Comparison of energy conservation measures considering adaptive thermal comfort and climate change in existing Mediterranean dwellings

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Abstract

There is currently a need to restore the existing building stock. For this purpose, an energy evaluation of the building is conducted before deciding which intervention should be made. In that intervention, setpoint temperatures based on the index Predicted Mean Vote (PMV) are considered. This research studies the energy and economic feasibility of carrying out different energy conservation measures (ECMs) of façades by applying adaptive setpoint temperatures. The energy saving was also studied for future scenarios of climate change (2050 and 2080). The case study was a building with a deficient energy behaviour and located in the Mediterranean climate region. Both ECMs of façades and the cost payback period were studied. The results showed that the façade improvement was not an effective measure in the Mediterranean climate: saving percentages were not high in cooling consumption, and the amortization period was economically unfeasible. On the other hand, the use of adaptive setpoint temperatures was the most efficient measure, achieving savings higher than 70% in cooling consumption. Finally, there were limitations in the use of the adaptive comfort model from EN 15251 in future scenarios.

Keywords

Adaptive comfort; energy consumption; energy conservation measures (ECMs); climate change; cost payback period; Mediterranean climate.

1. Introduction

As a result of the oil crisis of the 1970s, concerns about the effects of climate change on the planet have exponentially increased. Currently, global warming and the depletion of non-renewable resources are the main concerns in society. Based on these problems, a greater demand on the energy performance improvement has been reflected in several sectors, including the building sector as most of the existing building stock have a poor energy performance [1–4]. In quantified data, the building sector is responsible for approximately 30% of the energy consumption at a global level [5], generating 40% of pollutant gas emissions to the atmosphere [6,7].

The European Union has therefore established the steps required to reach a low carbon economy by 2050 [8]. To achieve this goal, the building sector needs to reduce pollutant gas emissions by 90%, among others. Recently, the Directive 2018/844 [9] has set that European countries should devise energy renovation strategies for the existing building stock to have efficient buildings before 2050. In this regard, the adoption of energy conservation measures (ECMs) constitutes one of the most significant performances. Among the different elements of buildings, the envelope elements are those mostly contributing to the inefficient energy performance of the existing building stock due to the heat losses or gains taking place through them [10–13].

Thus, adopting effective ECMs through the energy analysis of buildings is fundamental to fulfil the objectives of reducing pollutant gases by 2050. However, such adoption is currently a study gap, particularly in warm climatic regions. Most studies are focused on the analysis of the building envelope improvement in cold or mild climate regions. Some of these studies are as follows: (i) Aksoy and Inalli [14] analysed the influence of passive design parameters, such as the shape factor and the orientation position, in a building located in a cold region of Turkey; (ii) Invidiata et al. [15] studied the influence of six design strategies on a residential building located in the north of Italy in future scenarios of climate change. These authors analysed these strategies from the perspectives of the adaptive thermal comfort, the evaluation of the life cycle, the cost analysis of the life cycle, and of the multicriteria decision making to select the best option for the sustainability improvement of the building; and (iii) Bhikhoo et al. [16] carried out a sensibility analysis in different design aspects of a typical dwelling in Thailand: the dwelling was located in the wet-dry tropical climate region (Aw class according to Köppen-Geiger climate classification [17]). The results showed a great influence on the placing of insulating material at the ceiling or on the inclusion of balconies in the design.

Moreover, most of these studies focused on public buildings, such as offices or shops: (i) Spyropoulos and Balaras [18] analysed the energy performance of 39 office buildings in Greece by determining the most important aspects; (ii) Rubio-Bellido et al. [19] studied the influence of office buildings on the energy demand in future scenarios and showed that the relationship of the shape and the relationship window-wall can significantly influence the decrease of the energy demand during the design phase of these buildings; (iii) Ge et al. [20] analysed different strategies for energy efficiency optimization, such as the envelope improvement or solar protection, in a building located in the city of Hangzhóu (Cfa climate zone).

The setpoint temperatures used in the modellings analysed are also important to mention. The modification of setpoint temperature values significantly influences energy consumption [21]: (i) Spyropoulos and Balaras [18] established setpoint temperatures of 20°C for heating and 26°C for cooling in bank branches, according to the national legislation for public buildings in Greece. The results obtained a decrease of the energy consumption for HVAC by 45%; (ii) Hoyt et al. [22] used setpoint temperatures of 18.3 and 27.87 °C for heating and cooling, respectively, in an office building located in 7 different climate zones, achieving a saving between 32 and 73%; and (iii) Wan et al. [23] studied the impact of climate change on office buildings in subtropical climates and the influence of the setpoint temperatures used. By using setpoint temperatures for cooling higher than 25.5 °C, the energy demand in different future scenarios was reduced.

Variations of these setpoint temperatures can therefore modify the amortization periods of the ECMs to be carried out as the energy consumption varies. However, in most of the studies mentioned above, setpoint temperatures were based on the index Predicted Mean Vote (PMV). In recent years, several research studies have stressed the importance of using adaptive setpoint temperatures, which could be defined as setpoint temperatures, to keep the internal operative temperature within the adaptive comfort limits. Also, these research works are focused on the application of adaptive comfort models from ASHRAE 55 [24] and from EN 15251 [25] in setpoint temperatures by analysing their advantages and limitations with respect to the models based on the PMV. Some of these research studies are as follows: (i) Sánchez-García et al. [26] studied the use of adaptive setpoint temperatures in future climate scenarios to reduce the energy demand in office buildings; (ii) Holmes and Hacker [27] analysed the application of the adaptive thermal comfort approach in different office buildings in United Kingdom, both in current and future scenarios; and (iii) Kramer et al. [28] used the lower limit of the model developed by Van der Linden et al. [29] for Holland, established in the standard ISSO 74 [30], as the heating setpoint temperature of a museum, thus obtaining a reduction of the energy consumption by 74%. However, there is a lack of research studies on this field in Spain: (iv) Sánchez-Guevara Sánchez et al. [31] applied the adaptive comfort model from ASHRAE 55-2013 with setpoint temperatures monthly varying, thus reducing the heating and cooling energy demand by 20% and 80%, respectively; (v) Barbadilla-Martín et al. [32] compared the energy demands of a building with mixed mode by using usual setpoint temperatures and setpoint temperatures based on the neutral temperature of a thermal comfort model previously developed in the city of Seville [33]. Usual average setpoint temperatures were 23.5°C and 22.3°C for cooling and heating, respectively, whereas the average neutral temperatures were 24°C and 21°C for cooling and heating, respectively. The results showed reductions by 27.5% and 11.4% in cooling and heating, respectively.

There are many studies analysing the significant influence of thermophysical properties of the building envelope on their energy demand, as well as the advantages and limitations of using adaptive setpoint temperature models. However, there are few studies conducted in warm regions, such as the Mediterranean one. In these regions, high solar radiation and external air temperatures generate environmental conditions which influence the users' thermal comfort, and therefore the building energy demand [34–37] . Some researchers have analysed different methods for the energy improvement of buildings in this region: (i) Pérez-Andreu et al. [38] analysed 8 ECMs in a case study located in Almeria. The analyses were carried out for 2050 and 2100. The results showed that the combination of ECMs of the envelope are the most effective measures to reduce energy consumption; (ii) Ascione et al. [39] indicated that the efficiency improvement of energy systems was among the best options to reduce the energy consumption in Italian and Greek buildings (this type of measures allows energy consumption in historic buildings to be reduced due to the difficulties of modifying their enclosures [40]); (iii) Di Perna et al. [41] and Rossi and Rocco [42] studied different walls with different periodic thermal properties. The results showed that the control of the internal areal heat capacity and of the thermal mass reduced the energy demand; and (iv) Echarri et al. [43] evaluated the application of the Passivhaus standard in the Mediterranean region. The results reflected that the use of solar protections, thick insulation on facades, and the use of efficient air conditioning systems guarantee a correct application of the Passivhaus standard.

However, these studies do not consider the economic profitability of ECMs, the influence of HVAC systems or the variation of external conditions due to climate change. In this sense, the increase of external temperatures in future climate scenarios can be a serious problem for people's health, with an increase in the death rate [44–46]. It is therefore necessary to have specific regional studies determining the feasibility of the performance on the envelope elements (e.g., studies developed in cold climates [47]) which analyse future climate scenarios [48] to establish effective ECMs [49].

Within the context of climate change, this research studies the importance of performances in existing building envelopes located in warm climate regions. For this purpose, a characteristic case study with weak thermophysical properties in its envelope is used. The case study is in Andalusia, in the south of Spain (Csa climate region). The Spanish residential sector strongly affects the energy consumption and is responsible for 15.9% of the total energy consumption in 2016, with an increase of 4.1% with respect to the previous year [50]. In addition, more than 53.6% of residential buildings present a deficient energy behaviour [51], so the impact on the results obtained in this study could be of interest in the proposal of ECMs for these buildings.

Improvement performances on a building façade were analysed. To do this, variations presented by the energy consumption were evaluated by using adaptive setpoint temperatures. Likewise, the influence of the ECMs was analysed in future climate scenarios (2050 and 2080), and the cost and the payback period associated with each measure were determined.

This paper is divided into three sections. Firstly, the methodology used in this research is described by analysing the following aspects: (i) the analysis of the case study; (ii) the analysis of the climate zone under study and the characterization of future scenarios; (iii) the definition of the energy simulation model of the case study; (iv) the validation of the model; and (v) the proposal of ECMs. Secondly, the results are discussed, and this section is in turn divided into three parts: (i) a comparative study of the results of ECMs between the demand approach by using setpoint temperatures based on the index PMV and those based on the adaptive approach; (ii) the influence of ECMs on the building energy behaviour in future scenarios (2050 and 2080); and (iii) the payback period of ECMs. Finally, the main conclusions of results are summarized.

