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Thermochromic Paints on External Surfaces: Impact Assessment for a Residential Building through Thermal and Energy Simulation

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Abstract: This work addresses the effect of using thermochromic paints in residential buildings. Two different thermochromic paint types were considered: One that changes properties through a step transition at a certain temperature, and another that changes properties in a gradual/linear manner throughout a temperature range. The studied building was a two-floor villa, virtually simulated through a digital model with and without thermal insulation, and considering thermochromic paints applied both on external walls and on the roof. The performance assessment was done through the energy use for heating and cooling (in conditioned mode), as well as in terms of the indoor temperature (in free-floating mode). Three different cities/climates were considered: Porto, Madrid, and Abu Dhabi. Results showed that energy savings up to 50.6% could be reached if the building is operated in conditioned mode. Conversely, when operated in free-floating mode, optimally selected thermochromic paints enable reductions up to 11.0 °C, during summertime, and an increase up to 2.7 °C, during wintertime. These results point out the great benefits of using optimally selected thermochromic paints for obtaining thermal comfort, and also the need to further develop stable and cost-effective thermochromic pigments for outdoor applications, as well as to test physical models in a real environment.

Keywords: thermochromic paints; residential buildings; thermal comfort; energy demand; energy efficiency; building simulation

1. Introduction

Several policy initiatives around the world are boosting efforts to decarbonize the building stock. In the European Union, 50% of the final energy consumption is used for heating and cooling, of which about 80% is used in buildings [1]. Greenhouse gas (GHG) emissions are mainly related to the consumption of fossil energy. A combination of energy efficiency measures and a renewable energy supply are therefore key to achieve the decarburization goals.

To mitigate the rise in energy demand, passive building strategies should be considered to obtain indoor thermal comfort. The American Society of Heating Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE) defines thermal comfort as "*that condition of mind that expresses satisfaction* *with the thermal*" [2]. Different factors, such as air temperature, humidity, air speed, physical activity, and clothing, contribute to the thermal comfort sensation. In most buildings, the heat transfer through the building envelope is the most important factor to obtain indoor thermal comfort if the building does not have mechanical heating or cooling (and thus is operated in a so-called free-floating mode) [3]

Solar reflectance is the fraction of the solar irradiance reflected by a surface [4]. There is a linear correlation between the increase of solar reflectance of a surface and the decrease of its daily peak temperature [5]. A paint may be designed to absorb the solar irradiance (thus called hot paint) and then contribute to warming up a building. Alternatively, a high solar reflectance paint (thus called cool paint) should be applied to prevent solar irradiance absorption and then to avoid overheating of the building [6]. The building surface can reject (reflect) or absorb the heat of its surroundings, leading to less or more heat retention in the building envelope through its construction materials. The reflectance of the building surface is normally characterized by the so-called total solar reflectance value (TSR). High values of TSR are associated with light colors (cool paints) while dark colors (hot paints) have a low TSR.

The color, alongside the roughness and construction material (chemical composition), is one of the main physical characteristics that affect the thermal performance of a surface [7,8]. Bansal et al. [9] studied the influence of the external surface color on the thermal performance of a building. It was concluded that a white painted building, when compared with a black one, can reduce the indoor temperature by 6 °C during winter and 8 °C in summer months, if no ventilation is considered. This difference can be decreased to 4 and 6 °C, respectively, when a rate of three air exchanges is taken into account. Cool paints are a passive thermal comfort strategy, easy to apply as passive cooling, which can be used in any type of building with a short period of investment cost recovery [5,10]. For example, the application of cool roofs is reported to produce an 18%–93% decrease in cooling loads and 11%–27% decrease in terms of the peak cooling demand in air-conditioned buildings, leading to energy savings between 2% and 44% with an average of 20%, in both residential and nonresidential buildings [11,12]. Such figures vary significantly with the local climate, direct solar gain, building envelope type, and the use or not of a heating, ventilation and air-conditioning (HVAC) system [5,8].

Despite the positive impact of using cool paints, some studies show that these paints may also have a detrimental effect on the thermal comfort of a building. Dias et al. [10] simulated the impact of increasing the TSR value of a paint, from 50% to 92%, both at the external walls and on the roof of a residential building located in three different cities of Portugal. They observed a summer maximum indoor temperature reduction of ca. 4 °C, and cooling energy savings of up to 1.9 MWh·y^{-1}. However, these authors also observed a significant increase on the heating demand of up to 2.9 MWh·y^{-1} (a penalty of about 25.9%). The observed overall effect was then a significant increase in the energy consumption for obtaining indoor thermal comfort. The winter penalties of cool paints triggered the development of coatings that change reversibly their color as a thermal response to the environment [13].

Thermochromic paints contain thermochromic pigments or compounds that reversibly change color and optical properties according to the surface temperature [14,15]. The thermochromic effect is triggered by the temperature that produces: i) Changes of pH; ii) conversion of the crystalline type; iii) loss of crystalline water by heating; iv) a shift in the electron equilibrium between an electron donor and electron acceptor and; v) a ring-opening reaction of molecules by heating [16]. The temperature at which the reversible color-changing of thermochromic pigments occurs is named the transition temperature.

Thermochromic pigments or compounds can be used directly to formulate paints or can be first microencapsulated. The first reporting of thermochromic paints as coatings to a building's façade was by Ma et al. [17], in 2000. These authors added microencapsulated thermochromic dyes to a white interior and exterior facade coatings and used them to paint cubes. They showed that below the transition temperature (paint is colorful), the temperature of the cube was close to that of a cube painted with an ordinary paint, and above the transition temperature (paint is white), the temperature of the cube was 4 °C cooler. The accelerated aging tests for 400 h showed a fast color fading rate. In 2001, Ma et al. [16] repeated the reversible color-changing process more than 1000 times in an indoor environment and the pigments kept their color. Later, in 2002, the same researchers [18] studied the reversible effect, the energy-absorbing and energy-reflecting states of thermochromic building coatings, when exposed to solar radiation. Results showed that below the transition temperature, 18 °C in this case, the addition of thermochromic pigments to a white paint led to the same absorption amount of solar energy as an ordinary colored coating. On the other hand, the absorption of solar irradiance was minimized above the transition temperature since the paint turned white.

