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Climate change mitigation and adaptation in Spanish office stock through cool roofs

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ABSTRACT

In a context of climate change, the cooling period of buildings is increasing every year in Mediterranean countries. This will become a relevant issue when existing buildings are retrofitted. Cool roofs have a passive cooling effect on a building and can contribute to decreasing the annual cooling demand. In office buildings, thermal comfort has a considerable influence on workers' performance. In these buildings cooling energy demands tend to be high due to the high internal thermal loads. This paper describes annual energy simulations of Spanish office stock to evaluate the potential energy savings of cool roofs within the context of building retrofitting. The energy demand and thermal comfort of representative office buildings is compared before and after the application of a cool roof coating, in the present time and in the year 2050, for all climate areas of Spain, under the most optimistic and most pessimistic future weather scenarios. Results showed that the cooling energy demand of Spanish office stock can be potentially reduced by 25 % when a cool roof is applied, and the annual energy demand for heating and cooling can be cut by 6 %, 11 % and 12 % in the present, the optimistic future scenario and the pessimistic future scenario, respectively.

1. Introduction

The cooling season is increasing annually in Europe due to climate change. Mediterranean countries are especially affected by this increase, which is expected to reach 2 to 3 °C higher than in pre-industrial times by 2050 [1]. Therefore, the cooling energy consumption of buildings is an important issue and will continue to be highly relevant in coming decades. This is especially true of office buildings, where high internal energy loads and daytime schedules require heating, ventilation and air conditioning (HVAC) systems to guarantee workers' comfort [2]. Among passive strategies, cool roofs are a feasible way of cooling down the inner temperature of spaces located under them [3]. The simplicity of implementing cool roofs make them an attractive solution in energy retrofitting processes. Cool roofs work because they have a passive cooling effect on the building, through a combination of high roof thermal emittance and high daytime roof solar reflectance [4]. Hence, a cool roof requires materials whose outermost layer has a high emissivity in the atmospheric window (8–13 μm, infrared radiation) [5] along with high reflectivity in the solar spectrum wavelength (0.3–2.5 μm) for the daytime. Options can be found for nearly all types of roof coverings, including white asphalt shingles, white tiles or slates, membranes above built-up or modified bitumen sheet roofing and paint coatings (acrylic or silicone-based). Solar reflectivity of commercial cool roof materials typically ranges from 0.25 to 0.94, whereas their thermal emissivity ranges from 0.79 to 0.95 [6]. However ideal cool roofs are those with a solar reflectivity (ρ_s) and thermal emissivity (ε_{IR}) close to 1. Today, a new generation of cool roof materials, which are close to having achieved these ideal properties, can be found commercially [7–10].

Research on cool roofs has been increasing in recent times. Hernández-Pérez et al. [11] found that a reflective material can reduce a roof's daily heat gain between 11 % and 60 %, and cut indoor air temperature by around 1–7 °C. Hence, reflective roofs were found to decrease daily cooling energy consumption between 1 % and 80 %. When heating penalties were considered, cool roofs were found to save between 1 % and 20 % of energy annually. Rawat and Singh [12] undertook a comparative review of cool roof thermal performance with different types of surface coatings for residential buildings. They found energy savings ranging from 15 % to 35.7 % in different climatic zones (temperate, tropical, composite, hot and warm-humid).

Nutkiewicz et al. [13] created a generalizable energy simulation framework to evaluate heat stress exposure in informal settlements by analysing multiple design scenarios across 17 cities in India, Brazil,

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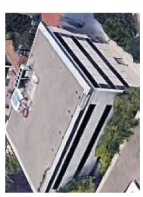
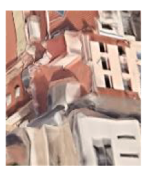
Table 1
Morphological characteristics of the representative office buildings.

	Office B1	Office B2	Office B3	Office B4	Office B5	Office B6	Office B7
	Office B1 	**Office B2** 	**Office B3** 	**Office B4** 	**Office B5** 	**Office B6** 	**Office B7** 
Building typology	Detached	Detached	Detached	Attached	Attached	Detached	Semidetached
Number of floors (ut)	1	7	4	3	2	3	2
Conditioned area (m^2)	145	5,188	1,782	172	420	1,837	208
Roof area (m^2)	145	1,027	446	86	211	733	208
Roof/conditioned ratio (%)	100 %	20 %	25 %	50 %	50 %	40 %	100 %
Glazed area (m^2)	26	828	480	18	8	502	9
Opaque facade area (m^2)	189	2,225	1,138	38	100	1,123	72
Glass/facade ratio (%)	14 %	37 %	42 %	47 %	8 %	45 %	12 %
Representativeness (%)	22 %	14 %	30 %	5 %	4 %	15 %	10 %

South Africa, Kenya and Indonesia. They found that cool roofs can reduce up to 91 % of annual heat stress exposure in low-income dwellings located in tropical climates. Piwaram et al. [14] assessed the performance of cool roofs in Jamaica, Ghana and Brazil and concluded that carbon dioxide generation can be reduced up to 40,000 $kgCO_2eq$, 14,000 $kgCO_2eq$ and 22,000 $kgCO_2eq$, respectively, over a 20-year period. Both papers highlighted the potential of cool roofs for reducing the energy demand in poorly insulated dwellings located in a tropical climate.

In relation to non-residential buildings, Yew et al. [15] reported that cool roof systems for industrial buildings in Malaysia reduced attic air temperature by about 15 °C compared to traditional roofs. Romeo and Zinzi [16] studied the impact of cool roof technology on energy and comfort performance in non-residential buildings in Sicily (Italy) and noted an average reduction of 2.3 °C in indoor temperature during the cooling season and up to 54 % reduction of cooling energy demand.

Recent studies have assessed cool roof energy savings potential at regional scale. Wijesuriya et al. [17] assessed semi-transparent cool roof coatings in a standard prototype building with residential use, for 68 locations across the United States. Net energy savings were found when average cooling degree days were higher than 5.5 or average heating degree days were lower than 10. Bambad [18] demonstrated that cool roofs can reduce annual energy loads by up to 14 % and 22 % in tropical and subtropical climates of Australia under present and future climates, respectively, based on the simulation of one residential building.

Although some studies have already analysed the application of high reflectivity roofs in commercial buildings [19–21], the literature review revealed that no research has yet assessed the potential energy savings that cool roofs can provide when tacking all the office stock of a country, under present and future weather scenarios. This gap is pertinent in Spain: a southern European country with diverse climatic regions that is experiencing increasing cooling energy demand due to climate change.

The aim of this paper is to assess the contribution of cool roofs, an affordable retrofitting solution, in mitigating climate change and adapting Spanish office stock to future weather projections. The sub-objectives are:

(1) To assess current and future potential energy savings for heating and cooling provided by cool roofs within Spanish office stock.
(2) To assess the potential thermal comfort improvement that cool roofs can provide for office spaces under the roof.
(3) To identify the climate areas where the contribution of cool roofs is more significant today and in coming decades.

To achieve these objectives, a comprehensive energy simulation of selected representative buildings in Spanish office stock is undertaken for all climate areas, considering three weather scenarios: the present, the future in 2050 with an optimistic weather projection, and the future in 2050 with a pessimistic projection. The energy simulation is carried out before and after the implementation of an ideal cool roof to the office. The energy demand and interior temperature results are discussed. The energy savings for heating and cooling are evaluated considering the building's energy demand. Thermal comfort is evaluated in a building's free-floating mode by the indoor temperatures in the spaces under the roof, the number of discomfort hours and the cooling degree days of each climate. This paper is divided into the following sections: Methodology (Section 2), Results and Discussion (Section 3) and Conclusions (Section 4).

2. Methodology

The methodology adopted in this paper is organized as follows. Firstly, representative offices of Spanish stock are identified. Secondly, climate areas and future weather scenarios are identified. Finally, the impact of cool roofs on the office building stock's energy demand for heating and cooling is estimated. In section 3.1, reported results refer to

Table 2
Current and future annual cooling degree days (°C·day) and heating degree days (°C·day), with 18 °C baseline, for climate zones in Spain.