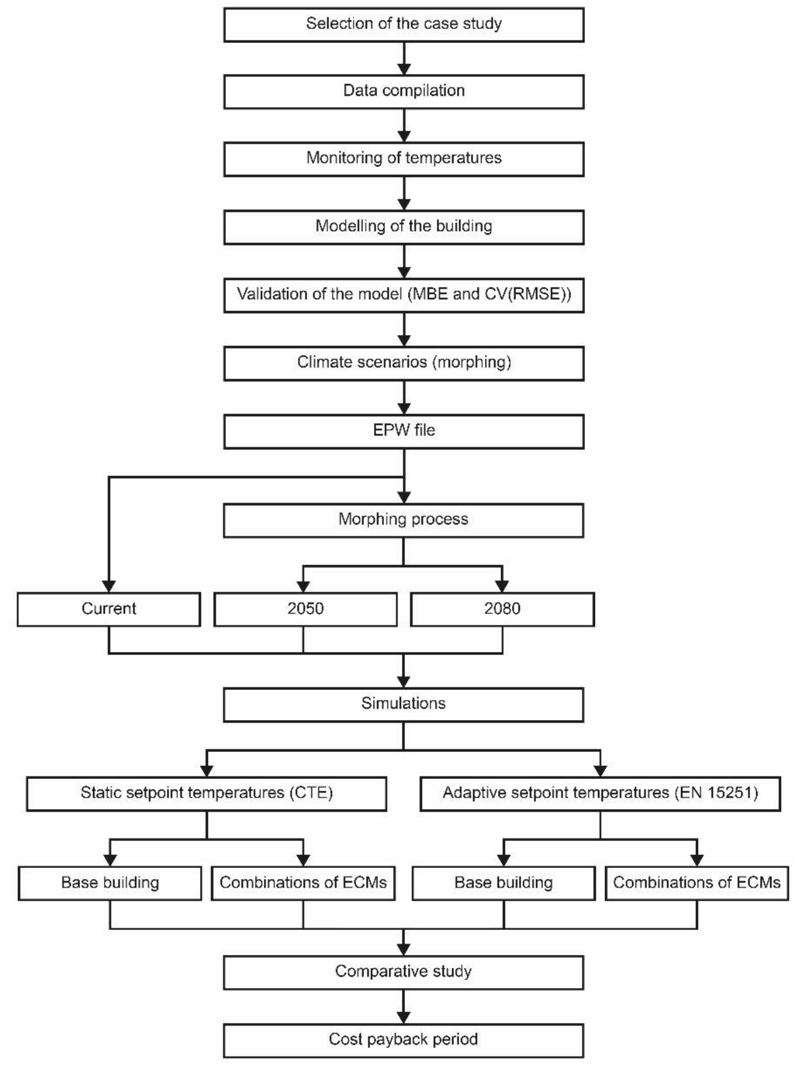


Fig. 1. Flowchart of the procedure followed in this research.

2. Methodology

The methodological framework consisted in selecting a case study with a deficient energy behaviour, representative of the Spanish building stock and whose technical documentation was available. After selecting the case study, it was modelled, monitored and validated. Afterwards, energy simulations of the different ECMs and future climate scenarios (2050 and 2080) were performed. Finally, the amortization period of the ECMs was analysed by using data of adaptive energy consumption. The flowchart of the research procedure is included in Fig. 1.

2.1. Case study

The case study is a building made up of 8 floors and built in 1978. This kind of building typology is the most plentiful in Spain. In this regard, according to the Housing Census in Spain [52], the building period with a larger number of buildings and dwellings of the building stock is the period between 1971 and 1979 (Fig. 2), anterior to the normative NBE-CT 79 [53]. Most of the existing building stock in Spain was therefore built in the period anterior to NBE-CT 79 [2], which was characterized by no using insulation in building solutions because it was not mandatory [2].

The dwellings of this case study have 6 rooms facing southeast, southwest, northeast, and northwest. The distribution of rooms can be seen in Fig. 3. As mentioned above, the case study was selected because it presented deficient thermophysical properties, and its technical documentation was available to define its envelope correctly. Following the methodology established by Ficco et al. [54], the number of layers, thickness and thermophysical properties of walls, slabs and windows were determined (Table 1).

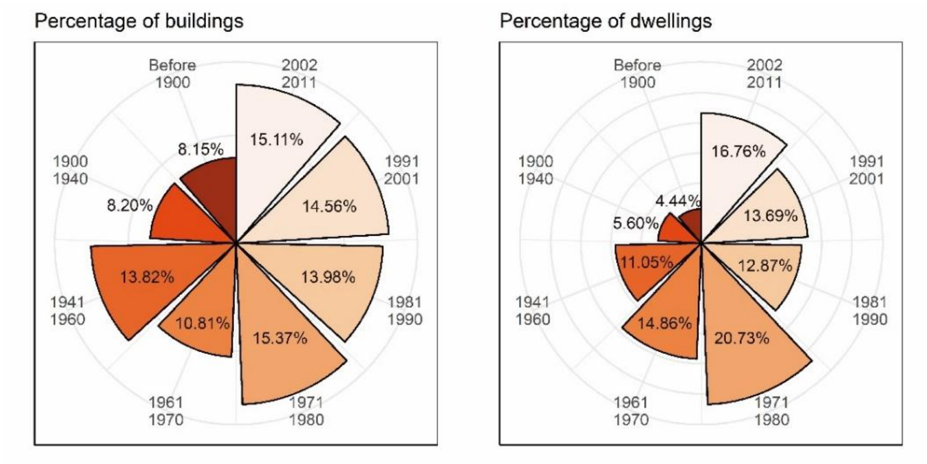
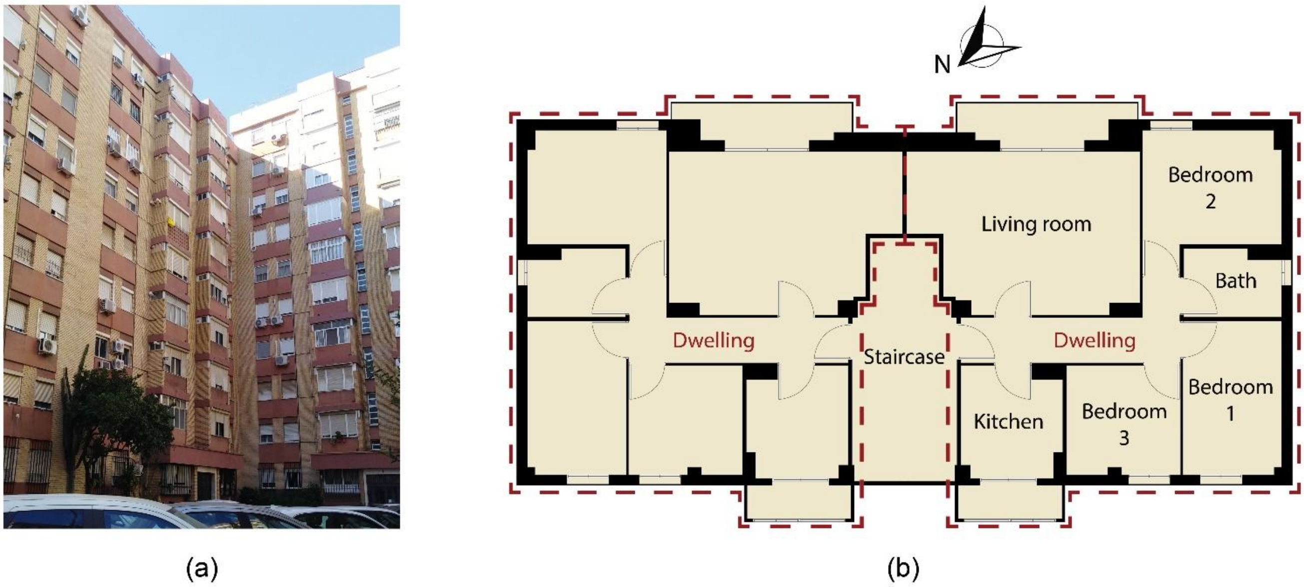


Fig. 2. Pie chart including the percentages of buildings and dwellings in each Spanish building period.



(a) (b)

Fig. 3. Case study selected: (a) a photograph of the building façade, and (b) a graphical representation of the typical floor.

Table 1. Thermophysical properties of the envelope elements.

Component	Layers				Thermal transmittance $[W/(m^2 \cdot K)]$	Internal heat capacity $[kJ/(m^2 \cdot K)]$
	Description	Thickness [mm]	Thermal conductivity $[W/(m \cdot K)]$	Thermal resistance $[(m^2 \cdot K)/W]$		
Exterior wall	Cement plaster	10	1,000	-	1.35	80.35
	Hollow brick masonry	70	0,375	-		
	Air gap	50	-	0.18		
	Cement plaster	15	1,300	-		
	Brick masonry facing	115	1,042	-		
Interior wall	Cement plaster	10	1,300	-	2.74	39.00
	Double hollow brick masonry	40	0,444	-		
	Cement plaster	10	1,300	-		
Windows	Aluminium frame	-	-	-	5.89	-
	Simple glazing 3 mm	-	-	-		
Floor and paving	Terrazzo paving	20	1,800	-	1.76	147.63
	Sand	30	2,000	-		
	Lightweight floor slab, cast in place, with a depth of 25 cm	250	0,893	-		

2.2. *Characteristics of climate and future scenarios*

The case study is in Seville, in the south of Spain, which is located in the Csa climate zone [17] characterized by dry, hot summers and mild winters, where maximum and minimum average temperatures are between 17.9 and 34 °C in summer, and between 7.14 and 18.6 °C in winter. The typical characteristics of the climate of the area are included in the EnergyPlus Weather (EPW) file of Seville. By using this file, climate scenarios for the years 2050 and 2080 can be obtained with a morphing process [55–57]. This process develops time series for future scenarios by using data from the EPW files with United Kingdom Met Office Hadley Centre (MOHC), which in turn uses coarse General Circulation Model (GCM) predictions for the A2 greenhouse gas emissions scenario (medium-high) [58]. There are several research studies verifying the potential of using future climate scenarios obtained by a morphing process [19,56,57], although some natural phenomena associated with climate change are not considered (e.g., hurricanes) as well as those typical effects of urban nuclei, such as the heat island [19].

By using the tool CCWorldWeatherGen, a total of 3 EPW files under A2 emissions scenario were obtained for 2050 and 2080. Fig. 4 shows the average temperature values of each EPW file.

2.3. *Definition of the model*

Simulations were carried out with DesignBuilder, which uses the calculation engine EnergyPlus. As usage profiles of the building, the profile defined by the Spanish Building Technical Code (CTE) for energy simulations was used [59]. Fig. 5 includes occupancy, lighting and equipment profiles. The sensible load in weekends corresponding to 100% of occupancy was 2.15 W/m^2, and the latent load was 1.36 W/m^2. During the week, the sensible and latent loads of occupancy varied from 100% in the night period to 0.54 W/m^2 and 0.34 W/m^2 (period from 8am to 3pm), and to 1.08 W/m^2 and 0.68 W/m^2 (period from 4pm to 11pm), respectively. The lighting and equipment loads varied throughout the day, being 100% (4.40 W/m^2) from 8pm to 11pm [59]. With respect to the characteristics of active systems of air-conditioning, those from the existing equipment installed in the case study were used (a heat pump with EER of 2.00 and with COP of 2.10).