In 2009, Karlessi et al. [19] developed and tested thermochromic paints intended to be applied in buildings. These authors used thermochromic pigments, colored below 30 °C, and translucent above this temperature. During the experimental period, August–mid-September 2007 in Athens, Greece, the temperatures of the thermochromic paint coatings were lower, ranging from 23.8 to 38.4 °C, than the temperatures of color-matched cool paints, from 28.1 to 44.6 °C; and common samples, from 29.8 to 48.5 °C. In 2012, Ye et al. [20] designed and evaluated a thermochromic roof coat for energy savings. These authors used an aqueous solution of a thermosensitive polymer with a transition temperature of 32 °C; below the transition temperature, the solution was transparent and above the solution it became opaque and the paint appeared white, reflecting most of the light. It was demonstrated that this transition between light-absorbing and light-reflecting states as triggered by the temperature was spontaneous and reversible. When the concentration of the thermosensitive polymer reached 0.05 g/mL, and above 32 °C, the paint coat reached the maximum reflectance of 33%, which led to a 6 °C decrease of the surface temperature compared to when it was coated with the absence of the thermochromic polymer.

More recently, in 2019, Ascione et al. [21] investigated the ideal radiative characteristics of a thermochromic paint to obtain optimized thermal comfort in both winter and summer seasons in Naples, Italy. The simulation results showed that a thermal absorptivity (α) between 0.90 and 0.95, and a thermal emissivity (ε) between 0.65 and 0.75 would be the ideal values for a thermochromic paint applied in that climate. Such a high absorptivity is expected to produce an increase of the cooling needs during summer. However, its effect on the reduction of the heating load surpasses the small penalties on the cooling ones. Globally, a reduction of the thermal energy demand of around 21.1 Wh·m^{-2} is expected (from 138.8 Wh·m^{-2}, when using a common white paint α = 0.7 and ε = 0.9, to 117.7 Wh·m^{-2})

The combination of the thermochromic properties with phase change materials (PCMs) has also been studied, with the aim of reaching better passive thermal comfort. Soudian, S. and U. Berardi [22] introduced thermochromic pigments into a PCM-finish plaster to achieve a dynamic response of the facade to different surface temperatures and solar radiation. The results supported an expected variation of the emissivity according to the seasons. However, the emissivity values showed a non-linear relation between PCM melting temperatures and the different thermochromic colors.

Overall, improved thermochromic pigments are required to ensure paints that do not change over time due to aging and photo-degradation problems. Karlessi and Santamouris [23] performed tests with thermochromic coatings protected with filters that only allowed visible radiation to reach the coatings' surface. These researchers concluded that the optical properties of the thermochromic paints used were not only affected by the ultraviolet radiation but also by the 400 to 480 nm spectrum. It is crucial to develop stable and cost-effective thermochromic pigments [13,19] with proven stability not only to radiation but also to temperature and weathering.

Several thermochromic paints are already available in the market in the field of art, design, and indoor architecture [24], but no outdoor applications are available yet [13,24]. Since the cost of thermochromic materials is still high [13,19], real exposure tests to study the thermochromic paints' application in buildings are difficult to perform. The present study intends to overcome this difficulty by assessing the potential benefits of these paints and simulating a residential building considering three cities/climates: Porto in Portugal (41°09′ N 8°37′ W), Madrid in Spain (40°25′ N 3°42′ O), and Abu Dhabi in the United Arab Emirates (24°28′ N 54°22′ E).

The assessment was performed through dynamic building simulation with an open source ESP-r software [25,26]. ESP-r is an integrated energy modeling tool and has been extensively used for the simulation of buildings' performance and assessment of their energy use related to environmental control systems.

The thermal behavior and energy demand was assessed for two different thermochromic paints: i) A paint using a single thermochromic pigment that changes color (and then the TSR) at a given temperature and ii) a paint containing various pigments that allow a continuum and linear change of the color and TSR value as a function of the temperature.

The present work intends to further assess the potential of thermochromic paints for residential buildings, by trying to identify the optimal transition temperature and their impact upon the energy demand (building conditioned mode) or indoor temperature (building in free-floating mode).

2. Simulation Scenarios and Alternatives

This study assessed a single villa with two living floors, with a floor area of 90 m^2 each, and an uninhabited attic. The residential building is represented in Figures 1 and 2 and also fully described elsewhere [10]. Briefly, the ground floor has a living room, a dining room, a kitchen, a toilet, a hall, and stairs. The first floor has three bedrooms, a suite, a toilet, a bathroom, a corridor, and stairs. The attic is an open space, as mentioned before it is not inhabited.

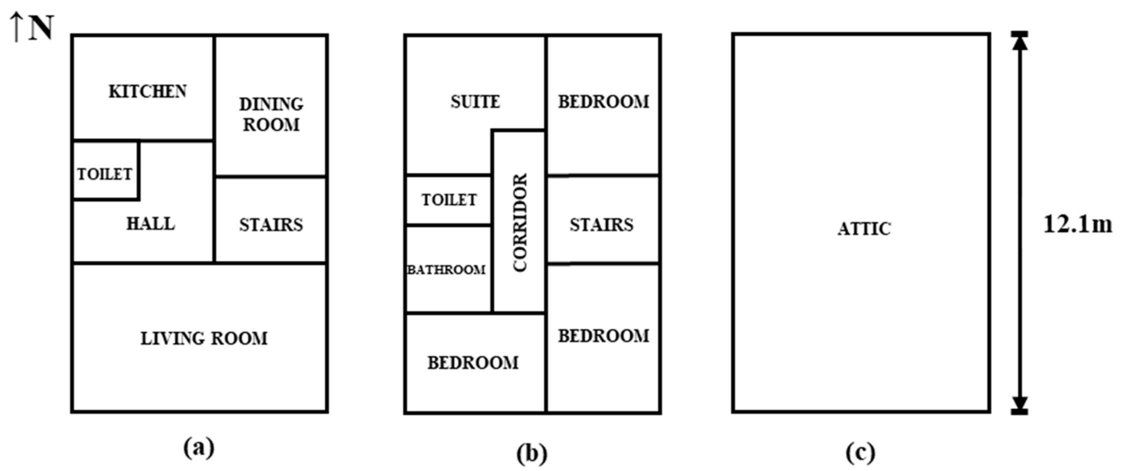

Figure 1. Plans of the building: (**a**) ground floor, (**b**) first floor, and (**c**) attic.