Climate zone	Cooling degree days			Heating degree days		
	Present	Future 126	Future 585	Present	Future 126	Future 585
A3 Las Palmas (Cfa*)	1044	1763	2161	40	28	11
A4 Almería (Bsh)	1023	1607	1870	670	463	348
B3 Palma de Mallorca (Csa)	875	1296	1346	1061	990	917
B4 Sevilla (Csa)	1321	1952	2248	821	690	557
C1 Bilbao (Cfb)	316	694	762	1431	1331	1240
C2 Barcelona (Csa)	820	1285	1536	1170	896	727
C3 Granada (Cfa)	636	1087	1222	1844	1785	1660
C4 Cáceres (Csa)	838	1309	1509	1540	1305	1102
D1 Lugo (Csb)	84	353	382	2172	2006	1881
D2 Cuenca (Cfa)	405	850	993	2434	2320	2150
D3 Madrid (Bsk)	850	1426	1651	1841	1579	1414
E1 Burgos (Cfb)	81	464	566	2974	2615	2295

* Köppen-Geiger climate classification

the entire building. In section 3.2, results refer to the office spaces located directly under the roof.

2.1. Identification of representative offices for the entire existing stock

To tackle the full Spanish office stock, this paper starts from the results obtained by the EOFF project, which is fully described in Gangolells et al. [22]. The authors identified and defined a set of reference buildings by applying the k-means clustering method to the Catalan energy performance certificate database, including a sample of 6,083 offices. First, the database was prepared and variables having an impact on energy consumption were pre-selected. Then, and in order to ensure the robustness of the analysis, data were pre-processed. Next, the k-means clustering method was applied. Finally, the resulting cluster centroids were used to identify the closest energy performance certificates in the database, in other words, the representative buildings that will then be used in this research. As a result of this process, seven representative office blocks and offices in industrial buildings were identified that represented 100 % of the total office building stock. Table 1 summarizes the main morphological characteristics of representative offices, and their representativeness, expressed as a % in relation to the entire office building stock. More details about the characteristics of representative office blocks and offices in industrial buildings can be found in Gangolells et al. [23].

2.2. Definition of climate zones and climate data sources

Climate zones are defined according to the Spanish Technical Building Code (TBC) [24]. This establishes twelve climate zones, defined according to the winter climate severity (identified with a letter) and summer climate severity (identified with a number). For the present weather scenario, EPW files with climate data series from 2004 to 2018 were used [25]. Future weather scenario files were obtained from the "Future Weather Generator" tool, developed within the CLING project [26]. For this research, two extreme future weather scenarios were selected. Future 126 is the most optimistic scenario and shares a socio-economic pathway in which global CO_2 emissions are cut severely to reach net zero after 2050, and temperatures stabilize around 1.8 °C higher by the end of the century. Future 585 is the most pessimistic scenario. It considers a shared socioeconomic pathway where current CO_2 emissions levels will roughly double by 2050, and by 2100 the average global temperature will increase by 4.4 °C. In all the climate areas, cooling degree days (CDD) are expected to increase in the future, while heating degree days (HDD) will decrease (Table 2).

2.3. Estimation of cool roof impact on heating and cooling energy demand

The seven representative offices were modelled using Open Studio as the graphical user interface. They were simulated using Energy-plus software. Representative offices were modelled for each climate zone, considering the minimum U-value requirements of the construction according to the regulation in force when the building was constructed. Spanish building regulations establish maximum heat transmission coefficients for individual closures. In Spain, the first regulation to establish a maximum heat transmission coefficient was NBE-CT 79 [27] in 1979, which was substituted in 2007 by a more restrictive one: TBC [24] (Table 3).

Standard EN 16798–1:2019 was used to define internal thermal loads due to lighting (1.5 W/m^2), equipment use (12 W/m^2), people occupancy (17 m^2/person and 100 W/person), and the set-point temperature for heating (20 °C) and cooling periods (26 °C) [28]. Shading produced by the surrounding buildings has been taken into account. Simulated office buildings do not have mobile solar shading. Only Office B1 had fixed solar shading.

The substrates where the application of the cool materials was made are the following: offices B1 and B2 ceramic tile (thickness = 2 cm, conductivity = 1 W/m·K, specific heat = 800 J/kg·K); offices B3, B4 and B7 cement mortar (thickness = 4 cm, conductivity = 2.3 W/m·K, specific heat = 1000 J/kg·K); office B5 steel (thickness = 0.1 cm, conductivity = 50 W/m·K, specific heat = 450 J/kg·K); and office B6 polypropylene layer (thickness = 0.5 cm, conductivity = 0.22 W/m·K, specific heat = 1800 J/kg·K).

Firstly, reference cases (REF) were simulated to obtain the baseline. All reference cases were assumed to have a rough surface material in the outer layer of the roof, with a solar reflectivity (ρ_s) of 0.07 and a thermal emissivity (ε_{IR}) of 0.90. Secondly, these variables were modified to simulate the application of a high emissivity coating, assuming ρ_s=0.99 and ε_{IR}=0.99, and a very smooth surface.

These simulations were replicated for each of the 7 offices buildings. Reference and cool roof cases were compared across each of the 12 climate areas of Spain, encompassing the current weather scenario and two projected scenarios for the year 2050. This resulted in up to 504 energy simulations. In all cases, annual energy demand for the cooling and heating periods (kWh/m^2·year) was obtained, considering the total conditioned area of the building. To streamline the analysis of indoor thermal comfort, only the most pertinent cases were simulated under free-floating conditions, which meant that 14 new simulations were added.

The simulations presented in this paper have not been validated through experimental means. Unfortunately, due to the extensive scope of the study, which involved simulating seven buildings across twelve different climate zones, experimental validation was not feasible. However, the energy simulations conducted using the EnergyPlus software are considered reliable, as previous studies by other authors have validated their experimental results involving radiative cooling film on the roof of a commercial building using the same software [29].

Table 3
U-values (W/m^{2}K) of the simulated office buildings, according to the climate zone and the building regulation.

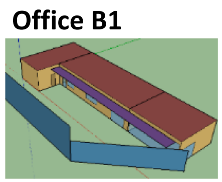
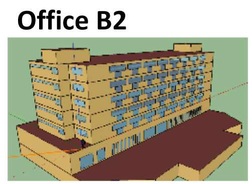
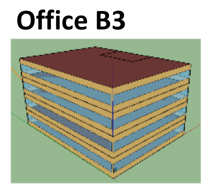
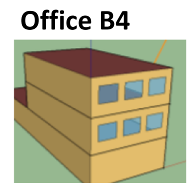
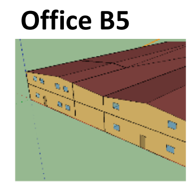
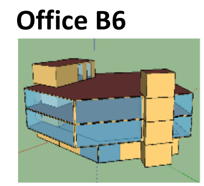
Climate zone	Closure	Office B1	Office B2	Office B3	Office B4	Office B5	Office B6	Office B7
								
A3 Las Palmas (Cfa)	Roof	1.45	1.12	0.39	1.40	1.40	0.50	1.40
	Facades	1.94	0.97	0.59	1.70	1.80	0.94	1.70
A4 Almería (Bsh)	Roof	1.45	1.12	0.39	1.40	1.40	0.50	1.40
	Facades	1.94	0.97	0.59	1.70	1.80	0.94	1.70
B3 Palma de Mallorca (Csa)	Roof	1.45	1.12	0.39	1.40	1.40	0.45	1.40
	Facades	1.94	0.97	0.59	1.70	1.80	0.82	1.70
B4 Sevilla (Csa)	Roof	1.45	1.12	0.39	1.40	1.40	0.45	1.40
	Facades	1.94	0.97	0.59	1.70	1.80	0.82	1.70
C1 Bilbao (Cfb)	Roof	1.45	1.12	0.39	1.20	1.20	0.41	1.20
	Facades	1.94	0.97	0.59	1.60	1.60	0.73	1.60
C2 Barcelona (Csa)	Roof	1.45	1.12	0.39	1.20	1.20	0.41	1.20
	Facades	1.94	0.97	0.59	1.60	1.60	0.73	1.60
C3 Granada (Cfa)	Roof	1.45	1.12	0.39	1.20	1.20	0.41	1.20
	Facades	1.94	0.97	0.59	1.60	1.60	0.73	1.60
C4 Cáceres (Csa)	Roof	1.45	1.12	0.39	1.20	1.20	0.41	1.20
	Facades	1.94	0.97	0.59	1.60	1.60	0.73	1.60
D1 Lugo (Csb)	Roof	1.45	1.12	0.39	0.90	0.90	0.38	0.90
	Facades	1.94	0.97	0.59	1.40	1.40	0.66	1.40
D2 Cuenca (Cfa)	Roof	1.45	1.12	0.39	0.90	0.90	0.38	0.90
	Facades	1.94	0.97	0.59	1.40	1.40	0.66	1.40
D3 Madrid (Bsk)	Roof	1.45	1.12	0.39	0.90	0.90	0.38	0.90
	Facades	1.94	0.97	0.59	1.40	1.40	0.66	1.40
E1 Burgos (Cfb)	Roof	1.45	1.12	0.39	0.70	0.70	0.35	0.70
	Facades	1.94	0.97	0.59	1.40	1.40	0.57	1.40