The values associated with setpoint temperatures varied according to the approach used. Hourly values of heating and cooling setpoint temperatures are included in Table 2. In the case of the static model, setpoints were established according to the residential profile included in the CTE, which did not consider external climate conditions and established an hourly profile depending on the season. From the two more widely used existing adaptive comfort models (ASHRAE 55 and EN 15251), the model from the standard EN 15251 was used in this work. Likewise, among the four types of classification of internal comfort described in this standard, the category III (existing buildings) was considered as it was the most adequate for the case study (performance on existing buildings). Upper and lower limit values from the category III were therefore applied to setpoint temperatures (Table 2). These values were applied by using different linear correlations for the external temperature, and they varied according to the type of limit: the lower limit was in the range of weighted average external temperatures (θ_{rm})) between 15 and 30 °C (see Eq. (1)), and the upper limit was in the range between 10 and 30 °C (see Eq. (2)). When these temperatures were overcome, the limit value in EN 15251 for active systems was used. As usage profiles of HVAC systems set by the Spanish Building Technical Code (CTE) do not consider heating or cooling in certain hours (e.g., from 8am to 3pm in summer), adaptive setpoint temperatures were adapted to these usage profiles. So, a comparative analysis of ECMs between the static demand models and the adaptive demand models was carried out.

$$Upper\ limit = 0.33 * \Theta_{rm} + 18.8 + 4 \quad [ºC] \tag{1}$$

$$Lower\ limit = 0.33 * \Theta_{rm} + 18.8 - 4 \quad [ºC] \tag{2}$$

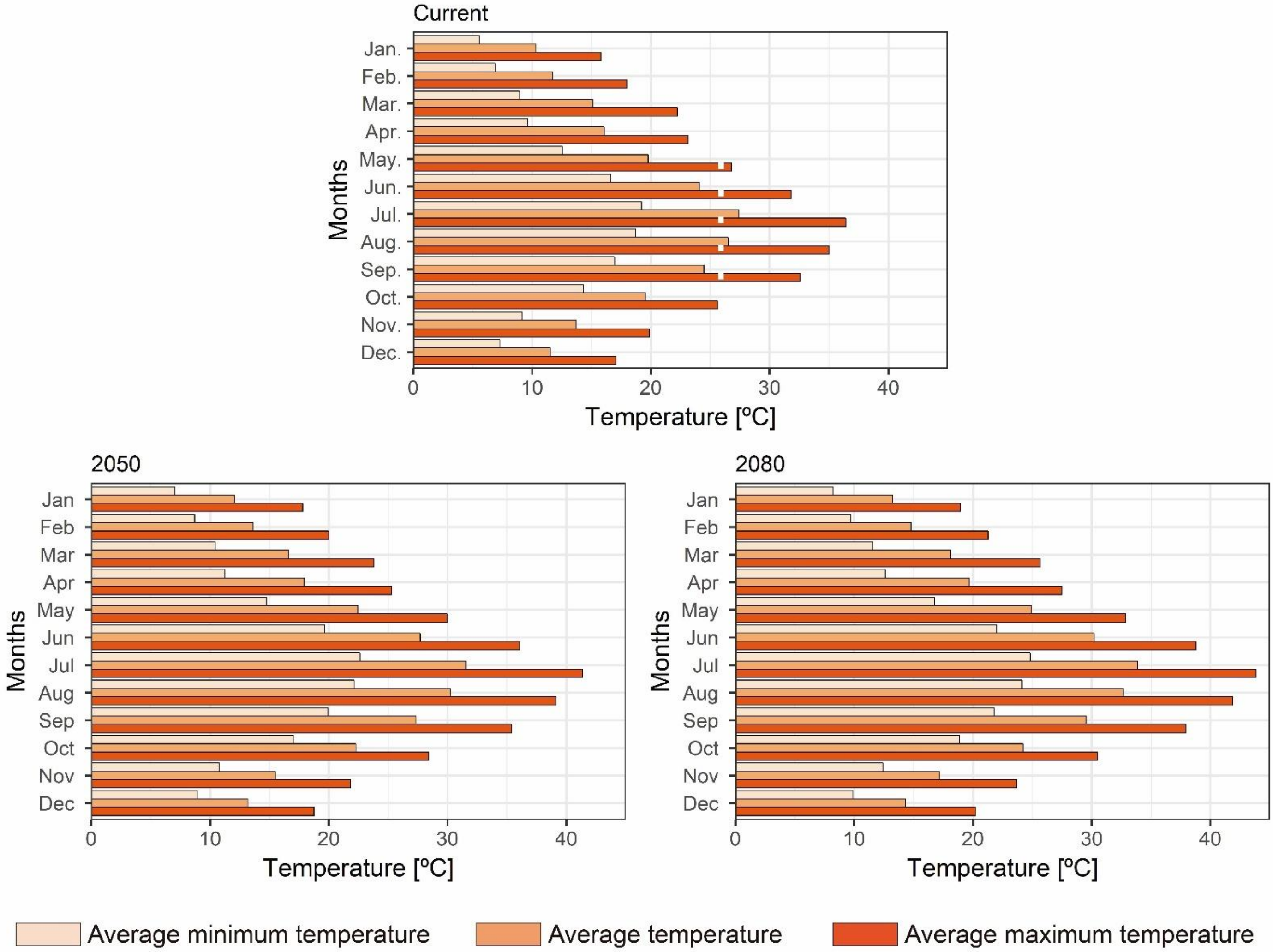


Fig. 4. Average temperatures of the EPW files (current, 2050 and 2080) of the city of Seville.

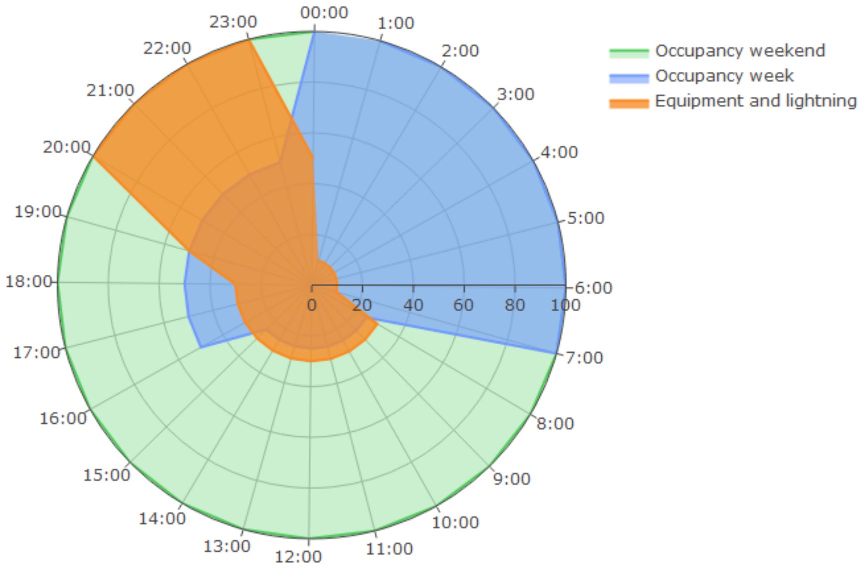


Fig. 5. Radar chart with hourly profiles of occupancy week (blue), occupancy weekend (green), and equipment and lightning (orange).

Table 2. Setpoint temperatures used in each model.

Model	Standard	Limit	Range	Setpoint temperature [ºC]								
				January - May			June - September			October - December		
				24-7	8-15	16-23	24-7	8-15	16-23	24-7	8-15	16-23
Static model	CTE	Upper limit	all	-	-	-	27	-	25	-	-	-
		Lower limit	all	17	20	20	-	-	-	17	20	20
Adaptive model	15251 Category III	Upper limit	$\Theta_{rm} < 10$ °C	-	-	-	25	-	25	-	-	-
			10 °C $\leq \Theta_{rm} <$ 30°C	-	-	-	Eq. (1)	-	Eq. (1)	-	-	-
			$\Theta_{rm} > 30$ °C	-	-	-	27	-	27	-	-	-
		Lower limit	$\Theta_{rm} < 15$ °C	18			-	-	-	18		
			15 °C $\leq \Theta_{rm} \leq$ 30°C	Eq. (2)			-	-	-	Eq. (2)		
			$\Theta_{rm} > 30$ °C	22			-	-	-	22		

2.4. Validation of the model

The ASHRAE Guideline 14-2014 (ANSI/ASHRAE)[60] establishes the limits that statistical parameters should adopt to determine the adjustment degree of a model. For this purpose, the Mean Bias Error (MBE) (Eq. (3)) and the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) (Eq. (4)) were used as statistical parameters. Many research studies have used these calibration criteria, such as those by Yang and Becerik-Gerber [61] and by Mustafaraj et al. [62], with accuracy levels adjusted for the models simulated. The limit values set by the Guideline 14 for hourly values are -10% ≤ MBE ≤ +10% and CV(RMSE) ≤30% [60]. Thus, if the model fulfils these requirements, then it is calibrated.

$$MBE = \frac{\sum_{i=1}^{n}(y_i - x_i)}{n} \cdot 100 \quad [\%] \tag{3}$$

$$CV(RMSE) = \frac{1}{\bar{y}}\left(\frac{\sum_{i=1}^{n}(y_i - x_i)^2}{n}\right)^{1/2} \cdot 100 \quad [\%] \tag{4}$$

Where n is the number of instances, y_i is the measured value, x_i is the simulated value, and $\bar{y}$ is the mean of the measured values.

To calibrate and validate the model, the indoor air temperature and the outdoor dry-bulb temperature of rooms 1 and 2 were monitored. Measurements were carried out using HOBO Pendant temperature/light data logger 8K-UA-002-08 sensors for external temperatures, and HOBO U12-012 sensors for internal temperatures. The accuracy of these sensors is ±0.7 °C. Internal sensors were placed in the bedrooms of the dwelling and external sensors were placed on a windowsill. Probes were placed to guarantee their protection from solar radiation and other radiating elements. Monitorings were carried out with an interval of data acquisition of 10 min and in 3 different seasons: (i) winter, from January 14th to February 03rd; (ii) spring, from May 14th to June 12th; and (iii) summer, from June 22nd to July 22nd. These periods were selected due to their representation with variable temperature conditions of Csa climate. In total, a dataset of 11,376 instances (measurements) were used to validate the model. Table 3 shows that the values of *MBE* and of *CV(RMSE)* obtained were within the criteria per hour established by the ASHRAE. The accuracy of the model was therefore within acceptable limits.