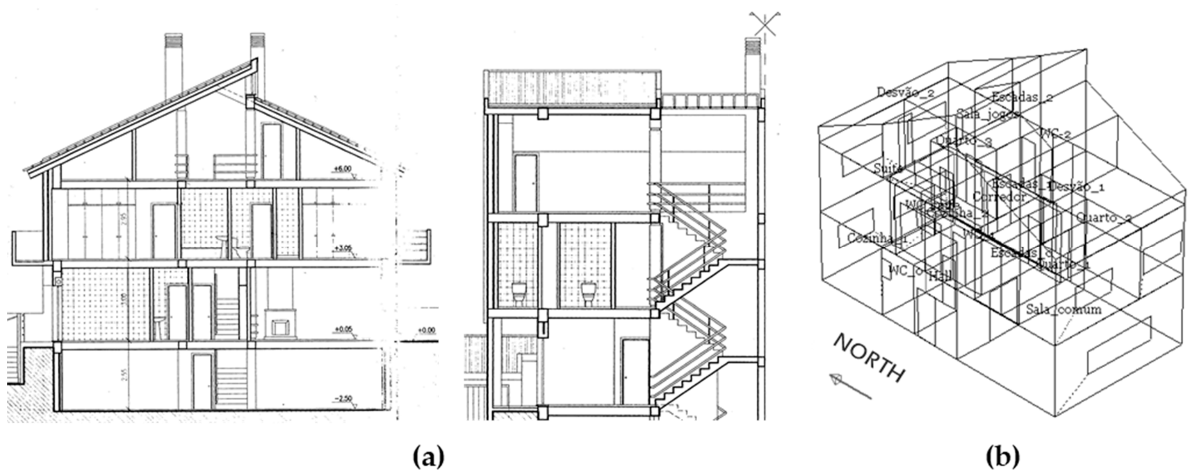

Figure 2. (**a**) Building sections, and (**b**) a 3D model of the simulated building.

All zones of the building were modelled explicitly in ESP-r. The air changes per hour and internal gains of each zone of the building were taken from the Portuguese legislation at the time of calculations [27]: A constant value of 0.6 air changes per hour in each zone. Internal gains of 4 W·m^{-2}

on the living room, dining room, kitchen, three bedrooms, and suite were considered; on the remaining zones, 1 W·m^{-2} of internal gains was assumed (except for the attic, where no internal gains were assumed). The residential building has a total area of 26.3 m^2 of windows with a single clear glass. The existence of venetian blinds covering 50% of each window was considered.

Full-year simulations were performed, with an hourly time step. Two building alternatives with different construction types were considered:

i) A building with no thermal insulation, neither on the façades nor on the roof (named building configuration BD1); and
ii) A building with 60 mm of expanded polystyrene (EPS) insulation, both on external walls and on the roof slab (named building configuration BD2). The conductivity value of this insulation material was considered to be 0.042 W·m^{-1}·K^{-1}.

The construction details of BD1 and BD2 are shown in Tables 1 and 2. The specifications of each layer of the construction (e.g., conductivity, density, specific heat, emissivity, and absorption) follow the recommendations by the Portuguese national legislation [28].

The performance of the buildings was assessed in two complementary ways:

- Through the energy needed to maintain the rooms between 20 and 25 °C during the whole year, assuming that there is an air-conditioning system (conditioned mode); and
- Through an analysis of the indoor temperatures in summer and in winter if there was no mechanical heating nor cooling available (free-floating mode).

Table 1. Construction details of the building with a single wall façade (BD1).

Construction	Layer	Thickness/mm	U/W·m^{-2}·K^{-1}
External wall	Coating Plaster Brick Plaster	0.2 30 190 10	1.3
Internal wall	Plaster Brick Plaster	10 110 10	2.1
Ground floor	Common earth Gravel Concrete Asphalt Concrete Wood floor	300 300 300 10 20 20	0.7
Window	Clear glass	8	5.6
Slab	Plaster Concrete Plaster	10 240 10	2.0
Roof slab	Clay tile Air Plaster Brick Plaster	5 3 5 110 5	1.6

Table 2. Construction details of case BD2—differences from BD1 in bold.

Construction	Layer	Thickness/mm	U/W·m^{-2}·K^{-1}
External wall	Coating	0.2	**0.5**
	Plaster	30	
	Insulation	**60**	
	Brick	190	
	Plaster	10	
Roof slab	Clay tile	5	**0.5**
	Air	3	
	Plaster	5	
	Insulation	**60**	
	Brick	110	
	Plaster	5	

All the weather data used in this article were obtained from the US Department of Energy/Energy Plus database. For the free-floating simulation, BD1 and BD2 were compared in the hottest and the coldest weeks of the year: The week's average daily maximum and minimum temperatures were determined and are presented in the following chapter.

The energy demand needed to keep the indoor temperature between 20 and 25 °C was assessed by a full-year simulation. The cooling and heating thermal energy needs were converted into the final electrical energy demand by considering as the air conditioning system a reference heat pump with an average coefficient of performance (COP) of 4 for heating and 3 for cooling (also called EER instead of COP, in some of the literature). The final heating and cooling energy demand are presented in the following chapter for both building simulation cases (BD1 and BD2).

In terms of paints, four different alternatives were considered:

- A conventional white paint with a TSR value of 90%, named WP (white paint);
- A conventional dark paint with 5% of TSR, named BP (black paint);
- A thermochromic paint with a specific transition temperature, named case ST (step transition) and;
- A thermochromic paint with a linear transition temperature, named case LT (linear transition).

Regarding the thermochromic step transition paints (ST), the thermochromic paint has a TSR of 5% below the transition temperature and a TSR of 90% above it. A parametric study on the transition temperature was performed to identify the nearly optimal value (Section 3).