Table 4
Energy demand (kWh/m^2·year) for cooling and heating periods and annual heating and cooling energy savings for each climate zone, office typology and case under current weather conditions.

Climate zone	Period	Case	Office B1	Office B2	Office B3	Office B4	Office B5	Office B6	Office B7	*Average value for the entire stock*
A3 Las Palmas (Cfa)	Cooling	REF	4.4	31.3	43.8	35.1	11.7	42.6	27.5	29.8
		CR	0.0	25.4	41.4	15.4	0.6	38.2	4.3	22.8
	Heating	REF	3.9	0.0	0.0	0.0	0.1	0.0	0.0	0.9
		CR	6.1	0.0	0.0	0.0	0.6	0.1	0.2	1.4
	Annual savings		2.2	5.9	2.5	19.7	10.7	4.4	23.1	**6.4**
A4 Almería (Bsh)	Cooling	REF	10.1	42.6	54.3	56.2	22.6	55.1	43.7	40.7
		CR	0.6	35.8	51.3	27.9	5.6	50.2	13.3	30.9
	Heating	REF	15.7	1.8	0.0	1.4	4.4	1.5	5.0	4.7
		CR	23.4	2.6	0.0	5.0	11.9	1.9	16.3	8.2
	Annual savings		1.8	5.9	3.0	24.8	9.5	4.5	19.1	**6.3**
B3 Palma de Mallorca (Csa)	Cooling	REF	10.2	40.5	53.3	53.7	20.9	53.6	42.4	39.6
		CR	0.5	34.5	50.4	26.4	4.7	48.4	13.1	30.0
	Heating	REF	27.2	6.5	0.2	7.2	12.1	3.3	15.3	9.9
		CR	35.2	7.9	0.3	13.6	21.6	3.8	29.1	14.0
	Annual savings		1.7	4.7	2.9	21.0	6.7	4.7	15.6	**5.4**
B4 Sevilla (Csa)	Cooling	REF	17.3	47.8	58.0	66.8	30.9	60.1	56.8	47.0
		CR	1.9	40.5	54.4	34.5	8.7	54.3	19.3	34.5
	Heating	REF	17.9	2.7	0.1	2.3	6.0	1.4	6.3	5.6
		CR	25.8	3.9	0.1	8.1	14.8	1.9	21.2	9.7
	Annual savings		7.5	6.0	3.5	26.6	13.3	5.3	22.5	**8.4**
C1 Bilbao (Cfb)	Cooling	REF	2.7	16.1	30.8	16.2	4.9	27.3	8.6	18.0
		CR	0.0	12.4	28.5	5.0	0.0	24.5	0.2	14.2
	Heating	REF	43.1	16.5	5.3	18.8	22.7	8.8	27.8	19.4
		CR	51.9	17.8	5.8	23.3	31.8	9.5	38.4	23.5
	Annual savings		−6.2	2.3	1.8	6.7	−4.3	2.1	−2.2	**−0.3**
C2 Barcelona (Csa)	Cooling	REF	7.3	37.0	51.5	42.1	15.9	47.0	32.2	35.1
		CR	0.3	31.8	48.9	24.6	3.3	43.2	9.9	27.9
	Heating	REF	29.7	8.4	1.2	8.4	13.4	3.3	17.2	11.3
		CR	38.8	9.9	1.4	14.1	22.7	4.0	29.6	15.6
	Annual savings		−2.1	3.7	2.3	11.8	3.3	3.2	10.0	**2.9**
C3 Granada (Cfa)	Cooling	REF	12.2	35.8	47.6	45.5	19.7	46.0	37.4	35.6
		CR	0.4	28.8	43.7	20.8	2.6	40.3	9.1	25.2
	Heating	REF	33.4	11.5	1.9	10.9	17.0	4.7	20.3	13.6
		CR	49.3	14.4	2.7	24.0	34.4	6.7	41.5	21.5
	Annual savings		−4.1	4.1	3.1	11.6	−0.2	3.8	7.1	**2.4**
C4 Cáceres (Csa)	Cooling	REF	11.8	37.0	48.9	48.3	20.8	47.0	40.1	36.6
		CR	0.4	30.0	44.9	22.2	2.9	41.2	9.1	26.0
	Heating	REF	32.6	10.5	2.9	10.8	16.0	5.2	18.2	13.4
		CR	45.4	13.1	3.5	18.8	29.5	6.3	34.9	19.5
	Annual savings		−1.4	4.5	3.5	18.1	4.4	4.6	14.2	**4.5**
D1 Lugo (Csb)	Cooling	REF	2.3	12.4	27.4	14.2	3.0	25.0	7.1	15.7
		CR	0.0	8.0	24.3	2.6	0.0	21.4	0.0	11.7
	Heating	REF	48.7	20.2	6.4	15.8	25.4	9.3	25.1	21.3
		CR	64.5	23.4	7.2	23.5	40.6	10.6	40.6	28.2
	Annual savings		−13.6	1.1	2.3	3.8	−12.2	2.3	−8.4	**−3.0**
D2 Cuenca (Cfa)	Cooling	REF	7.8	26.7	39.5	32.4	11.1	37.3	23.9	27.3
		CR	0.1	20.2	35.7	13.8	0.6	32.4	4.3	19.5
	Heating	REF	50.3	21.7	7.1	20.4	27.7	10.1	31.9	23.2
		CR	70.2	25.8	8.4	32.4	45.3	12.2	51.8	32.1
	Annual Savings		−12.1	2.4	2.5	6.6	−7.1	2.9	−0.4	**−1.2**
D3 Madrid (Bsk)	Cooling	REF	11.1	35.4	47.6	42.6	16.7	44.7	33.9	34.5
		CR	0.6	29.1	44.1	24.5	3.8	40.0	12.2	26.0
	Heating	REF	46.8	19.3	5.6	18.3	24.7	8.6	29.4	20.9
		CR	60.6	22.0	6.4	25.3	36.2	9.8	42.2	26.9
	Annual Savings		−3.3	3.7	2.7	11.1	1.3	3.3	8.9	**2.6**
E1 Burgos (Cfb)	Cooling	REF	2.5	15.1	28.5	16.2	2.3	28.4	6.5	17.0
		CR	0.0	10.3	25.6	4.6	0.0	24.1	0.2	12.9
	Heating	REF	70.0	34.2	16.5	32.8	42.3	17.7	44.8	35.7
		CR	84.5	37.2	17.4	39.0	52.5	19.1	55.8	41.7
	Annual Savings		−12.1	1.8	2.0	5.4	−7.9	2.9	−4.8	**−1.9**

2.3.1. Energy demand

Energy savings (S) provided by the cool roof were estimated by comparing the overall energy demand of the baseline case (REF) with the cool roof (CR) one, including both cooling and heating periods (Equation (1). Negative values of S mean that the installation of cool roofs leads to an increase in the total cooling and heating building load for a given climate.

$$S_{k,i} = (D_c + D_h)_{REF,i} - (D_c + D_h)_{CR,i} \quad (1)$$

Where S is the net energy saving per m^2 and year, D_c represents the cooling energy demand, D_h denotes the heating energy demand, REF is the reference building and CR is the building when the cool roof is applied. Subscript $_k$ represents the office typology, whereas subscript $_i$ represents the weather scenario, i.e. current or future (2050). Units are in kWh/m^2·year.