Table 3. Results of the validation of the model.

Monitoring period	Room	Indoor air temperature		Outdoor dry-bulb temperature	
		MBE [%]	CV(RMSE) [%]	MBE [%]	CV(RMSE) [%]
14th Jan 2015 - 03rd Feb 2015	Bedroom 1	-4.71	13.42	4.47	25.74
	Bedroom 2	-6.30	16.47	4.61	25.35
14th May 2015 - 12th Jun 2015	Bedroom 1	3.43	7.36	5.87	26.26
	Bedroom 2	4.51	8.03	5.46	29.27
22nd Jun 2015 - 22nd Jul 2015	Bedroom 1	-0.56	7.55	5.93	21.41
	Bedroom 2	0.45	8.42	6.15	23.04

2.5. *The Energy Conservation Measures analysed*

The actual problem of the building is the poor thermal properties of its envelope. High thermal transmittance values are associated with a high energy consumption. According to Gangolells et al. [63], the use of insulation (interior or exterior) could improve the energy behaviour of these buildings. For this reason, 4 ECMs for façades were defined (see Table 4). These measures were selected based on the solutions commonly adopted in the energy improvement performances in Spain [64–66]. Mineral wool was used as insulating material for all ECMs of the façade (thermal conductivity of $0.037 \mathrm{W}/(\mathrm{m} \cdot \mathrm{K})$) as this type of insulating material is the most used [67]. Moreover, the thickness used in each ECM was the same (4 cm) to make representative comparisons among the ECMs.

The investment price and the maintenance cost of each ECM were obtained from a Spanish building price database [68]. In such database, the investment costs of each ECM include the material required to be installed (e.g., the insulation), the costs of auxiliary means (e.g., scaffoldings) and labour, and the costs associated with the management of the wastes generated. The improvement obtained by each measure as well as investment and maintenance prices are indicated in Table 4.

Table 4. Improvement, and investment and maintenance prices of each dwelling associated with each ECM.

ECM	Description	*U*-value	Investment [€]	Maintenance [€/year]
ECM 1	Insufflation of the interior of the air gap with insulation.	0.64	1,069.88	58.14
ECM 2	Internal plasterboard with insulation.	0.50	3,841.54	89.98
ECM 3	External Thermal Insulation Composite Systems (ETICS).	0.55	7,175.26	48.87
ECM 4	Façade ventilated with insulation.	0.54	15,674.00	233.90

A different simulation model was defined for each ECM in Table 4. In this sense, it is important to note that the ECM 0 model corresponded to the building in current state (without improving the façade).

2.6. *Cost payback period*

The cost payback period of each ECM was assessed to analyse the return of work execution costs (investment cost) with the energy consumption saving (return cash flow). The cost payback period was therefore obtained by the amortization of the investment cost by means of return cash flows. Given that investment and maintenance costs were obtained for each ECM, two assumptions were considered: (i) a fixed cost of investment corresponding to the cost of implementing the ECM (Eq. (5)); and (ii) an investment cost accumulated from the sum of the work execution cost and annual maintenance costs (Eq. (6)).

$$Payback\ period_{without\ maintenance} = N_{j-1} + \frac{i_0 - R_{j-1}}{r_j} \tag{5}$$

$$Payback\ period_{with\ maintenance} = N_{j-1} + \frac{I_j - R_{j-1}}{r_j} \quad (6)$$

Where N_{j-1} [years] is the number of years before the year of amortization j, i_0[€] is the investment cost of the ECM, R_{j-1} [€] is the return cash flow accumulated before the year j, r_j [€] is the return cash flow in the year j, and I_j [€] is the investment cost accumulated from the cost of implementing the ECM and annual maintenance costs.

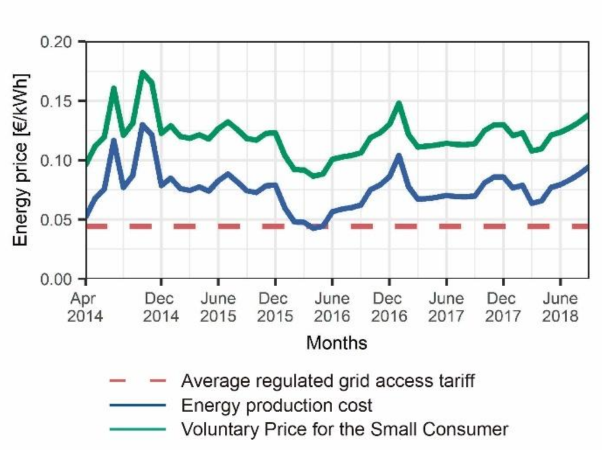


Fig. 6. Monthly evolution of the VPSC. The average regulated grid access tariff is represented by the red line, the energy production cost is represented by the blue line, and VPSC is represented by the green line.

It is worth noting that two aspects were considered for the return cash flow: (i) the energy saving was obtained from the existing difference between the energy consumption of the building with the ECM and the energy consumption of the building without the ECM (called ECM 0 for this study). The energy saving by using adaptive setpoint temperatures was not considered because it was not a characteristic of the façade improvement; and (ii) the rate of the light was obtained by means of the Voluntary Price for the Small Consumer (VPSC, or PVPC in Spanish). Since 2014, the price of the electricity rate in Spain is assigned by the VPSC [69]. VPSC is an hourly rate of energy established by the Spanish government. The rate is obtained by the sum of two prices: the regulated grid access tariff and the energy production cost. The regulated grid access tariff is a fixed value (0.044027 €/kWh), whereas the energy cost varies according to the energy supply and demand of the previous day. Nowadays, the main companies supplying energy provide this rate to those users with a contracted power lower than 10 kW. Thus, the VPSC was used to establish the base price of the energy and to estimate the rate of increase in the next years. For this purpose, data included in the Spanish Transmission System Operator, which is developed by the electricity grid in Spain, were used (see Fig. 6). The average price of VPSC in 2018 (for this study, until September) was 0.1226 €/ kWh. This price was designed as the base price. The rate of increase of 2018 with respect to 2017 was 1.91%, and this is the rate of increase considered for the VPSC in the next years.

Given that the investment cost significantly influences the payback period, a possible scenario of decreasing this price with government aids was analysed. In Spain, the Ministry of Energy, Tourism and Digital Agenda implemented an aid program for building energy measures: it is known as Aids Program for Energy Rehabilitation in Existing Buildings (APEREB, or PAREER in Spanish) [70]. With a budget of €204,000,000, such program finances reductions by 30% in the ECM execution price in building envelopes. The scenarios and assumptions considered in the cost payback period are summarized in Table 5.

Table 5. Scenarios and assumptions considered in the cost payback period.

Scenario	Considerations of the investment cost	Number of the payback periods obtained by each ECM.
Without government aids	Two options: (i) without considering maintenance costs; and (ii) considering maintenance costs.	2
With government aids	Two options: (i) without considering maintenance costs; and (ii) considering maintenance costs.	2

3. Results and discussion

3.1. Performance of ECMs in the current scenario

Firstly, the influence of using adaptive setpoint temperatures with respect to the static setpoint temperature established by CTE in the current scenario was analysed. As indicated in Section 2, a simulation was performed for each ECM suggested, and another for the building without improving the façade (ECM 0). Fig. 7 shows the results obtained from the simulations. The point clouds of Fig. 7 shows that the use of adaptive setpoint temperatures decreased the hourly energy consumption. Points of hourly consumption gathered near the axis of abscissas due to the low consumption values associated with the adaptive model. In this sense, for the current building (ECM 0), the use of adaptive setpoint temperatures achieved, at an hourly level, a mean absolute difference of 0.17 kWh for the heating consumption, and of 0.29 kWh for the cooling consumption. Thus, the use of these setpoint temperatures significantly reduced the cooling energy consumption. This reduction achieved a saving of 26.24%, 73.10%, and 57.41% for annual heating, cooling and total consumption, respectively, in the ECM 0 model.

With respect to the ECMs, the effect generated by the façade improvement depended on the type of energy consumption: the reduction of the cooling energy consumption was lower than the heating energy consumption. Likewise, the effect depended on the type of setpoint temperature used. In this regard, the maximum decrease of heating consumption was 197.45 kWh for the adaptive model, whereas it was 177.15 kWh for the static model (case ECM 2) (Table 6-7). Concerning the cooling consumption, it can be seen in Tables 6-7 that the effect of improving the thermal transmittance of façades increased the cooling consumption of the adaptive model between 4.41 kWh and 66.81 kWh in all ECMs, whereas reductions with values similar to the heating consumption were achieved for the static model.

In the annual energy consumption, the same tendency was found with respect to the static model of ECM 0 (see Table 8): (i) for static models, the *U*-value improvement of the façade presented a higher influence in the saving of heating consumption than in the saving of cooling consumption, with percentages lower than 43% and 16%, respectively; and (ii) the combination of adaptive setpoint temperatures with the façade improvement achieved average decreases of 60.73%, 70.80%, and 67.42% for annual heating, cooling and total consumptions, in contrast to those of the static model (39.69%, 12.95%, and 21.91%, respectively).

Regarding the façade improvement with the best performance, Table 9 shows that the percentages of energy saving obtained by the ECMs were similar (except ECM 4, which had a different behaviour in the cooling energy consumption). As indicated above, the effect of the ECM was higher in the heating energy consumption than in the cooling energy consumption. However, the low value of annual heating energy consumption (a typical characteristic of the Mediterranean climate) caused that the façade improvement in the current scenario generated a not very influential effect on the energy consumption. The use of adaptive setpoint temperatures also allowed similar percentages to be achieved in heating, whereas in ECM 1, 2, and 3, it was the only decrease contribution in cooling (Table 9).