A thermochromic linear transition (LT) paint was also considered. Below the linear transition temperature zone, the thermochromic paint has a TSR value of 5%, and above the linear transition temperature zone, the thermochromic paint is assumed to have a TSR value of 90%. The TSR value over the linear transition temperature zone depends linearly on the temperature and ranges between TSR values of 5% and 90%. A parametric study on the initial and final temperatures of the linear transition zone was also performed to find the optimum (Section 3).

3. Results and Discussion

The residential building cases, BD1 and BD2, were compared for each of the three reference locations. In the conditioned mode (i.e., building with heating and cooling), the results were expressed in terms of the electricity demand for heating, E_{Heating}, and electricity demand for cooling, E_{Cooling}, over one year, taking into account the COP and EER stated in Section 2. In the free-floating mode (i.e., building without active heating or cooling), the results were expressed in terms of the weekly average daily maximum temperature, T_M, and the weekly average daily minimum temperature, T_m, over the hottest and coldest week of the year, respectively.

3.1. Porto, Portugal

3.1.1. Case ST—Thermochromic Paint with a Specific Transition Temperature

Concerning the residential building configurations BD1 and BD2, a set of parametric simulations varying the value of the transition temperature were performed to determine its optimal value—the one that minimizes the energy use required to maintain the indoor temperature between 20 and 25 °C—Figure 3.

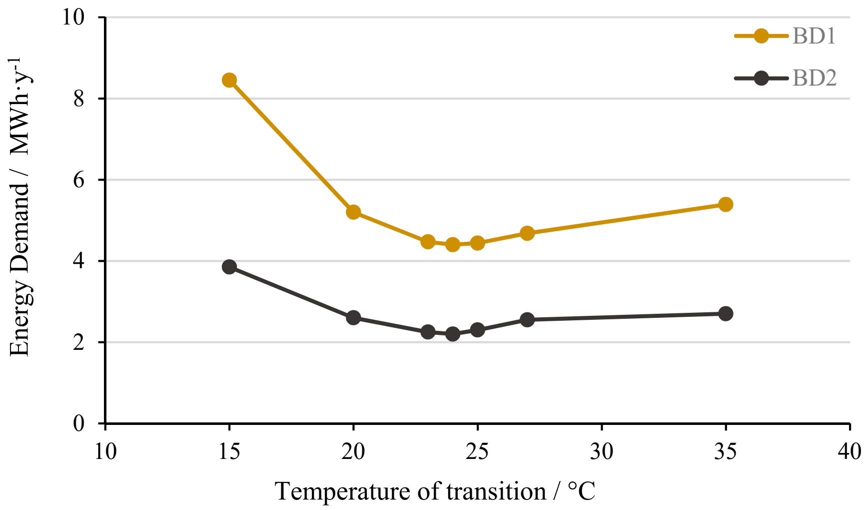

Figure 3. Annual energy demand, for building configurations BD1 and BD2, located in Porto, Portugal, considering different transition temperatures for the thermochromic paint.

As it can be seen from Figure 3, for Porto, the optimum transition temperature of the thermochromic paint is 24 °C for both BD1 and BD2. For this transition temperature, the annual energy demand is ca. 4.4 and 2.2 MWh·y^{-1}, respectively, for building configurations BD1 and BD2.

The thermal behavior of the residential buildings painted with the optimized thermochromic coat is given in Tables 3 and 4. Table 3 shows T_{Max} over the hottest week of the year and T_{min} over the coldest week of the year, in each of the three floors of each building case (BD1 and BD2). The annual energy demand, in terms of the electricity used by the reference system, for cooling, for heating, and in total are shown in Table 4 for both building configurations.

Table 3. Average maximum indoor temperature (T_{Max}) over the hottest week of the year and average minimum indoor temperature (T_{min}) over the coldest week of the year, for a building painted with an optimized thermochromic step transition paint (ST), located in Porto, Portugal.

Building Configuration	Case	T_{Max}/°C			T_{min}/°C		
		Ground Floor	First Floor	Second Floor	Ground Floor	First Floor	Second Floor
BD1	BP	30.5	32.3	35.9	8.3	8.9	7.2
	WP	24.8	27.0	24.4	6.4	6.4	4.9
	ST	26.2	27.7	26.5	8.3	8.9	7.1
	ST − BP [1]	**−4.3**	**−5.3**	**−9.4**	**0**	**0**	**−0.1**
	ST − WP [2]	**+1.4**	**+0.7**	**+2.1**	**+1.9**	**+2.5**	**+2.2**
BD2	BP	28.7	29.9	29.4	9.3	9.4	8.8
	WP	25.0	26.4	24.2	7.8	7.7	6.5
	ST	25.7	26.9	25.4	9.3	9.4	8.8
	ST − BP [1]	**−3.0**	**−3.0**	**−4.0**	**0.0**	**0.0**	**0.0**
	ST − WP [2]	**+0.7**	**+0.5**	**+1.2**	**+ 1.5**	**+1.7**	**+2.3**

[1] **ST − BP:** saving between a thermochromic step transition paint (ST) and a black paint (BP). [2] **ST − WP:** saving between a thermochromic step transition paint (ST) and a white paint (WP).

Table 4. Final energy demand for heating ($E_{Heating}$), and cooling ($E_{Cooling}$), total final energy demand (E_{Total}), and energy savings over the year, for a building painted with an optimized thermochromic step transition paint (ST), located in Porto, Portugal.

Building Configuration	Case	Energy/MWh·y^{-1}			Energy Savings/%
		$E_{Heating}$	$E_{Cooling}$	E_{Total}	
BD1	BP	4.17	1.34	5.51	
	WP	8.51	0.02	8.53	
	ST	4.33	0.09	4.42	
	ST − BP [1]	**+0.16**	**−1.25**	**−1.09**	**19.8**
	ST − WP [2]	**−4.18**	**+0.08**	**−4.11**	**48.2**
BD2	BP	2.14	0.57	2.71	
	WP	3.83	0.01	3.85	
	ST	2.20	0.04	2.23	
	ST − BP [1]	**+0.06**	**−0.53**	**−0.48**	**17.6**
	ST − WP[2]	**−1.63**	**+0.03**	**−1.61**	**41.9**

[1] **ST − BP:** saving between a thermochromic step transition paint (ST) and a black paint (BP). [2] **ST − WP:** saving between a thermochromic step transition paint (ST) and a white paint (WP).