The total energy savings (TS) of the full office stock is calculated by weighting the percentage of representativeness of each office typology (Equation (2).

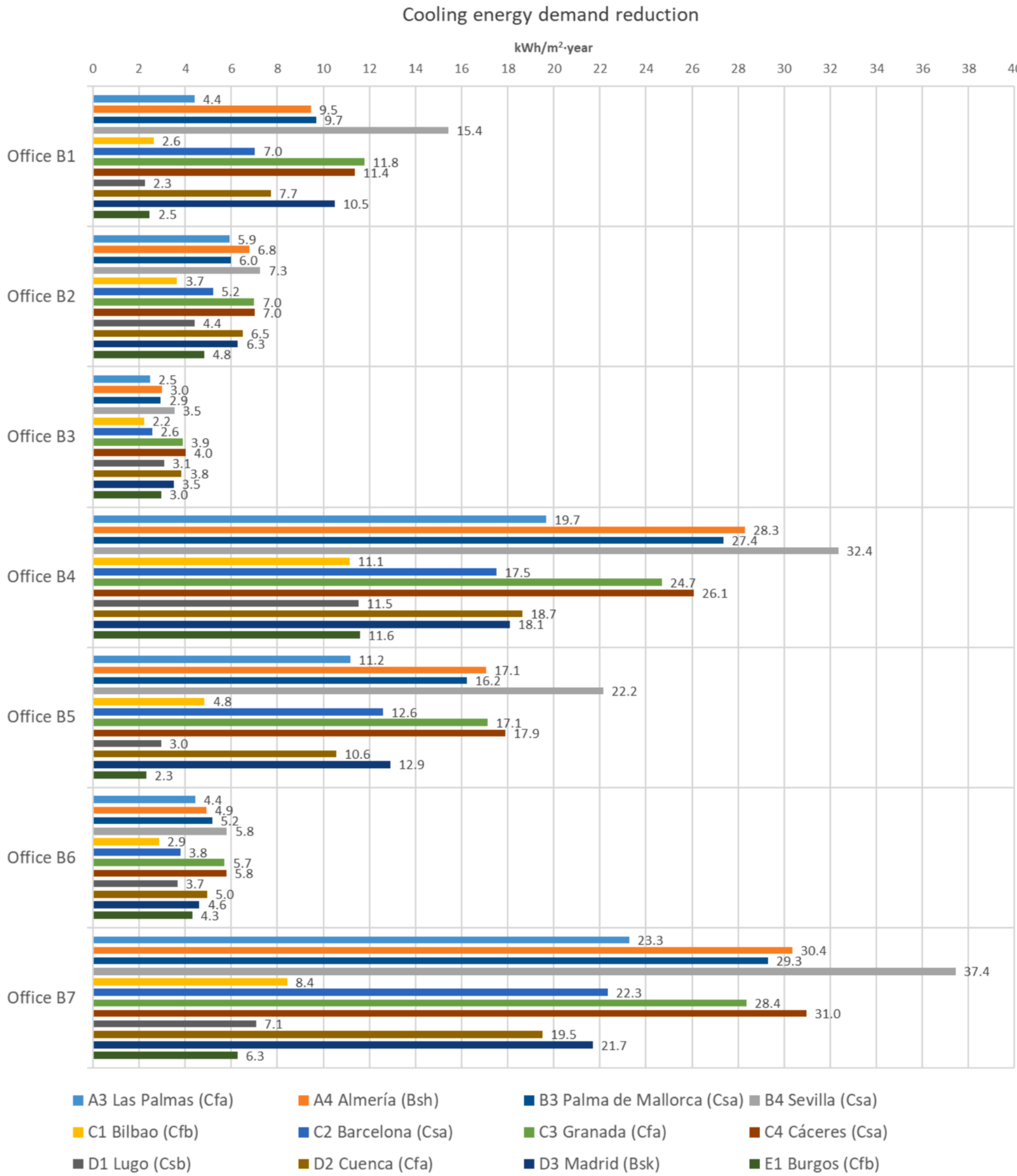


Fig. 1. Cooling energy demand reduction (kWh/m^2·year), according to each office typology and climate zone, under current weather conditions.

$$TS_{k,i} = \sum \binom{n}{i} S_{k,i} \cdot R_k \quad (2)$$

Where TS is the heating and cooling energy savings of the total office stock, $S_{k,I}$ denotes the energy saving provided by the k office typology under the I weather scenario, and R is the ratio of representativeness of each office typology (see Table 1). Units are in kWh/m^2·year.

2.3.2. *Thermal comfort*

The thermal behaviour of office buildings was assessed by obtaining the indoor operative temperatures from the free-floating simulation in the office space influenced directly by the roof. Comfort conditions in this space were assessed according to ASHRAE's adaptive comfort model [30]. In this model, comfort temperature conditions are variable, and depend on the prevailing mean outdoor air temperature, which is the average outdoor temperature over the past seven days. In this paper and along the lines of Rincón et al. [31], the key annual indicator to evaluate comfort throughout the year is discomfort degree days (DDD), which can be calculated using Equation (3):

$$DDD = \frac{\sum_{1}^{8760}(Top - Tup,\lim)_{(Top-Tup,\lim)>0} + \sum_{1}^{8760}(Tlow,\lim - Top)_{(Tlow,\lim-Top)>0}}{24} \quad (3)$$

Where DDD represents the discomfort degree days for the building's annual free-floating simulation (expressed in °C·day), T_{op} is the office operative temperature, $T_{up,lim}$ is the upper limit for adaptive comfort, and $T_{low,lim}$ is the lower limit for adaptive comfort (all expressed in °C). Note that these limits are not fixed but are calculated for each hour as a function of the prevailing mean outdoor temperature.