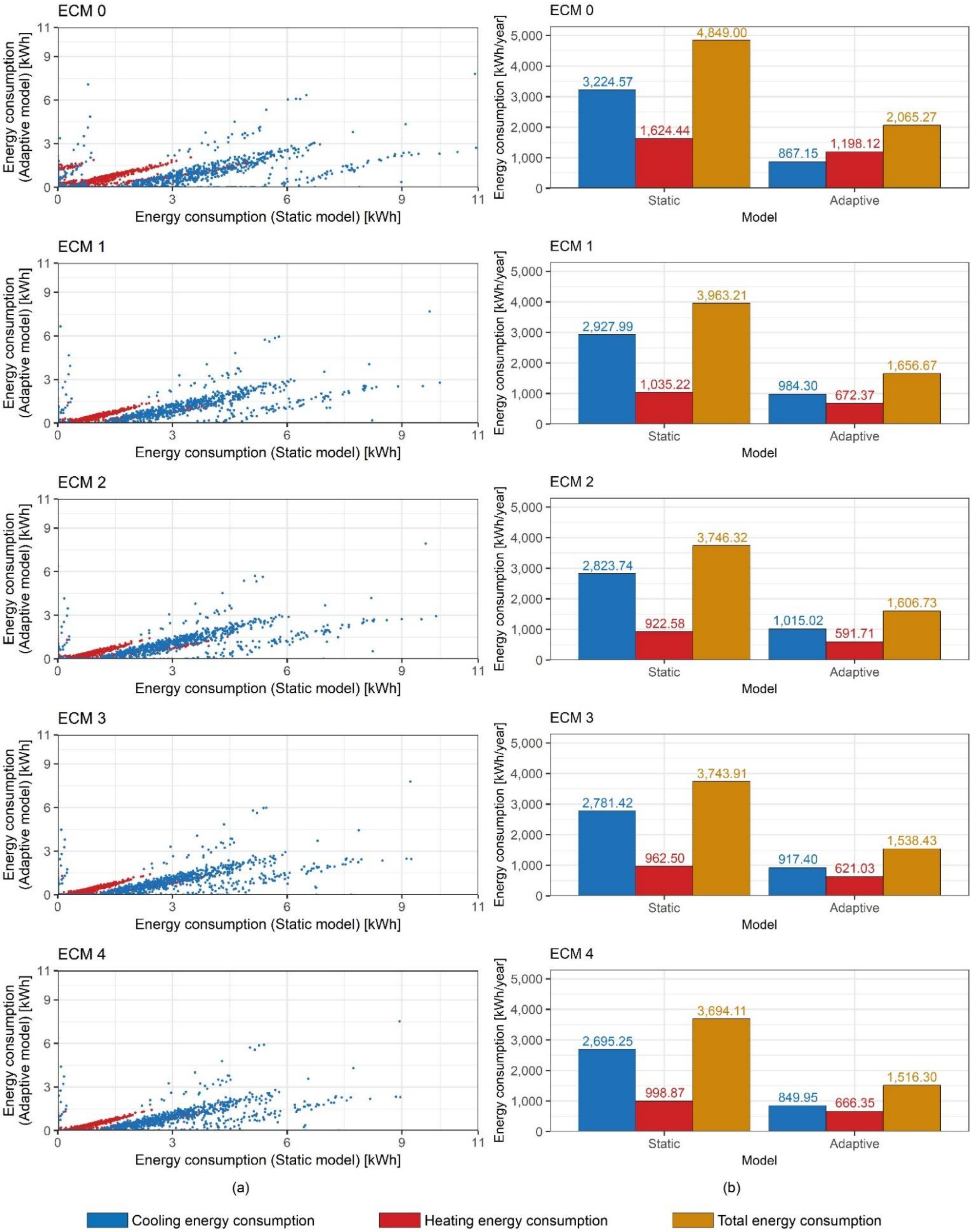


Fig. 7. Comparison of the consumption values obtained by each ECM model: (a) relationship in the current scenario between the heating energy consumption (red) and the cooling energy consumption (blue) of static and adaptive models; and (b) annual energy consumption values.

Table 6. Difference in the monthly energy consumption between the static models of the façade improvement (ECM 1, 2, 3, and 4) and the static model of the building without improving the façade (ECM 0 – static model).

Month	Difference in energy consumption [kWh]							
	ECM1		ECM 2		ECM 3		ECM 4	
	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling
January	-162.93	0.00	-197.45	0.00	-183.50	0.00	-174.05	0.00
February	-103.08	0.00	-123.53	0.00	-112.41	0.00	-104.38	0.00
March	-55.88	0.00	-66.25	0.00	-61.25	0.00	-56.47	0.00
April	-38.35	0.00	-42.45	0.00	-45.14	0.00	-43.66	0.00
May	-1.37	0.00	-1.62	0.00	-1.72	0.00	-1.64	0.00
June	0.00	-21.89	0.00	-37.02	0.00	-50.32	0.00	-71.62
July	0.00	-127.14	0.00	-167.97	0.00	-178.74	0.00	-202.00
August	0.00	-93.13	0.00	-124.83	0.00	-134.03	0.00	-157.54
September	0.00	-54.42	0.00	-71.00	0.00	-80.06	0.00	-98.15
October	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
November	-85.47	0.00	-99.73	0.00	-98.62	0.00	-92.32	0.00
December	-142.15	0.00	-170.82	0.00	-159.29	0.00	-153.05	0.00
Total	-589.22	-296.58	-701.86	-400.83	-661.94	-443.15	-625.57	-529.32

Table 7. Difference in the monthly energy consumption between the adaptive models of the façade improvement (ECM 1, 2, 3, and 4) and the adaptive model of the building without improving the façade (ECM 0 – static model).

Month	Difference in energy consumption [kWh]							
	ECM 1		ECM 2		ECM 3		ECM 4	
	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling
January	-150.56	0.00	-177.15	0.00	-168.97	0.00	-156.42	0.00
February	-90.34	0.00	-104.71	0.00	-95.21	0.00	-84.13	0.00
March	-45.80	0.00	-51.43	0.00	-48.28	0.00	-42.95	0.00
April	-27.34	0.00	-28.04	0.00	-28.23	0.00	-28.23	0.00
May	-0.45	0.00	-0.45	0.00	-0.45	0.00	-0.45	0.00
June	0.00	50.93	0.00	66.81	0.00	31.02	0.00	14.85
July	0.00	4.41	0.00	0.89	0.00	-17.42	0.00	-38.66
August	0.00	41.31	0.00	53.18	0.00	24.97	0.00	6.06
September	0.00	20.50	0.00	26.98	0.00	11.67	0.00	0.55
October	-1.36	0.00	-1.36	0.00	-1.36	0.00	-1.36	0.00
November	-82.38	0.00	-93.95	0.00	-95.75	0.00	-88.59	0.00
December	-127.53	0.00	-149.32	0.00	-138.83	0.00	-129.64	0.00
Total	-525.75	117.15	-606.40	147.86	-577.08	50.25	-531.77	-17.20

Table 8. Percentage deviation in the annual energy consumption between the models of the façade improvement (ECM 1, 2, 3 and 4) and the static model of the building without improving the façade (ECM 0 – static model).

ECM	Percentage difference with respect to ECM 0 (static model) in the annual energy consumption [%]					
	Static model			Adaptive model		
	Heating	Cooling	Total	Heating	Cooling	Total
ECM 1	-36.27	-9.20	-18.27	-58.61	-69.47	-65.83
ECM 2	-43.21	-12.43	-22.74	-63.57	-68.52	-66.86
ECM 3	-40.75	-13.74	-22.79	-61.77	-71.55	-68.27
ECM 4	-38.51	-16.42	-23.82	-58.98	-73.64	-68.73

Table 9. Contributions of percentage difference in the energy consumption for adaptive models with respect to the static model of the building without improving the façade (ECM 0 – static model).

ECM	Percentage difference in heating energy consumption [%]			Percentage difference in cooling energy consumption [%]		
	Adaptive setpoint temperatures [a]	U-value improvement [b]	Total saving [c]	Adaptive setpoint temperatures [a]	U-value improvement [b]	Total saving [c]
ECM 1	-26.24	-32.37	-58.61	-73.10	3.63	-69.47
ECM 2	-26.24	-37.33	-63.57	-73.10	4.58	-68.52
ECM 3	-26.24	-35.53	-61.77	-73.10	1.55	-71.55
ECM 4	-26.24	-32.74	-58.98	-73.10	-0.54	-73.64

[a] Percentage deviation with respect to the static model of ECM 0 by using adaptive setpoint temperatures.

[b] Percentage deviation with respect to the static model of ECM 0 by improving the façade.

[c] Total percentage deviation with respect to the static model of ECM 0.

3.2. *Performance of ECMs in future scenarios*

Regarding future scenarios, Fig. 8 shows how the increase of external temperatures reduced the heating energy consumption and increased the cooling energy consumption. This tendency shows improvement strategies in future scenarios where the cooling energy consumption should be reduced (the annual values obtained in the building without improvements were higher than 4,000 kWh). In this regard, the use of adaptive setpoint temperatures for ECM 0 allowed important savings to be achieved in annual energy consumptions with respect to the use of static setpoint temperatures (see Fig. 8):

- For the scenario 2050, a percentage saving of 36.83%, 36.26%, and 36.34% for annual heating, cooling and total consumptions, respectively, were achieved. The maximum monthly saving was 112.85 kWh for heating and 617.90 kWh for cooling.
- For the scenario 2080, a percentage saving of 40.54%, 20.07%, and 21.75% for annual heating, cooling and total consumptions, respectively, were achieved. The maximum monthly saving was 103.11 kWh for heating and 487.64 kWh for cooling.