Results with the free-floating mode show that, for Porto, a thermochromic paint with an optimized transition temperature leads to significant reductions in the weekly average maximum temperature indoors. $\boldsymbol{T_{Max}}$ decreased by 9.4 and 4.0 °C in the upper floor, and about 5 and 3 °C in the inhabited floors, respectively, for building configurations BD1 and BD2, when compared with a common black paint. During winter, $\boldsymbol{T_{min}}$ increased on average by 2 °C, when using thermochromic paints instead of common white paints. These results show a positive thermal effect in summer and winter seasons, leading to indoor temperatures closer to the thermal comfort range.

Regarding the analysis in the conditioned mode (indoors kept between 20 and 25 °C), the thermochromic paint with an optimized transition temperature originates annual energy savings up to 4.1 MWh·y^{-1} for building configuration BD1 and 1.6 MWh·y−1 for configuration BD2. These correspond to about 48.2% and 41.9% for BD1 and BD2, respectively. Since the climate in Porto leads to $\boldsymbol{E_{Heating}}$ higher than $\boldsymbol{E_{Cooling}}$, the impact of thermochromics' application is more expressive when compared with common white than black plaints—energy savings of around 18%.

3.1.2. Case LT—Thermochromic Paint with a Linear Transition Temperature

The use of a hypothetic thermochromic paint with a linear transition behavior was also assessed. This thermochromic paint was assumed to have a TSR value of 5% when the surface temperature of the paint is below the transition temperature range, a TSR value of 90% when the surface temperature is above this range, and a TSR value with a linear variation between 5% and 90% in the transition temperature range. Additionally, in this case, the optimal transition temperature range (defined by the low transition limit and by a high transition limit) was sought to minimize the annual energy demand required to maintain the indoor temperature between 20 and 25 °C. For an optimization process using 1 °C steps, the best result was obtained when both the low and high transition points were 24 °C, see Figure 4, which means that for this building and in the Porto climate, the best performing thermochromic paint is a step transition temperature.

Although a single transition temperature provides better energy savings, its energy demand is only 7% and 10% lower for BD1 and BD2, respectively, than the wider transition temperature range considered (18–30 °C). This slight variation allows a gradual color transition for a thermochromic paint without compromising its performance significantly.

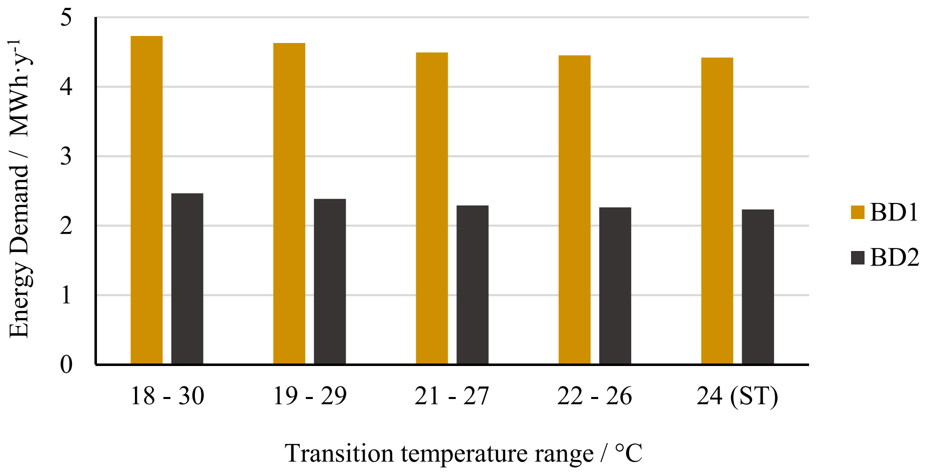

Figure 4. Annual final energy demand for building configurations BD1 and BD2 located in Porto, Portugal, considering different transition temperature ranges.

3.2. Madrid, Spain

3.2.1. Case ST—Thermochromic Paint with a Specific Transition Temperature

A similar study was performed for Madrid. Different transition temperatures were also studied, and the optimum transition temperature was selected taking into account the minimum annual energy demand of both residential building configurations, BD1 and BD2, as shown in Figure 5.

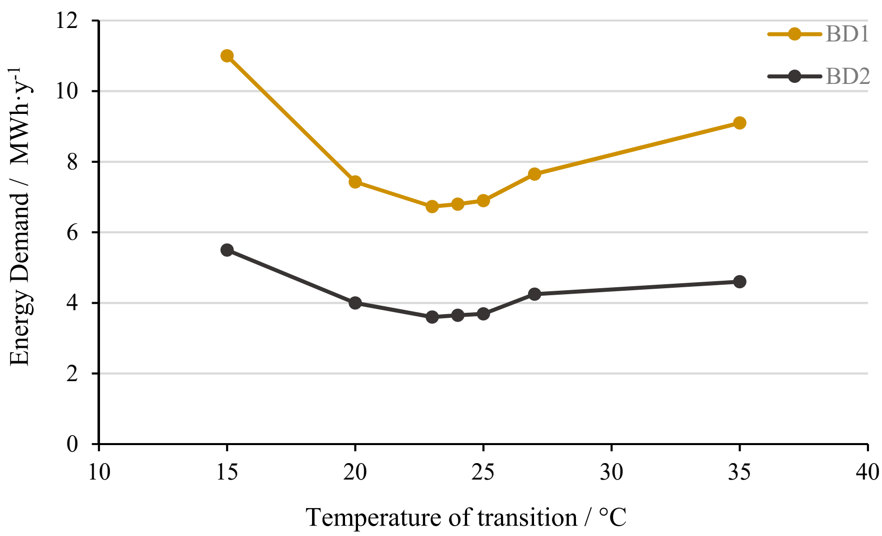

Figure 5. Annual energy demand for building configurations BD1 and BD2 located in Madrid, Spain, considering different transition temperatures for the thermochromic paint.