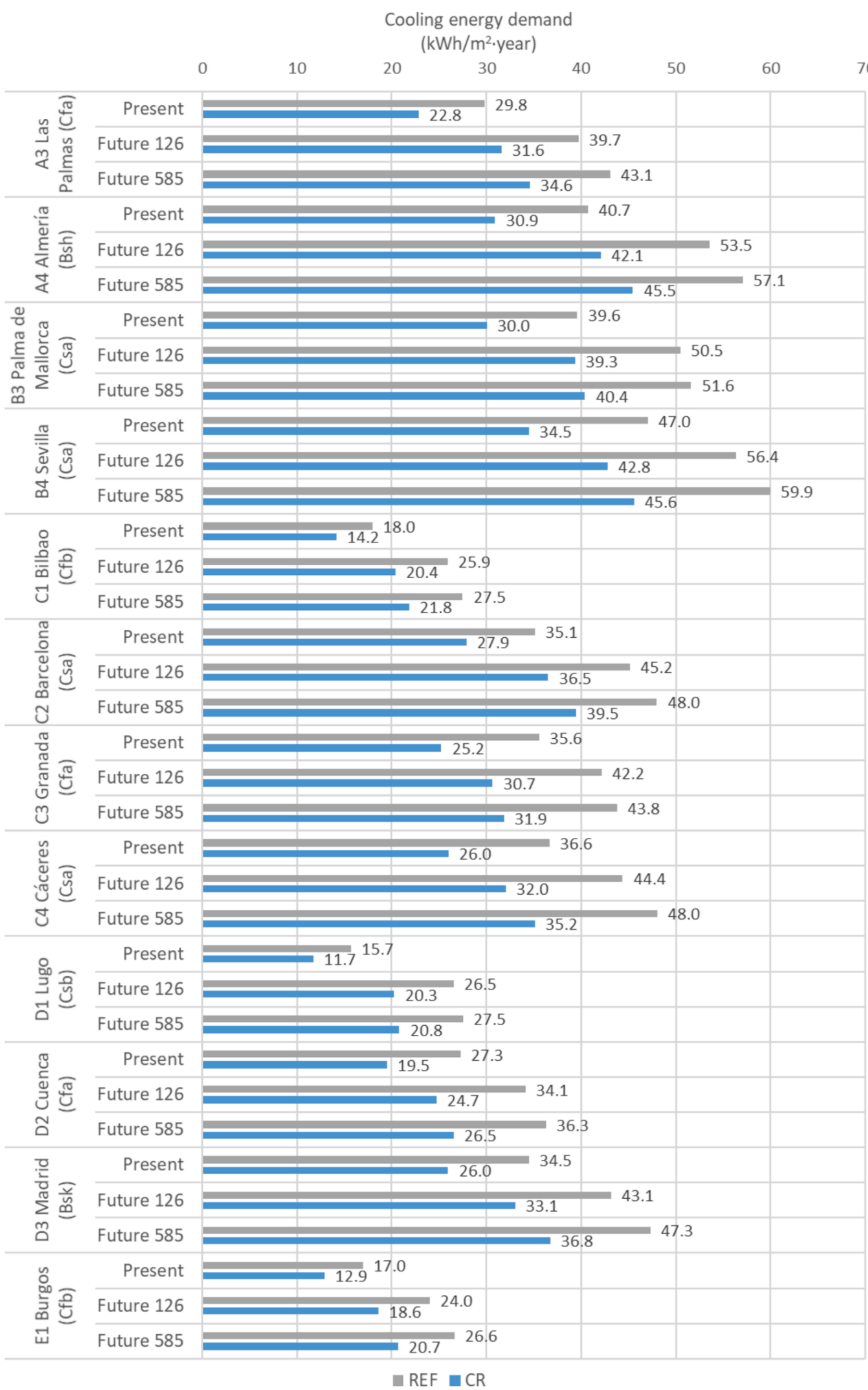


Fig. 2. Cooling energy demand (kWh/m^2·year) of the total office building stock under current and both future weather scenarios for the reference building (REF) and after application of the cool roof (CR).

Table 5
Cooling energy savings (kWh/m^2·year), percentage of reduction (%), and average of the total office building stock, according to each climate zone and under current and both future weather scenarios.

Climate zone	Cooling energy savings (kWh/m^2·year)			Percentage of reduction (%)		
	Present	Future 126	Future 585	Present	Future 126	Future 585
A3 Las Palmas (Cfa)	6.9	8.2	8.5	23 %	21 %	20 %
A4 Almería (Bsh)	9.8	11.4	11.6	24 %	21 %	20 %
B3 Palma de Mallorca (Csa)	9.6	11.2	11.2	24 %	22 %	22 %
B4 Sevilla (Csa)	12.6	13.6	14.3	27 %	24 %	24 %
C1 Bilbao (Cfb)	3.8	5.5	5.7	21 %	21 %	21 %
C2 Barcelona (Csa)	7.2	8.7	8.5	21 %	19 %	18 %
C3 Granada (Cfa)	10.3	11.5	11.9	29 %	27 %	27 %
C4 Cáceres (Csa)	10.7	12.3	12.9	29 %	28 %	27 %
D1 Lugo (Csb)	4.0	6.3	6.7	25 %	24 %	24 %
D2 Cuenca (Cfa)	7.8	9.4	9.7	29 %	28 %	27 %
D3 Madrid (Bsk)	8.5	10.1	10.5	25 %	23 %	22 %
E1 Burgos (Cfb)	4.1	5.4	5.9	24 %	22 %	22 %
Average	*7.9*	*9.5*	*9.8*	*25 %*	*23 %*	*23 %*

3. Results and discussion

In this section, the results are shown following this structure: (1) savings in heating and cooling energy demand of the Spanish office building stock under current and future weather scenarios, focusing on cooling energy demand reduction, and (2) analysis of the thermal comfort in office spaces located under the roof.

3.1. Savings in energy demand of office stock in the present and the future

Table 4 summarizes the annual savings provided by cool roofs for the 7 office typologies and 12 climate zones under current weather conditions. The lowest energy savings were found in typologies with a glass/facade ratio of about 42 % to 45 %, with energy savings ranging from 5 % to 10 %. In these buildings, other parameters such as the solar radiation through the windows and their orientation have a high influence on total energy demand. The highest energy savings were found in office buildings with small coefficient glass/facade and one or two floors, where the influence of the roof heat transfer of the roof over the volume of the office was higher. The office with the highest representativeness among current stock is B3 with a glass/facade ratio of 42 % and 3 high floors. This office also showed overall energy savings due to the effect of the cool roof (Table 4).

Annual heating and cooling energy savings were found in all office typologies, even in buildings with more than one floor, for climate zones Csa, Cfa, Bsk and Bsh, but not in climates with low annual cooling degree days (Csb and Cfb). Even when the heating period penalty was considered, energy demand reduction was still found in all climate areas and in all office typologies, with the exception of offices B1, B5 and B7 in Cfb (Burgos and Bilbao) and Csb (Lugo) climates, where the heating penalty was higher than the cooling energy savings. Buildings in Csa (Sevilla) and Cfa (Las Palmas) climates showed the highest annual heating and cooling energy demand reduction for all office typologies (Table 4).

Focusing on cooling energy demand, all office typologies showed a significant decrease in all climate zones under current weather conditions (Fig. 1). The highest cooling energy demand reduction of office stock was found to be in climate Csa (Sevilla), where the cooling energy demand reduction ranged from 3.5 to 37.4 kWh/m^2·year, depending on the office typology.

In the analysis of future trends, the cooling energy demand of office stock was found to increase in all climate zones and in both future weather scenarios (Fig. 2). There was an average increase of 9 kWh/m^2·year for the optimistic scenario, and 12 kWh/m^2·year for the pessimistic one. Reference offices simulated in climate zone Bsh (Almería) showed the highest increase in cooling energy demand, with 13 kWh/m^2·year and 16 kWh/m^2·year, respectively. In contrast, climate zone Cfa (Granada) had the lowest increase, resulting only in 7 kWh/m^2·year and 8 kWh/m^2·year. When the cool roof was implemented, the cooling energy demand of the office stock was reduced by 25 % in current weather scenario, and 23 % in both future weather scenarios (Table 5). Cool roof offices simulated in climate zone Csa showed the highest cooling energy savings, with 14.3 kWh/m^2·year in Sevilla and 12.9 kWh/m^2·year in Cáceres. Fig. 3 graphically illustrates these results in terms of cooling energy savings.

As shown in Table 6, when the heating penalty is considered, annual heating and cooling energy savings are found in both future weather scenarios (Future 126 and Future 585) for all the climates and office building typologies, with the exception of B1 and B5 offices located in the coldest climates: Cfb (Bilbao and Burgos), Csb (Lugo) and Cfa (Cuenca).

In the future, the annual heating and cooling energy savings for the total office stock is positive in all the climates (Fig. 4). Currently, a cool roof can contribute to annual energy savings of 6 %. In future scenarios, these savings are expected to increase to 11 % under the Future 126 scenario and 12 % under the Future 585 scenario (Table 7). The highest energy savings potential in the future is also found in climate Csa (Sevilla), with 18 % for Future 126 and 21 % for Future 585. Note that the coldest climates Cfb (Burgos and Bilbao), Csb (Lugo) and Cfa (Cuenca) in the future will also have annual heating and cooling energy savings of between 1 and 7 %.

3.2. Analysis of indoor thermal comfort in office space located under the roof

According to the above results, the hottest climates have the highest energy saving potential. Therefore, and focusing on the Csa climate (Sevilla), the results indicate that a cool roof reduces the number of discomfort degree days from 26 to 78 % in the floor located under the roof (Fig. 5).

