temperatures ranging from 21 to 37 °C. In this case, temperatures drop considerably to 28.5 °C, between 0:00 and 8:00, exceeding 33 °C between 13:00 and 21:00, with a maximum temperature of 34.5 °C due to the significant increase in outdoor temperature and solar radiation. Restricting ventilation to an outdoor air temperature of 26.8 °C, an improvement of 1 °C is observed at night between 2:00 and 8:00, rising slightly to 1.5 °C in the daytime between 11:00 and 21:00.

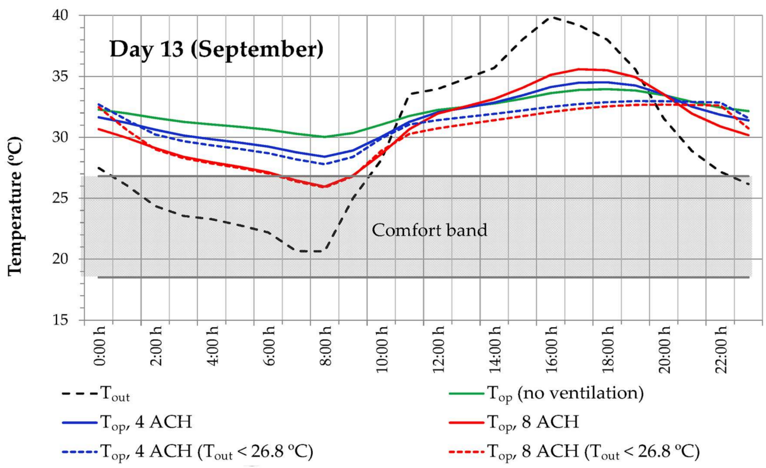


Figure 16. Influence of ventilation on thermal evolution during the hottest day in September, considering free-running protocols studied (night-time ventilation: 22:00 to 8:00).

The increase in the ventilation rate to 8 ACH only allows comfort conditions to be reached for 2.5 h (from 7:00 to 9:30), with a mismatch of approximately 6 h from the start of ventilation.

Controlled ventilation as a passive cooling action improves indoor conditions, but is insufficient during severe summers, given the especially high daytime temperatures. Under these conditions, south-facing ETICS facades only allow up to 50% of hours in comfort, applying high air flow rates

(8 to 10 ACH). In north cells, the comfort percentage increases to 60%. The effect of ventilation reduces comfort hours by around 10% when facades have insufficient or no thermal insulation.

4. Conclusions

In this paper, thermal performance and comfort conditions have been assessed in relation with the implications of an improvement strategy based on the implementation of thermal insulation in facades, considering a warm climate in the Mediterranean area. An ETICS solution is compared with a basic facade, established as the most representative of pre-regulatory housing stock, and in combination with natural ventilation actions. This energy evaluation has been conducted through on site monitoring in test cells, considering free-running conditions, with a complementary analysis using simulation models.

Techniques based exclusively on adding insulation material to facades for improving performance are less efficient in the Mediterranean area than in cooler climates, with no substantial improvement in indoor conditions in warm seasons. Although this action is slightly more favourable for extreme summers, indoor conditions are still far from acceptable.

With a low window to wall ratio or no window, the action of the insulation is more obvious, but is not assumed to be beneficial. In extremely warm periods, these insulated envelopes result in a better performance for peak temperatures, but inhibit the nocturnal cooling of the enclosure compared to non-retrofitted solutions, where indoor temperatures drop during nocturnal periods, improving sleep time.

In the mild season (March and April), the effect of adding insulation presents an overall improvement of indoor conditions in retrofitted cells (ETICS). The thermal variation ranges of indoor ambient are stabilized and narrowed, with a slightly higher number of hours in acceptable comfort conditions (6–7%), compared to the basic solution.

In winter, with soft climate conditions and maximum temperatures similar to indoor temperatures (a common aspect of the Mediterranean climate), an ETICS facade presents values closer to the comfort band when the ventilation system is off. In contrast, when the ventilation system is on, although both solutions have a similar thermal performance with minimum outdoor temperatures, the ETICS facade presents lower indoor temperatures with high outdoor temperatures.

In interventions for retrofitting and improving housing with no insulation in envelopes, adding insulation clearly benefits indoor conditions in free-running conditions over the whole year. However, it is necessary to carefully optimize the thickness of thermal insulation added and adapt the ventilation strategies to each specific period of the year, adjusting the dynamic performance of the envelope to avoid negative effects in warm conditions, especially when heatwaves peak. The optimization of these parameters in future scenarios of climate change, particularly in summer, will be the subject of future research.

Supplementary Materials: The following are available online at http://www.mdpi.com/1996-1073/11/4/788/s1, Figure S1: Box-and-whisker plots of outdoor temperatures and indoor operative temperatures for the four protocols analysed: (**a**) March; (**b**) April; (**c**) July; (**d**) September; (**e**) December; and (**f**) January.

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Conflicts of Interest: The authors declare no conflict of interest.

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