For Madrid, the optimum transition temperature of the thermochromic coating is 23 °C, for both building configurations BD1 and BD2. This transition temperature corresponds to annual energy demands of about 6.9 and 3.6 MWh·y^{-1} for BD1 and BD2, respectively.

The curves from Figure 5 present a similar tendency to the ones from Figure 6 (Porto case). In both climates, a transition temperature lower than the optimal value (e.g., 15 °C) would have a more detrimental impact on the energy savings than choosing higher temperatures (e.g., 35 °C). It is also visible that the changes in the transition temperature lead to smoother variations in the energy demand for insulated buildings (BD2) than buildings without insulation (BD1).

Tables 5 and 6 show the indoor thermal behavior and the annual energy demand of buildings BD1 and BD2 using a thermochromic paint with a transition temperature of 23 °C. Additionally, for Madrid, values of T_{Max} over the hottest week of the year, T_{min} over the coldest week of the year, and the annual energy demand for cooling, for heating, and in total are presented.

Table 5. Average maximum indoor temperature (T_{Max}) over the hottest week of the year and average minimum indoor temperature (T_{min}) over the coldest week of the year, for a building painted with an optimized thermochromic step transition paint (ST), located in Madrid, Spain.

Building Configuration	Case	T_{Max}/°C			T_{min}/°C		
		Ground Floor	First Floor	Second Floor	Ground Floor	First Floor	Second Floor
BD1	BP	35.5	38.4	43.1	4.2	4.1	2.2
	WP	30.4	32.6	32.1	2.6	1.7	0.2
	ST	30.4	32.6	32.1	4.2	4.1	2.2
	ST − BP [1]	**−5.1**	**−5.8**	**−11.0**	**0**	**0**	**0**
	ST − WP [2]	**0**	**0**	**0**	**+1.6**	**+2.4**	**+2.0**
BD2	BP	30.9	33.1	36.3	5.5	4.7	3.7
	WP	28.3	29.9	29.9	4.2	2.9	1.5
	ST	28.3	29.9	29.9	5.5	4.7	3.7
	ST − BP [1]	**−2.6**	**−3.2**	**−6.4**	**0**	**0**	**0**
	ST − WP [2]	**0**	**0**	**0**	**+1.3**	**+1.8**	**+2.2**

[1] **ST − BP:** saving between a thermochromic step transition paint (ST) and a black paint (BP). [2] **ST − WP:** saving between a thermochromic step transition paint (ST) and a white paint (WP).

Table 6. Final energy demand for heating ($E_{Heating}$), and cooling ($E_{Cooling}$), total final energy demand (E_{Total}), and energy savings over the year, for a building painted with an optimized thermochromic step transition paint (ST), located in Madrid, Spain.

Building Configuration	Case	Energy/MWh·y^{-1}			Energy Savings/%
		$E_{Heating}$	$E_{Cooling}$	E_{Total}	
BD1	BP	5.95	3.35	9.30	
	WP	10.74	0.52	11.26	
	ST	6.28	0.58	6.86	
	ST − BP [1]	**+0.32**	**−2.77**	**−2.45**	**26.3**
	ST − WP [2]	**−4.46**	**+0.06**	**−4.40**	**39.1**
BD2	BP	3.18	1.49	4.67	
	WP	5.15	0.32	5.47	
	ST	3.29	0.33	3.62	
	ST − BP [1]	**+0.13**	**−1.16**	**−1.05**	**22.4**
	ST − WP [2]	**−1.85**	**+0.01**	**−1.84**	**33.7**

[1] **ST − BP:** saving between a thermochromic step transition paint (ST) and a black paint (BP). [2] **ST − WP:** saving between a thermochromic step transition paint (ST) and a white paint (WP).

For Madrid, residential buildings with a thermochromic paint with a transition temperature of 23 °C could have reductions of T_{Max} of up to 11.0 °C and rises of $\boldsymbol{T_{min}}$ of up to 2.4 °C, when compared with common black and white paints, respectively. During the coldest week of the year, this thermochromic paint has the same behavior of a common black paint, while during the hottest week of the year, it has the same behavior of a common white paint. The near 6 °C decrease in T_{Max} for the first floor in case BD1 endorses the estimation predicted (6–8 °C) by Bansal et al. [9] for the surface color effect when comparing a white surface color to a black one.

Additionally, for Madrid, thermochromic paint with an optimized transition temperature always leads to annual energy savings. Maximum reductions of about 4.4 and 1.8 MWh·y^{-1} are observed for BD1 and BD2, respectively, corresponding to maximum energy savings of 39.1% and 33.7%. Ascione et al.'s [21] simulations reported energy savings of ca. 15% with an optimized thermochromic coating in Naples, Italy. That value is considerably lower than those obtained for Madrid and Porto in case BD1 and BD2. In fact, their comparison was made with a 30% TSR paint, while this study used white (90% TSR) and black paints (5% TSR) as references, which can, alongside climate variations, explain this difference.

3.2.2. Case LT—Thermochromic Paint with a Linear Transition Temperature

A hypothetic thermochromic paint with a linear transition temperature was also assessed for Madrid in Spain. Similar to Porto, a TSR value of 5% below the transition temperature range, a TSR value of 90% above this range, and a linear variation between 5% and 90% in the transition temperature range were assumed The transition temperature range was selected taking into account the minimum annual energy demand needed to keep the inside temperature of the residential buildings between 20 and 25 °C, as shown in Figure 6.