The close-to-ideal optical properties of a roof (combination of 99 % thermal emissivity and 99 % solar reflectivity) reduce the operative temperatures in office spaces under the roof. Radiative cooling and daytime reflectivity decrease surface roof temperatures under outdoor air temperatures, which reduces heat transfer to the interior. As an example, Fig. 6 summarizes the thermal performance of office B5 when it is located in Sevilla. In this graph, the outdoor temperatures (T_{out}) and

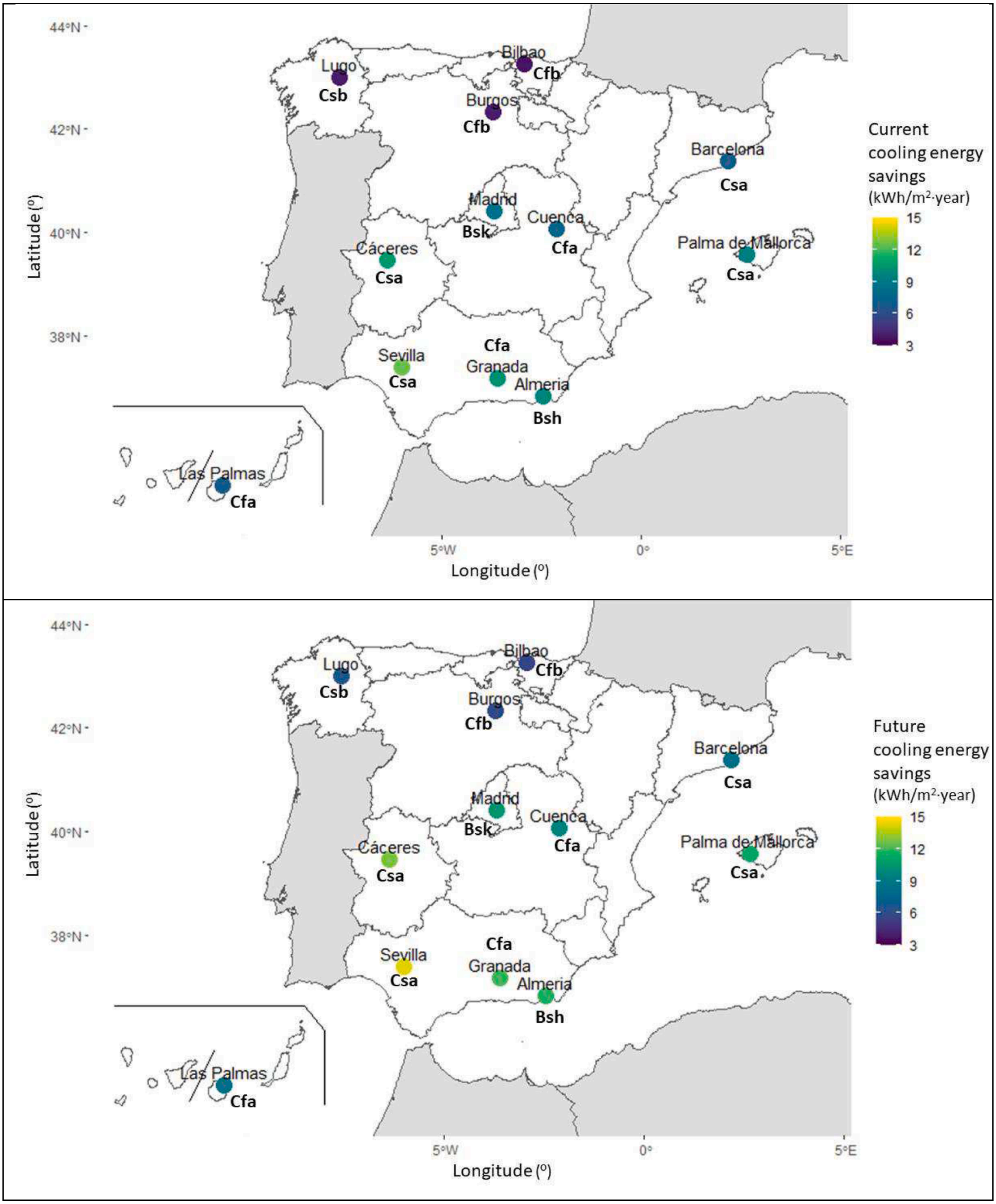


Fig. 3. Cooling energy savings (kWh/m^2·year), according to each climate zone under current conditions (top) and Future 585 (bottom).

Table 6
Annual heating and cooling savings in energy demand (kWh/m^2·year) for the current and both future weather scenarios.

Climate zone	Weather scenario	Office B1	Office B2	Office B3	Office B4	Office B5	Office B6	Office B7
A3 Las Palmas (Cfa)	Present	2.21	5.91	2.47	19.67	10.7	4.41	23.06
	Future 126	7.72	5.4	2.5	23.52	14.58	4.02	25.87
	Future 585	9.38	5.49	2.49	20.04	15.39	4.03	25.87
A4 Almería (Bsh)	Present	1.81	5.94	2.97	24.75	9.5	4.49	19.1
	Future 126	10.28	10.28	10.28	10.28	10.28	10.28	10.28
	Future 585	12.95	12.95	12.95	12.95	12.95	12.95	12.95
B3 Palma de Mallorca (Csa)	Present	1.72	4.66	2.85	20.99	6.68	4.67	15.57
	Future 126	8.78	5.16	2.99	23.72	11.52	4.38	21.97
	Future 585	9.44	5.21	2.99	23.7	11.96	4.4	22.31
B4 Sevilla (Csa)	Present	7.48	5.97	3.48	26.6	13.31	5.31	22.46
	Future 126	13	6.42	3.42	29.73	18.11	5.77	29.4
	Future 585	20.15	6.9	3.9	29.63	19.78	5.94	32.25
C1 Bilbao (Cfb)	Present	−6.17	2.32	1.79	6.71	−4.32	2.09	−2.22
	Future 126	−1.24	3.06	1.99	10.69	2.03	2.62	6.8
	Future 585	−0.75	3.18	1.97	11.2	2.16	2.62	8.35
C2 Barcelona (Csa)	Present	−2.05	3.72	2.34	11.81	3.29	3.17	9.97
	Future 126	4.49	4.25	3.13	15.07	7.96	3.47	14.86
	Future 585	6.96	4.33	1.78	13.87	9.6	3.5	16.35
C3 Granada (Cfa)	Present	−4.08	4.13	3.06	11.64	−0.19	3.8	7.08
	Future 126	0.75	4.72	3.46	16.1	5.48	4.34	12.77
	Future 585	2.69	4.9	3.67	16.8	7.97	4.64	14.44
C4 Cáceres (Csa)	Present	−1.43	4.48	3.46	18.11	4.41	4.61	14.22
	Future 126	5.59	6.07	3.86	23	12.06	5.4	23.07
	Future 585	8.66	6.42	3.92	23.51	14.8	5.57	26.36
D1 Lugo (Csb)	Present	−13.59	1.13	2.27	3.82	−12.17	2.27	−8.44
	Future 126	−7.02	2.62	2.65	12.51	−4.19	2.87	12.38
	Future 585	−6.49	3.03	3.61	12.48	−3.71	3.29	13.15
D2 Cuenca (Cfa)	Present	−12.12	2.42	2.53	6.61	−7.05	2.87	−0.42
	Future 126	−5.96	3.8	2.89	10.94	−0.72	3.54	5.81
	Future 585	−4.56	3.84	2.97	12.3	0.05	3.6	7.39
D3 Madrid (Bsk)	Present	−3.27	3.65	2.71	11.13	1.33	3.34	8.94
	Future 126	2.87	4.61	3.06	14.29	6.19	3.93	13.91
	Future 585	5.87	4.93	3.11	14.56	7.92	4.08	15.47
E1 Burgos (Cfb)	Present	−12.07	1.8	2.01	5.38	−7.93	2.88	−4.79
	Future 126	−7.4	3.34	2.47	9.48	−2.73	2.83	3.09
	Future 585	−4.59	4.14	2.56	11	−0.23	3.07	6.54

the comfort temperature range of ASHRAE's adaptative comfort model (zone between *Upper T limit 90 %, Lower T limit 90 %*) are shown and the indoor temperature in the reference case (T_{REF}) and the cool roof case (T_{CR}). In office B5, the cool roof reduced the interior temperatures of this office space in a range of 7 °C to 12 °C. This meant that the space was mostly within the comfort range during the summer period, while the reference case was far above the upper comfort temperature limit.