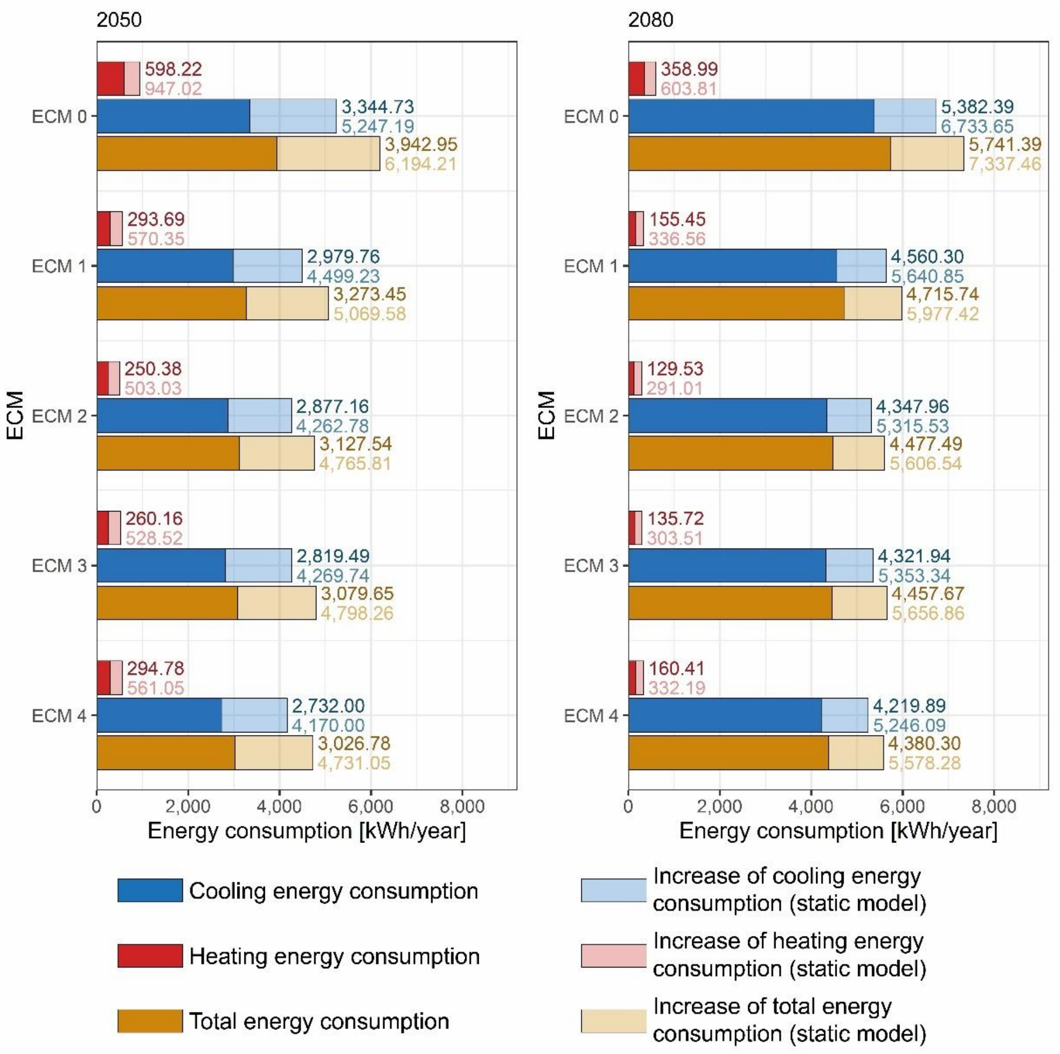


Fig. 8. Comparison of energy consumption values of each model simulated in future scenarios (2050 and 2080).

These percentages of the energy consumption saving achieved by using adaptive setpoint temperatures in the base building were higher than those achieved by ECMs with static setpoint temperatures in each scenario. The saving in the cooling energy consumption with the implementation of ECMs in the static model was lower than 23% in all cases, whereas the use of adaptive setpoint temperatures always achieved improvements higher than 20% (Tables 10-12).

On the other hand, the implementation of adaptive setpoint temperatures in ECMs allowed cooling savings to be achieved with respect to the static model of each ECM, which oscillated between 32.28% and 61.03% according to the scenario analysed (Tables 10-11). Although the reduction percentages of ECMs were lower than those achieved by the implementation of adaptive setpoint temperatures in the base model, the total reduction in the cooling energy consumption was higher due to the combination of measures (Table 12). In this sense, average annual values of cooling reduction of 2,395.38 kWh, and 2,371.12 kWh were obtained (see Fig. 8). Like the current scenario (section 3.1), the reduction obtained by improving the façade was similar (see Table 12).

Despite the best performance by using adaptive setpoint temperatures, a decreasing tendency in future scenarios was caused by the energy saving as the adaptive comfort model used in this study (EN 15251) dates from 2007, so it does not consider the possible adaptation capacity of people to increasing temperatures of climate change. It should be taken into account that the adaptation capacity of the occupants' thermal comfort usually has asymmetric trajectories [71] (i.e., it is easier for users with less demanding thermal requirements than for those who use more the air-conditioning). Thus, it is more common and easier for occupants to accept a neutral indoor climate than to reduce their expectations and to adapt to environments with less thermal comfortable conditions. The use of adaptive setpoint temperatures designed for future scenarios would achieve a greater reduction in the energy consumption as well as to present a behaviour like that of the current scenario. However, the increasing need for using the air conditioning could hinder using adaptive setpoint temperatures in the future based on current thermal comfort models. It is therefore necessary that users have greater awareness of the impact of the thermal behaviour on their dwellings. Also, the use of automated HVAC systems with automatic control of setpoint temperatures [72] could guarantee greater user's adaptability.

Table 10. Percentage deviation in the annual energy consumption in the scenario 2050 between the models of the façade improvement (ECM 1, 2, 3, and 4) and the static model of the building without improving the façade (ECM 0 – static model).

ECM	Percentage difference with respect to ECM 0 (static model) in the annual energy consumption [%]					
	Static model			Adaptive model		
	Heating	Cooling	Total	Heating	Cooling	Total
ECM 1	-39.77	-14.25	-18.16	-68.99	-43.21	-47.15
ECM 2	-46.88	-18.76	-23.06	-73.56	-45.17	-49.51
ECM 3	-44.19	-18.63	-22.54	-72.53	-46.27	-50.28
ECM 4	-40.76	-20.53	-23.62	-68.87	-47.93	-51.14

Table 11. Percentage deviation in the annual energy consumption in the scenario 2080 between the models of the façade improvement (ECM 1, 2, 3, and 4) and the static model of the building without improving the façade (ECM 0 – static model).

ECM	Percentage difference with respect to ECM 0 (static model) in the annual energy consumption [%]					
	Static model			Adaptive model		
	Heating	Cooling	Total	Heating	Cooling	Total
ECM 1	-44.26	-16.23	-18.54	-74.26	-32.28	-35.73
ECM 2	-51.80	-21.06	-23.59	-78.55	-35.43	-38.98
ECM 3	-49.73	-20.50	-22.90	-77.52	-35.82	-39.25
ECM 4	-44.98	-22.09	-23.98	-73.43	-37.33	-40.30

Table 12. Contributions of percentage difference in the cooling energy consumption in future scenarios for adaptive models (ECM 1, 2, 3, and 4) with respect to the static model of the building without improving the façade (ECM 0 – static model).

ECM	Percentage difference in cooling energy consumption [%]					
	2050			2080		
	Adaptive setpoint temperatures [a]	U-value improvement [b]	Total saving [c]	Adaptive setpoint temperatures [a]	U-value improvement [b]	Total saving [c]
ECM 1	-36.26	-6.95	-43.21	-20.07	-12.21	-32.28
ECM 2	-36.26	-8.91	-45.17	-20.07	-15.36	-35.43
ECM 3	-36.26	-10.01	-46.27	-20.07	-15.75	-35.82
ECM 4	-36.26	-11.67	-47.93	-20.07	-17.26	-37.33

[a] Percentage deviation with respect to the static model of ECM 0 by using adaptive setpoint temperatures.

[b] Percentage deviation with respect to the static model of ECM 0 by improving the façade.

[c] Total percentage deviation with respect to the static model ECM 0.

3.3. Scenarios of the cost payback period

As mentioned in section 2.6, two possible scenarios were considered for the calculation of the cost payback period: (i) the investment of the ECM without government aids, and (ii) the investment of the ECM with government aids by means of the PAREER program. Likewise, the hypothesis of including or not maintenance costs in the investment of each scenario was considered. Calculations were carried out by considering the energy saving in the current scenario. In the reduction percentages of measures, the decrease achieved with adaptive setpoint temperatures was not considered because the objective was to analyse the cost payback period of the façade improvement. Tables 13 and 14 show the return periods obtained for each ECM.

For the scenario without government aids, most measures obtained amortization periods economically unfeasible. For the static model, only ECM 1 obtained a low amortization period (8.96 years), although the incorporation of annual maintenance costs in the calculation of the payback increased the number of years required for the economic recovery (14.88 years). The incorporation of maintenance costs also influenced ECM 2 and ECM 3, increasing 13.25 and 7.19 the payback period, respectively. For the adaptive model, ECM 1 was the only measure with an amortization period economically unfeasible, although without considering the maintenance costs associated. It is worth noting the low economic profitability of the ECMs with the maintenance costs as the annual return cash flow for most ECMs was very similar to the annual maintenance cost.

Table 13. Cost payback period obtained by each ECM (scenario without government economic aids)

ECM	Cost payback period [years]			
	Static model		Adaptive model	
	Without maintenance	With maintenance	Without maintenance	With maintenance
ECM 1	8.96	14.88	17.79	45.81
ECM 2	22.56	35.81	43.58	>50
ECM 3	36.44	43.63	>50	>50
ECM 4	>50	>50	>50	>50

These high amortization periods took place because of to two factors: (i) the energy consumption saving obtained by ECMs was not high. As seen in section 3.1, the saving was mainly in the heating consumption. However, there are many studies which reflect that the main consumption source in the area is cooling [73,74]; and (ii) the high investment cost associated with ECMs, as only ECM 1 had a price near to €1,000. In this sense, the reduction of investment costs in the scenario with aids from the PAREER program slightly reduced the payback periods, with a behaviour like that of the other scenario: for the static model, ECM 1 obtained acceptable payback periods in both assumptions (with or without maintenance); and for the adaptive model, only ECM 1 obtained a valid payback period without considering maintenance costs.

Table 14. Cost payback period obtained by each ECM (scenario with government economic aids by means of the PAREER program).

ECM	Cost payback period [years]			
	Static model		Adaptive model	
	Without maintenance	With maintenance	Without maintenance	With maintenance
ECM 1	6.42	10.92	13.06	39.93
ECM 2	17.75	28.73	32.83	>50
ECM 3	27.88	34.60	47.52	>50
ECM 4	47.41	>50	>50	>50

Given the paybacks periods obtained in the different scenarios, which were economically unfeasible, these measures are not adequate in buildings located in the Mediterranean climate. In this sense, although ECM 1 obtained acceptable periods for the static model, the energy consumption saving was lower than that obtained by using adaptive setpoint temperatures (savings of 18.27% and 57.41%, respectively).

Thus, the combination of the façade improvement by insufflation of the interior of the air gap with insulation and the use of adaptive setpoint temperatures was the most appropriate ECM for existing buildings. This combination guaranteed a low payback period and adequate energy savings. The use of the adaptive thermal comfort model therefore obtained the best building energy behaviour. In such way, the potential of using adaptive setpoint temperatures as an energy conservation measure was reflected, as well as the use of ECM of the envelope with low economic cost.