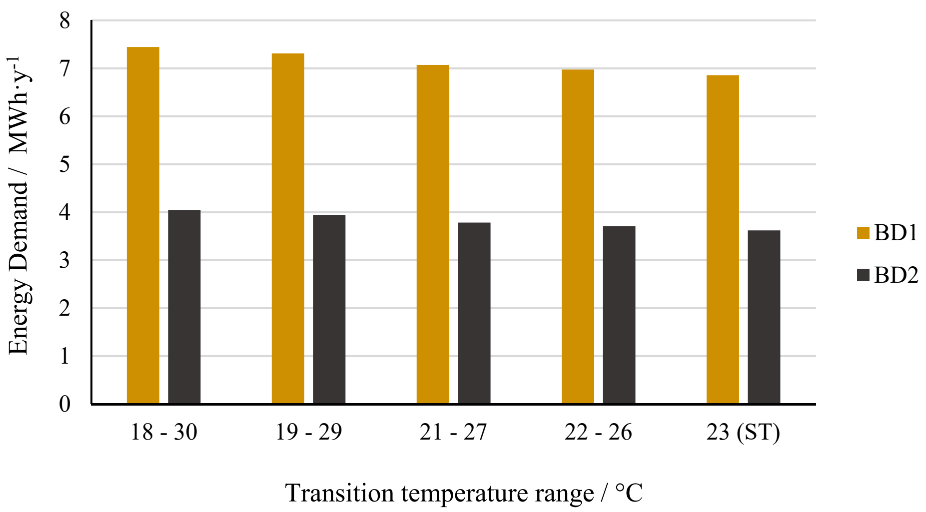

Figure 6. Annual final energy demand, for building configurations BD1 and BD2 located in Madrid, Spain, considering different transition temperature ranges.

As one can see, the same conclusion from Porto can be drawn for Madrid. Additionally, for Madrid, higher energy savings could be achieved with a thermochromic paint with the specific transition temperature of 23 °C, applied both on external walls and on the roof of residential buildings. If the larger transition temperature range is considered, 18–30 °C, the energy demand can increase of up to 8% and 12% in case BD1 and BD2, respectively. Widening the thermochromic transition seems to lead to higher penalties in insulated buildings than buildings without thermal insulation.

3.3. Abu Dhabi, United Arab Emirates

3.3.1. Case ST—Thermochromic Paint with a Specific Transition Temperature

Additionally, for Abu Dhabi in the United Arab Emirates, a similar study was performed and the optimum transition temperature was also selected taking into account the minimum annual energy demand of both residential building configurations, BD1 and BD2, as shown in Figure 7.

For Abu Dhabi, the optimum transition temperature of the thermochromic coating is also 23 °C, both for BD1 and BD2. This transition temperature corresponds to annual energy demands of about 6.0 and 3.4 MWh·y^{-1} for BD1 and BD2, respectively. The very small variations in energy demand for transition temperatures lower than 23 °C are a consequence of dealing with a warm and dry climate. The annual energy demand is not significantly affected by color changes in the building surface when the temperature is low because the outdoor temperature rarely achieves low values.

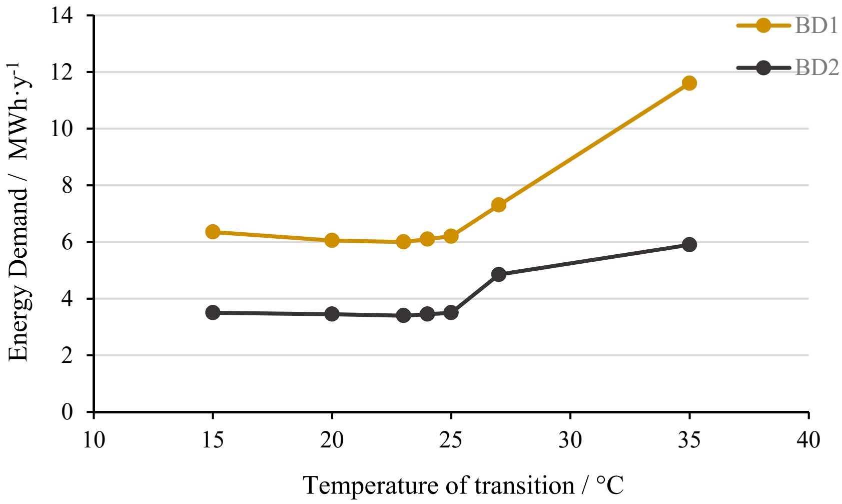

Figure 7. Annual energy demand, for building configurations BD1 and BD2 located in Abu Dhabi, United Arab Emirates, considering different transition temperatures for the thermochromic paint.

Tables 7 and 8 show the indoor thermal behavior and the annual energy demand of building configurations BD1 and BD2 using a thermochromic paint with a transition temperature of 23 °C, where values of T_{Max} over the hottest week of the year, T_{min} over the coldest week of the year, and the annual energy demand for cooling for heating and total are presented.

The residential buildings located in Abu Dhabi, United Arab Emirates, having a thermochromic paint with a transition temperature of 23 °C, could have reductions of T_{Max} of up to 7.7 °C and rises of T_{min} of up to 2.7 °C, when compared with common black and white paints, respectively.

For the three locations studied in this article, the indoor maximum temperature was reduced on average by 5 °C in Abu Dhabi, 6 °C in Porto, and 7 °C in Madrid, without considering thermal insulation. In the literature, Ma et al. [17], Karlessi et al. [19], and Ye et al. [20] reported maximum surface temperature reductions from 4 to 10 °C with the use of thermochromic paints.

Table 7. Average maximum indoor temperature (T_{Max}) over the hottest week of the year and average minimum indoor temperature (T_{min}) over the coldest week of the year, for a building painted with an optimized thermochromic step transition paint (ST), in Abu Dhabi, United Arab Emirates.

Building Configuration	Case	T_{Max} /°C			T_{min}/°C		
		Ground Floor	First Floor	Second Floor	Ground Floor	First Floor	Second Floor
BD1	BP	40.5	44.9	47.2	16.5	17.5	17.5
	WP	37.5	41.0	39.5	13.6	16.0	14.7
	ST	37.4	41.0	39.5	16.1	17.5	17.4
	ST − BP [1]	**−3.1**	**−3.9**	**−7.7**	**−0.4**	**0**	**−0.1**
	ST − WP[2]	**−0.1**	**0**	**0**	**+2.5**	**+2.5**	**+2.7**
BD2	BP	36.3	40.1	41.9	16.5	17.5	18.1
	WP	34.1	37.3	36.9	14.2	16.7	15.5
	ST	34.1	37.4	36.9	16.0	17.5	18.0
	ST − BP [1]	**−2.2**	**−2.7**	**−5.0**	**−0.5**	**0**	**−0.1**
	ST − WP [2]	**0**	**−0.1**	**0**	**−1.8**	**+0.8**	**+2.5**

[1] **ST − BP:** saving between a thermochromic step transition paint (ST) and a black paint (BP). [2] **ST − WP:** saving between a thermochromic step transition paint (ST) and a white paint (WP).