The cooling effect was observed in the remaining offices when they were located in the same climate zone, but with a smaller range. This is the case of office B6, where the cool roof also decreased the indoor temperatures by almost 3 °C throughout the period (Fig. 7). However, the cooling effect was not enough to bring the high indoor temperatures closer to the comfort range. In this case, the indoor temperature was strongly influenced by other parameters, such as the glass area and the facade orientation, rather than heat transfer from the roof. Still, the cooling effect of the cool roof helped to reduce the cooling energy demand of the full building by 10 %.

4. Conclusions

This research explored the potential energy savings that cool roofs can provide for Spanish office stock. For this purpose, 518 energy simulations were carried out to assess the contribution of a cool roof to the adaptation of office stock to future weather projections.

A representative sample of the Spanish office stock, composed of seven different office buildings, was modelled using Open Studio and Energy Plus. These seven office buildings were simulated in the 12 climate zones of Spain, including zone A3 Las Palmas (Cfa), A4 Almería (Bsh), B3 Palma de Mallorca (Csa), B4 Sevilla (Csa), C1 Bilbao (Cfb), C2 Barcelona (Csa), C3 Granada (Cfa), C4 Cáceres (Csa), D1 Lugo (Csb), D2 Cuenca (Cfa), D3 Madrid (Bsk), and E1 Burgos (Cfb). Subsequently, the cooling and heating energy demand (measured in kWh/m^2·year) was compared before and after the application of a cool roof coating with a solar reflectivity ρ_s=0.99 and a thermal emissivity ε_{IR}=0.99. This comparison was made for the current weather and for the year 2050 predicted weather, under both the most optimistic and most pessimistic future weather scenarios.

The results showed that cool roofs can reduce the cooling and heating annual energy demand of Spanish office building stock by 6 % (in average 2.7 kWh/m^2·year), under current climate conditions. The highest savings were found in Csa (Sevilla) with 8.4 kWh/m^2·year, Cfa (Las Palmas) with 6.4 kWh/m^2·year, and Bsh (Almería) with 6.3 kWh/m^2·year. The heating period had an energy savings penalty only in specific building typologies in the coldest climates of Spain. This resulted in a extra consumption for the office stock of 3 kWh/m^2·year in Csb (Lugo), 1.9 kWh/m^2·year in Cfb (Burgos), and 1.2 kWh/m^2·year in Cfa (Cuenca).

Future weather scenarios indicate an increasing need for cooling in all climates. In both future weather scenarios, energy savings were found to be higher, with a reduction in the annual cooling and heating energy demand of the Spanish office building stock of 11 % (5.5 kWh/m^2·year) in the optimistic scenario, and 12 % (6.3 kWh/m^2·year) in the pessimistic scenario. Even the buildings located in traditionally cold climate zones (Csb, Cfb and Cfa) will require greater cooling energy use in both optimistic and pessimistic weather scenarios. In the medium-term, stakeholders may consider a cool roof as a passive measure when existing office buildingsare retrofitted to adapt buildings to the future climate.

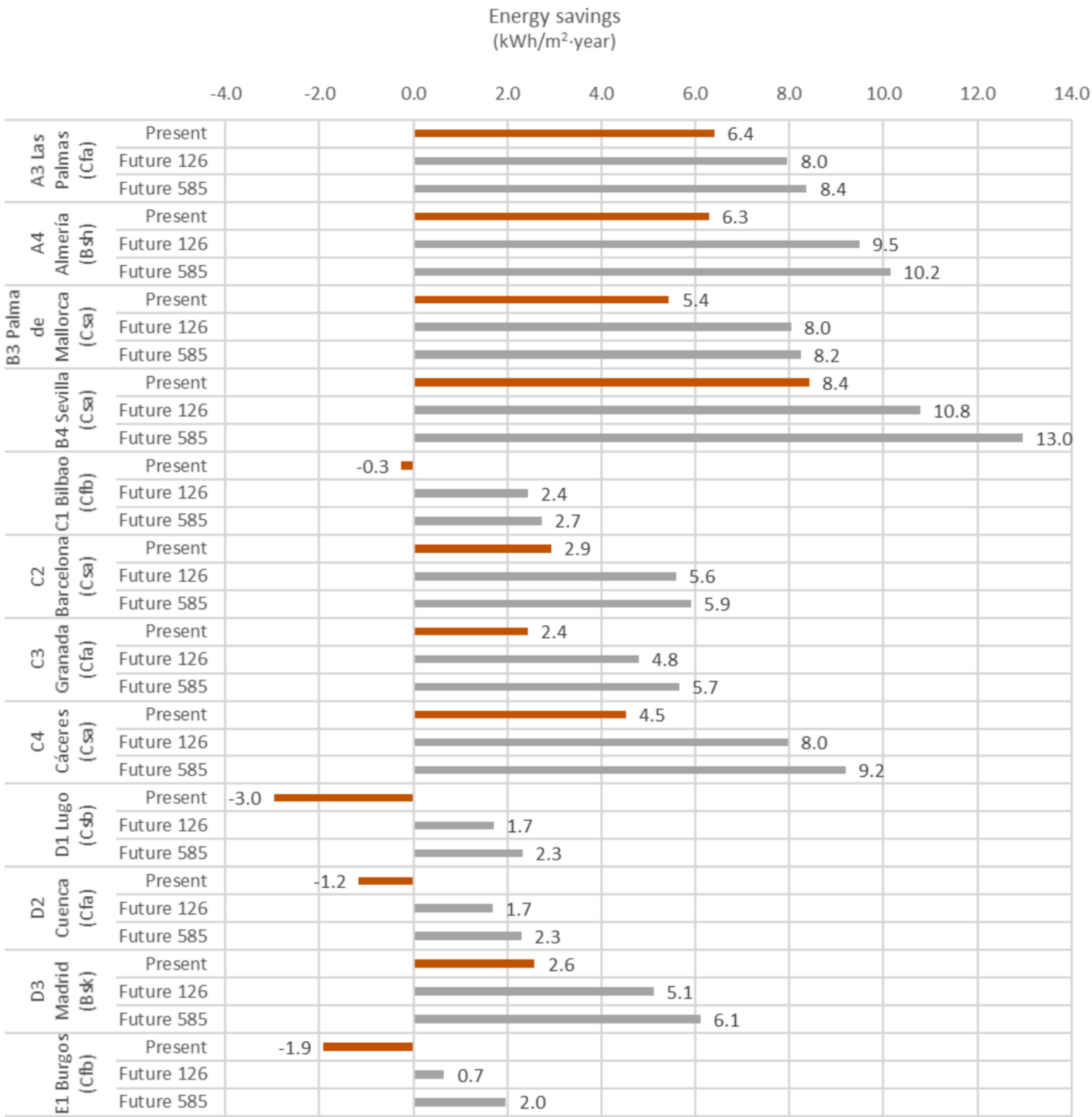


Fig. 4. Energy savings for heating and cooling (kWh/m^2·year) of Spanish office building stock under current and both future weather scenarios.

Focusing only on the cooling period, the cooling energy demand of the Spanish office building stock had a reduction of 25 % (7.9 kWh/m^2·year), under current climate conditions, and 23 % in future climate conditions (9.5 kWh/m^2·year for the optimistic future and 9.8 kWh/m^2·year for the pessimistic future).

Office buildings in the hottest climate of Spain, Csa (Sevilla) had the highest savings in heating and cooling energy demand and the highest potential for reducing energy demand. Considering both cooling and heating periods, the annual heating and cooling energy demand was found to be reduced by 16 % today, and 18 % to 21 % in the future.

Cool roofs have been found to substantially improve the thermal comfort in the summer period in office spaces directly under the roof. The annual discomfort degree days of the space under the roof was found to decrease in all office typologies. For example, the annual discomfort degree days reduction in Csa climate in climate Csa was found to range between 26 % and 78 %.

According to the results, in most climate areas, office building retrofitting with a cool roof could benefit office buildings that only have a ground floor and also those with several floors, as well as those with a high area of glass.

For these reasons, roofing materials, and specifically the outer layer, should be developed considering their optical properties, to save energy and improve the indoor thermal comfort of offices located under the roof. New technologies in this field should target solar reflectivity (ρ_s) and IR emissivity (ε_{IR}) as close to 1 as possible.