4. Conclusions

This paper studies the effect of improving the thermophysical properties of building envelopes in Mediterranean climate. A representative case study of the area was selected, and the effect of using different energy conservation measures was analysed. This analysis was carried out under the assumptions of using static and adaptive setpoint temperatures. Based on the results, conclusions were drawn as follows:

- The use of adaptive setpoint temperatures greatly reduced the energy consumption of the building in the current scenario. Reductions by 26.24%, 73.10%, and 57.41% were obtained for annual heating, cooling and total consumption, respectively. The building façade improvement in the static model did not reach such high reductions in the total energy consumption (between 18.27 and 23.82%).
- The improvement of the thermophysical properties of the façade in the adaptive model of the current scenario generated two opposite effects according to the type of consumption: the energy consumption decreased for heating and increased for cooling. Only ECM 4 (façade ventilated) achieved a light decrease in the cooling consumption (a saving of 17.20 kWh).
- In future scenarios (2050 and 2080), the use of adaptive setpoint temperatures constituted the main contribution to the energy consumption saving. However, the increase of temperature resulted in that the adaptive comfort model would not be applicable more frequently, thus using the model for active systems and limiting the reduction of the energy consumption. Moreover, although in parallel the heating consumption decreased in the advance of climate scenarios, the cooling increase was higher, and the total was also higher. In this way, the application of adaptive setpoint temperatures in future scenarios presented a decreasing tendency in the reduction of the energy consumption, thus generating that the influence of the U-value improvement of the façade was greater than the influence of the current scenario. On the other hand, for static models, the decrease was lower for both cooling and heating.
- The cost payback periods obtained for the façade improvements in both scenarios (with or without government economic aids) were economically unfeasible. For most of the energy conservation measures, the payback period was higher than 30 years, and only a lower payback period was achieved for the insufflation of mineral wool. Façade improvements were therefore not economically feasible in this region, whereas the use of adaptive setpoint temperatures in HVAC systems allowed a greater saving to be achieved by using the existing air conditioning system. The combination of the envelope improvement with a low economic cost (e.g., the insufflation of the interior of the air gap with insulation) and the use of adaptive setpoint temperatures is therefore the most appropriate energy conservation measures for existing buildings in the Mediterranean climate zone.

To conclude, it is worth noting that the results of this research could be useful for both engineers and architects to be able to reduce the energy consumption of the existing buildings. The use of adaptive setpoint temperatures constitutes an actual opportunity to reduce significantly energy consumption, particularly due to the low economic profitability of the façade improvement. However, these results could only be applied in the Mediterranean climate zone. The profitability of improving façades in other climate zones with respect to adaptive models will therefore be studied in further works. Likewise, some limitations of the adaptive comfort model from EN 15251 (e.g., external temperatures in future scenarios, the typical characteristics of each climate zone or possible effects of urban heat island) should be studied in future works to improve these energy conservation measures.

Nomenclature

Symbols

I_j	Investment cost accumulated from the cost of implementing the ECM and annual maintenance costs [€]
i_0	Investment cost of the ECM [€]
N_{j-1}	Number of years before the year of amortization j [years]
n	The number of instances [dimensionless]
$Payback\ period_{with\ maintenance}$	Payback period considering works execution costs and the annual maintenance costs [years] as investment cost
$Payback\ period_{without\ maintenance}$	Payback period considering work execution costs as investment cost [years]
R_{j-1}	Return cash flow accumulated before the year of amortization j [€]
r_j	Return cash flow in the year of amortization j [€]
U-value	Thermal transmittance [W/(m^2·K)]
x_i	The simulated value [ºC]
y_i	The measured value [ºC]

$\bar{y}$	The mean of measured values [ºC]
Greek letters	
θ_{rm}	Running mean outdoor air temperature [ºC]
Abbreviations	
ANSI/ASHRAE	American National Standards Institute/American Society of Heating Refrigerating and Air-Conditioning Engineers
APEREB	Aids Program for Energy Rehabilitation in Existing Buildings
CTE	Spanish Building Technical Code
CV(RMSE)	Coefficient of Variation of the Root Mean Square Error [%]
ECM	Energy conservation measures
EPW	EnergyPlus Weather
GCM	General Circulation Model
HVAC	Heating, Ventilating and Air Conditioning
MBE	Mean Bias Error [%]
NBE-CT-79	Spanish Basic Building Norm about the Thermal Conditions in Buildings (repealed in 2006)
MOHC	Met Office Hadley Centre
PMV	Predicted Mean Vote
VPSC	Voluntary Price for the Small Consumer

References

[1] Horne R, Hayles C. Towards global benchmarking for sustainable homes: an international comparison of the energy performance of housing. J Hous Built Environ 2008;23:119–30. doi:10.1007/s10901-008-9105-1.

[2] Kurtz F, Monzón M, López-Mesa B. Energy and acoustics related obsolescence of social housing of Spain's post-war in less favoured urban areas. The case of Zaragoza. Inf La Construcción 2015;67:m021. doi:10.3989/ic.14.062.

[3] Lowe R. Technical options and strategies for decarbonizing UK housing. Build Res Inf 2007;35:412–25. doi:10.1080/09613210701238268.

[4] Park K, Kim M. Energy Demand Reduction in the Residential Building Sector: A Case Study of Korea. Energies 2017;10:1–11. doi:10.3390/en10101506.

[5] The United Nations Environment Programme. Building Design and Construction: Forging Resource Efficiency and Sustainable. Nairobi, Kenya: 2012.

[6] European Commission. Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings. vol. 1. Brussels, Belgium: 2002.

[7] European Union. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings. vol. 153. Brussels, Belgium: 2010.

[8] European Commission. A Roadmap for moving to a competitive low carbon economy in 2050. Brussels, Belgium: 2011.

[9] European Union. Directive 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency. vol. 2018. 2018.

[10] De Lieto Vollaro R, Guattari C, Evangelisti L, Battista G, Carnielo E, Gori P. Building energy performance analysis: A case study. Energy Build 2015;87:87–94. doi:10.1016/j.enbuild.2014.10.080.

[11] Escorcia O, García R, Trebilcock M, Celis F, Bruscato U. Envelope improvements for energy efficiency of homes in the south-central Chile. Inf La Construcción 2012;64:563–74. doi:10.3989/ic.11.143.

[12] Friedman C, Becker N, Erell E. Energy retrofit of residential building envelopes in Israel: A cost-benefit analysis. Energy 2014;77:183–93. doi:10.1016/j.energy.2014.06.019.

[13] Pacheco R, Ordóñez J, Martínez G. Energy efficient design of building: A review. Renew Sustain Energy Rev 2012;16:3559–73. doi:10.1016/j.rser.2012.03.045.

[14] Aksoy UT, Inalli M. Impacts of some building passive design parameters on heating demand for a cold region. Build Environ 2006;41:1742–54. doi:10.1016/j.buildenv.2005.07.011.

[15] Invidiata A, Lavagna M, Ghisi E. Selecting design strategies using multi-criteria decision making to improve the sustainability of buildings. Build Environ 2018;139:58–68. doi:10.1016/j.buildenv.2018.04.041.

[16] Bhikhoo N, Hashemi A, Cruickshank H. Improving thermal comfort of low-income housing in Thailand through passive design strategies. Sustain 2017;9:1–23. doi:10.3390/su9081440.

[17] Rubel F, Kottek M. Observed and projected climate shifts 1901-2100 depicted by world maps of the Köppen-Geiger climate classification. Meteorol Zeitschrift 2010;19:135–41. doi:10.1127/0941-2948/2010/0430.

[18] Spyropoulos GN, Balaras CA. Energy consumption and the potential of energy savings in Hellenic office buildings used as bank branches - A case study. Energy Build 2011;43:770–8. doi:10.1016/j.enbuild.2010.12.015.

[19] Rubio-Bellido C, Pérez-Fargallo A, Pulido-Arcas JA. Optimization of annual energy demand in office buildings under the influence of climate change in Chile. Energy 2016;114:569–85. doi:10.1016/j.energy.2016.08.021.

[20] Ge J, Wu J, Chen S, Wu J. Energy efficiency optimization strategies for university research buildings with hot summer and cold winter climate of China based on the adaptive thermal comfort. J Build Eng 2018;18:321–30. doi:10.1016/j.jobe.2018.03.022.

[21] Ren Z, Chen D. Modelling study of the impact of thermal comfort criteria on housing energy use in Australia. Appl Energy 2018;210:152–66. doi:10.1016/j.apenergy.2017.10.110.

[22] Hoyt T, Arens E, Zhang H. Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings. Build Environ 2014;88:89–96. doi:10.1016/j.buildenv.2014.09.010.

[23] Wan KKW, Li DHW, Lam JC. Assessment of climate change impact on building energy use and mitigation measures in subtropical climates. Energy 2011;36:1404–14. doi:10.1016/j.energy.2011.01.033.

[24] American National Standards Institute/American Society of Heating Refrigerating and Air-Conditioning Engineers (ANSI/ASHRAE). ANSI/ASHRAE Standard 55-2013. Thermal Environmental Conditions for Human Occupancy. vol. 2013. 2013.

[25] European Committee for Standardization. EN 15251: Indoor environmental input parameters for design and assessment of energy performance of buildings- addressing indoor air quality, thermal environment, lighting and acoustics. vol. 3. Brussels, Belgium: 2007.

[26] Sánchez-García D, Rubio-Bellido C, Marrero Meléndez M, Guevara-García FJ, Canivell J. El control adaptativo en instalaciones existentes y su potencial en el contexto del cambio climático. Hábitat Sustentable 2017;7:06–17.

[27] Holmes MJ, Hacker JN. Climate change, thermal comfort and energy: Meeting the design challenges of the 21st century. Energy Build 2007;39:802–14. doi:10.1016/j.enbuild.2007.02.009.

[28] Kramer RP, Maas MPE, Martens MHJ, van Schijndel AWM, Schellen HL. Energy conservation in museums using different setpoint strategies: A case study for a state-of-the-art museum using building simulations. Appl Energy 2015;158:446–58. doi:10.1016/j.apenergy.2015.08.044.

[29] van der Linden AC, Boerstra AC, Raue AK, Kurvers SR, De Dear RJ. Adaptive temperature limits: A new guideline in the Netherlands: A new approach for the assessment of building performance with respect to thermal indoor climate. Energy Build 2006;38:8–17. doi:10.1016/j.enbuild.2005.02.008.

[30] Arets MJP. Thermische behaaglijkheid : eisen voor de binnentemperatuur in gebouwen : een nieuwe richtlijn voor thermische behaaglijkheid in (kantoor)gebouwen. ISSO; 2004.

[31] Sánchez-Guevara Sánchez C, Mavrogianni A, Neila González FJ. On the minimal thermal habitability conditions in low income dwellings in Spain for a new definition of fuel poverty. Build Environ 2017;114:344–56. doi:10.1016/j.buildenv.2016.12.029.

[32] Barbadilla-Martín E, Guadix Martín J, Salmerón Lissén JM, Sánchez Ramos J, Álvarez Domínguez S. Assessment of thermal comfort and energy savings in a field study on adaptive comfort with application for mixed mode offices. Energy Build 2017;167:281–9. doi:10.1016/j.enbuild.2018.02.033.

[33] Barbadilla-Martín E, Salmerón Lissén JM, Martín JG, Aparicio-Ruiz P, Brotas L. Field study on adaptive thermal comfort in mixed mode office buildings in southwestern area of Spain. Build Environ 2017;123. doi:10.1016/j.buildenv.2017.06.042.

[34] Echarri-Iribarren V, Rizo-Maestre C, Echarri-Iribarren F. Healthy climate and energy savings: Using thermal ceramic panels and solar thermal panels in Mediterranean housing blocks. Energies 2018;11. doi:10.3390/en11102707.

[35] Attia S, Eleftheriou P, Xeni F, Morlot R, Ménézo C, Kostopoulos V, et al. Overview and future challenges of nearly zero energy buildings (nZEB) design in Southern Europe. Energy Build 2017;155:439–58. doi:10.1016/j.enbuild.2017.09.043.

[36] Attia S, Carlucci S. Impact of different thermal comfort models on zero energy residential buildings in hot climate. Energy Build 2015;102:117–28. doi:10.1016/j.enbuild.2015.05.017.

[37] Mazzeo D, Oliveti G, Arcuri N. Mapping of the seasonal dynamic properties of building walls in actual periodic conditions and

effects produced by solar radiation incident on the outer and inner surfaces of the wall. Appl Therm Eng 2016;102:1157–74. doi:10.1016/j.applthermaleng.2016.04.039.

[38] Pérez-Andreu V, Aparicio-Fernández C, Martínez-Ibernón A, Vivancos JL. Impact of climate change on heating and cooling energy demand in a residential building in a Mediterranean climate. Energy 2018;165:63–74. doi:10.1016/j.energy.2018.09.015.

[39] Ascione F, Bianco N, Mauro GM, Napolitano DF. Retrofit of villas on Mediterranean coastlines: Pareto optimization with a view to energy-efficiency and cost-effectiveness. Appl Energy 2019;254:113705. doi:10.1016/j.apenergy.2019.113705.

[40] Bottino-Leone D, Larcher M, Herrera-Avellanosa D, Haas F, Troi A. Evaluation of natural-based internal insulation systems in historic buildings through a holistic approach. Energy 2019;181:521–31. doi:10.1016/j.energy.2019.05.139.

[41] Di Perna C, Stazi F, Casalena AU, D'Orazio M. Influence of the internal inertia of the building envelope on summertime comfort in buildings with high internal heat loads. Energy Build 2011;43:200–6. doi:10.1016/j.enbuild.2010.09.007.

[42] Rossi M, Rocco VM. External walls design: The role of periodic thermal transmittance and internal areal heat capacity. Energy Build 2014;68:732–40. doi:10.1016/j.enbuild.2012.07.049.

[43] Echarri-Iribarren V, Sotos-Solano C, Espinosa-Fernández A, Prado-Govea R. The Passivhaus standard in the Spanish Mediterranean: Evaluation of a house's thermal behaviour of enclosures and airtightness. Sustain 2019;11. doi:10.3390/su11133732.

[44] Basu R, Samet JM. Relation between elevated ambient temperature and mortality: a review of the epidemiologic evidence. Epidemiol Rev 2002;24:190–202.

[45] Basu R. High ambient temperature and mortality: a review of epidemiologic studies from 2001 to 2008. Environ Heal 2009;8:40.

[46] Gasparrini A, Guo Y, Hashizume M. Mortalité attribuable au froid et à la chaleur: Analyse multi-pays. Environnement, Risques et Sante 2015;14:464–5. doi:10.1016/S0140-6736(14)62114-0.

[47] Pérez-Fargallo A, Rubio-Bellido C, Pulido-Arcas JA, Gallego-Maya I, Guevara-García FJ. Influence of adaptive comfort models on energy improvement for housing in cold areas. Sustain 2018;10:1–15. doi:10.3390/su10030859.

[48] Rubio-Bellido C, Pérez-Fargallo A, Pulido-Arcas JA, Trebilcock M. Application of adaptive comfort behaviors in Chilean social housing standards under the influence of climate change. Build Simul 2017;10. doi:10.1007/s12273-017-0385-9.

[49] Bienvenido-Huertas D, Quiñones JAF, Moyano J, Rodríguez-Jiménez CE. Patents Analysis of Thermal Bridges in Slab Fronts and Their Effect on Energy Demand. Energies 2018;11:2222. doi:10.3390/en11092222.

[50] Andalusian Energy Agency. Energy data of Andalusia. Seville, Spain: 2015.

[51] Gangolells M, Casals M. Resilience to increasing temperatures: Residential building stock adaptation through codes and standards. Build Res Inf 2012;40:645–64. doi:10.1080/09613218.2012.698069.

[52] Spanish Institute of Statistics. Population and Housing Census 2011. https://www.ine.es/censos2011_datos/cen11_datos_resultados.htm# (accessed November 9, 2018).

[53] The Government of Spain. Royal Decree 2429/79. Approving the Basic Building Norm NBE-CT-79, about the Thermal Conditions in Buildings. 1979.

[54] Ficco G, Iannetta F, Ianniello E, D'Ambrosio Alfano FR, Dell'Isola M. U-value in situ measurement for energy diagnosis of existing buildings. Energy Build 2015;104:108–21. doi:10.1016/j.enbuild.2015.06.071.

[55] Belcher S, Hacker J, Powell D. Constructing design weather data for future climates. Build Serv Eng Res Technol 2005;26:49–61. doi:10.1191/0143624405bt112oa.

[56] Jentsch MF, Bahaj ABS, James PAB. Climate change future proofing of buildings-Generation and assessment of building simulation weather files. Energy Build 2008;40:2148–68. doi:10.1016/j.enbuild.2008.06.005.

[57] Jentsch MF, James PAB, Bourikas L, Bahaj ABS. Transforming existing weather data for worldwide locations to enable energy and building performance simulation under future climates. Renew Energy 2013;55:514–24. doi:10.1016/j.renene.2012.12.049.

[58] Nakicenovic N, Swart R. Special report on emissions scenarios. A special report of working group III of the intergovernmental panel on climate change. Cambridge, United Kingdom: 2000.

[59] The Government of Spain. Royal Decree 314/2006. Approving the Spanish Technical Building Code. Madrid, Spain: 2013.

[60] American National Standards Institute/American Society of Heating Refrigerating and Air-Conditioning Engineers (ANSI/ASHRAE). ASHRAE Guideline 14-2014: Measurement of Energy, Demand, and Water Savings. 2014.

[61] Yang Z, Becerik-Gerber B. A model calibration framework for simultaneous multi-level building energy simulation. Appl Energy

2015;149:415–31. doi:10.1016/j.apenergy.2015.03.048.

[62] Mustafaraj G, Marini D, Costa A, Keane M. Model calibration for building energy efficiency simulation. Appl Energy 2014;130:72–85. doi:10.1016/j.apenergy.2014.05.019.

[63] Gangolells M, Casals M, Forcada N, MacArulla M, Cuerva E. Energy mapping of existing building stock in Spain. J Clean Prod 2016;112:3895–904. doi:10.1016/j.jclepro.2015.05.105.

[64] Giancola E, Soutullo S, Olmedo R, Heras MR. Evaluating rehabilitation of the social housing envelope: Experimental assessment of thermal indoor improvements during actual operating conditions in dry hot climate, a case study. Energy Build 2014;75:264–71. doi:10.1016/j.enbuild.2014.02.010.

[65] Suárez R, Fernández-Agüera J. Retrofitting of Energy Habitability in Social Housing: A Case Study in a Mediterranean Climate. Buildings 2011;1:4–15. doi:10.3390/buildings1010004.

[66] Martinez RG. Highly Insulated Systems for Energy Retrofitting of Façades on its Interior. Procedia Environ Sci 2017;38:3–10. doi:10.1016/j.proenv.2017.03.065.

[67] Rodríguez-Soria B, Domínguez-Hernández J, Pérez-Bella JM, Del Coz-Díaz JJ. Review of international regulations governing the thermal insulation requirements of residential buildings and the harmonization of envelope energy loss. Renew Sustain Energy Rev 2014;34:78–90. doi:10.1016/j.rser.2014.03.009.

[68] CYPE Ingenieros. Generador de precios de la construcción. CYPE Ingenieros, S.A. 2018. http://www.generadordeprecios.info/ (accessed September 13, 2018).

[69] The Government of Spain. Royal Decree 216/2014, of 28 March, sets out the methodology for the calculation of the Voluntary Price for the Small Consumer. n.d.

[70] Spanish Institute for Diversification and Energy Savings (IDAE). Resolution of 14 December 2017, which establishes the regulatory bases of the second aids program for the energy rehabilitation of buildings 2017.

[71] Luo M, Wang Z, Brager G, Cao B, Zhu Y. Indoor climate experience, migration, and thermal comfort expectation in buildings. Build Environ 2018;141:262–72. doi:10.1016/j.buildenv.2018.05.047.

[72] Bienvenido-Huertas D, Rubio-Bellido C, Pérez-Ordóñez J, Martínez-Abella F. Estimating Adaptive Setpoint Temperatures Using Weather Stations. Energies 2019;12:1197. doi:10.3390/en12071197.

[73] Sghiouri H, Mezrhab A, Karkri M, Naji H. Shading devices optimization to enhance thermal comfort and energy performance of a residential building in Morocco. J Build Eng 2018;18:292–302. doi:10.1016/j.jobe.2018.03.018.

[74] Zinzi M, Carnielo E. Impact of urban temperatures on energy performance and thermal comfort in residential buildings. The case of Rome, Italy. Energy Build 2017;157:20–9. doi:10.1016/j.enbuild.2017.05.021.