Regarding the limitations of this study, note that these results present an ideal cool roof, with optimal maintenance and durability. To avoid a reduction in cool roof effectiveness, future cool roof technologies should consider, for instance, the implementation of dust control systems and special chemicals that prevent mould or algae growth in wet locations. Future research should also explore the contribution of cool roofs to the heat island effect of high-density urban areas.

Table 7
Annual heating and cooling energy savings (kWh/m^2·year), percentage of reduction (%), and average of the total office building stock, according to each climate zone and under current and both future weather scenarios.

Climate zone	Annual energy savings (kWh/m^2·year)			Percentage of reduction (%)		
	Present	Future 126	Future 585	Present	Future 126	Future 585
A3 Las Palmas (Cfa)	6.4	8.0	8.4	21 %	20 %	19 %
A4 Almería (Bsh)	6.3	9.5	10.2	14 %	17 %	17 %
B3 Palma de Mallorca (Csa)	5.4	8.0	8.2	11 %	14 %	14 %
B4 Sevilla (Csa)	8.4	10.8	13.0	16 %	18 %	21 %
C1 Bilbao (Cfb)	−0.3	2.4	2.7	−1%	6 %	7 %
C2 Barcelona (Csa)	2.9	5.6	5.9	6 %	10 %	11 %
C3 Granada (Cfa)	2.4	4.8	5.7	5 %	9 %	11 %
C4 Cáceres (Csa)	4.5	8.0	9.2	9 %	15 %	17 %
D1 Lugo (Csb)	−3.0	1.7	2.3	−8%	4 %	6 %
D2 Cuenca (Cfa)	−1.2	1.7	2.3	−2%	3 %	4 %
D3 Madrid (Bsk)	2.6	5.1	6.1	5 %	9 %	10 %
E1 Burgos (Cfb)	−1.9	0.7	2.0	−4%	1 %	4 %
Average	*2.7*	*5.5*	*6.3*	*6 %*	*11 %*	*12 %*

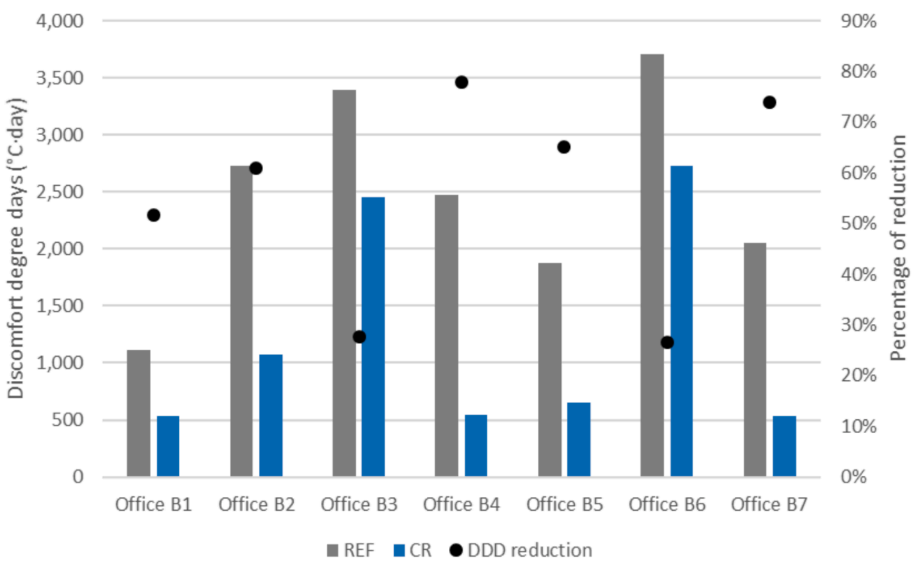


Fig. 5. Annual discomfort degree days (°C·day) for Sevilla (Csa) and for each office typology.

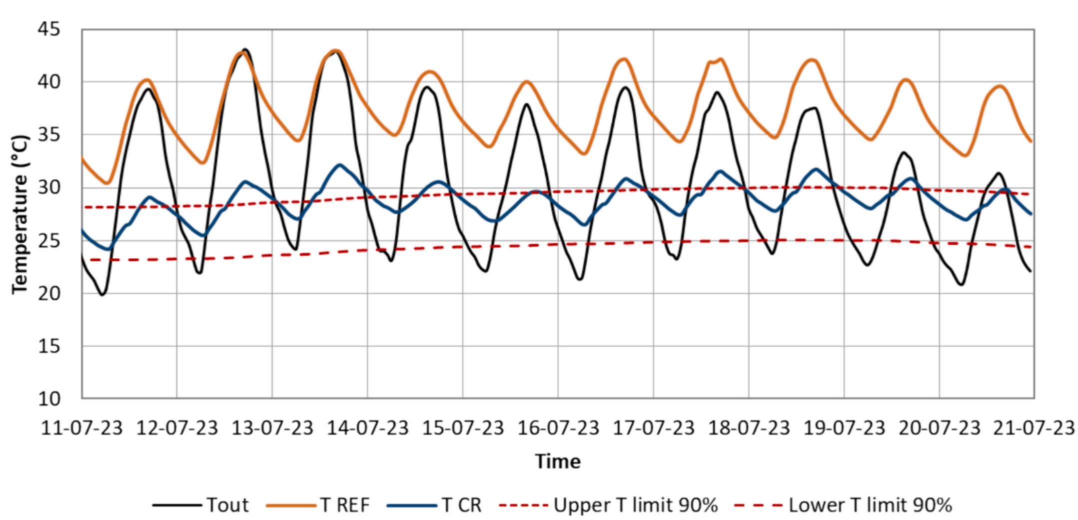


Fig. 6. Free-floating temperature (°C) in summer conditions for office B5 located in Sevilla (Csa), built under the NBE building regulation.

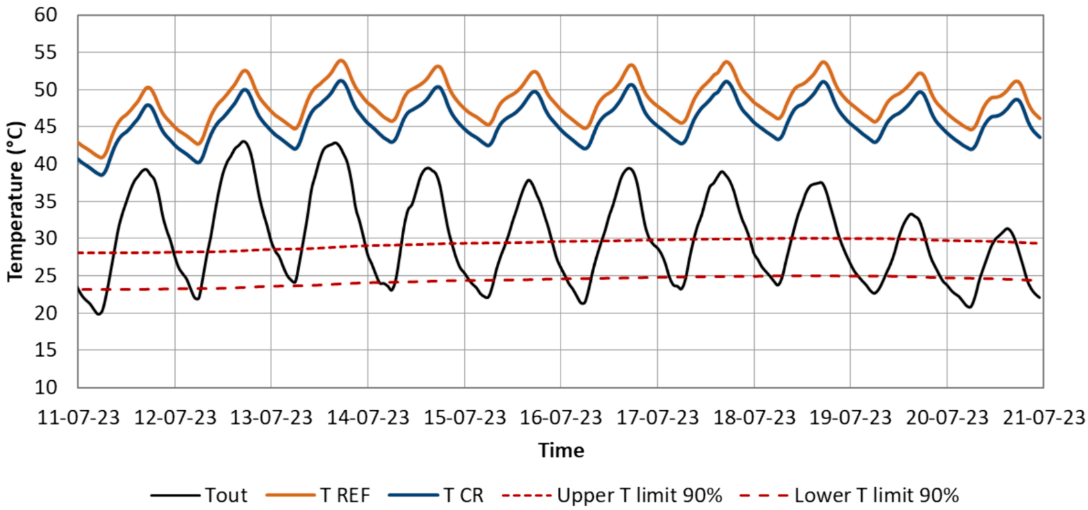


Fig. 7. Free-floating temperatures (°C) in summer conditions for office B6 located in Sevilla (Csa), built under the Technical Building Code.

CRediT authorship contribution statement

Lídia Rincón: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marta Gangolells:** Writing – original draft, Validation, Supervision, Resources, Methodology, Investigation, Conceptualization. **Marc Medrano:** Writing – review & editing, Validation, Conceptualization. **Miquel Casals:** Writing – review & editing, Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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