Table 8. Final energy demand for heating ($E_{Heating}$), and cooling ($E_{Cooling}$), total final energy demand (E_{Total}), and energy savings over the year, for a building painted with an optimized thermochromic step transition paint (ST), located in Abu Dhabi, United Arab Emirates.

Building Configuration	**Case**	**Energy/MWh·y^{-1}**			**Energy Savings /%**
		$E_{Heating}$	$E_{Cooling}$	E_{Total}	
BD1	BP	0.04	12.23	12.27	
	WP	0.46	6.11	6.57	
	ST	0.07	6.00	6.06	
	ST − BP [1]	**+0.03**	**−6.23**	**−6.21**	**50.6**
	ST − WP [2]	**−0.40**	**−0.11**	**−0.51**	**7.7**
BD2	BP	0.02	5.97	5.99	
	WP	0.17	3.38	3.54	
	ST	0.03	3.39	3.42	
	ST − BP [1]	**+0.01**	**−2.58**	**−2.56**	**42.8**
	ST − WP [2]	**−0.14**	**+0.01**	**−0.12**	**3.4**

[1] **ST − BP:** saving between a thermochromic step transition paint (ST) and a black paint (BP). [2] **ST − WP:** saving between a thermochromic step transition paint (ST) and a white paint (WP).

For Abu Dhabi, a thermochromic paint with a transition temperature of 23 °C always leads to annual energy savings. Maximum reductions of about 6.2 and 2.6 MWh·y^{-1} are observed for building configurations BD1 and BD2, respectively, corresponding to maximum energy savings of about 50.6% and 42.8%, when compared to dark coatings. However, the energy savings are less meaningful when the comparison is made with white paints—7.7% to BD1 and 3.4% to BD2. Since this climate has negligible heating needs ($\boldsymbol{E_{Heating}} \approx 0$), the use of cool paints (high TSR value) would contribute substantially to a decrease of the energy demand of the building, with winter penalties of around 3%–8%. A similar response would be expected from a typically cold climate, with negligible cooling needs ($\boldsymbol{E_{Cooling}} \approx 0$). A thermochromic paint application would have a very small positive impact when compared to a dark coating. Nonetheless, the overall energy performance is expected to be always better with thermochromic paints, with a more or less notable effect, because the paint is expected to respond thermally to its environment, independently of the climate.

3.3.2. Case LT—Thermochromic Paint with a Linear Transition Temperature

The use of a hypothetic thermochromic paint with a linear transition temperature was also assessed for Abu Dhabi in the United Arab Emirates. A thermochromic paint with a TSR value of 5% below the transition temperature range, a TSR value of 90% above this range, and a linear variation between 5% and 90% in the transition temperature range were assumed. The transition temperature range was selected taking into account the minimum annual energy demand needed to keep the indoor temperature between 20 and 25 °C, as shown in Figure 8.

As observed in Figure 8, only the transition temperature range of 22 to 24 °C has, for case BD1, a slightly lower annual energy demand compared with case ST (23 °C). This small difference is not sufficient to consider the use of a thermochromic paint with a linear transitional temperature instead of a thermochromic paint with a step transition one beneficial.

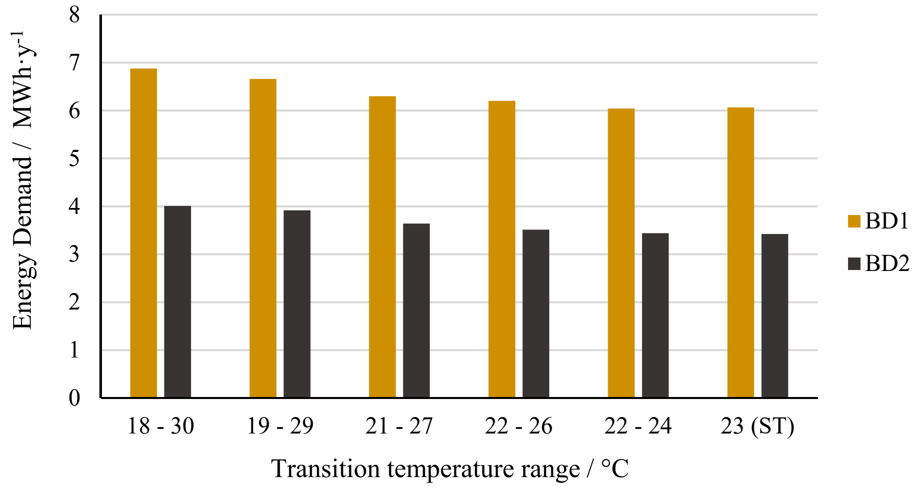

Figure 8. Annual final energy demand for building configurations BD1 and BD2, located in Abu Dhabi, the United Arab Emirates, considering different transition temperature ranges.

4. Conclusions

The thermal behavior of a residential building was simulated, assessing the impact of using thermochromic paints with a step transition or with linear transition, applied both on external walls and on the roof. This simulation study was performed using the open source software ESP-r, for building configurations with and without thermal insulation, and virtually located in three different cities/climates: Porto in Portugal, Madrid in Spain, and Abu Dhabi in the United Arab Emirates.

For the three different locations, the optimized step transition temperatures were determined; the results indicated that these temperatures are 24 °C for Porto and 23 °C for Madrid and Abu Dhabi. Considering the thermochromic paint with a linear transition, it was found that the optimal transition range was very narrow and around the optimal transition temperature of the step transition case.

Regarding the assessment in free-floating mode, i.e., without any active mechanical heating or cooling, the highest indoor temperature reduction in summer was achieved in Madrid, from 43.1 to 32.1 °C, in the upper floor of the detached house. The highest indoor temperature increment during the winter was observed for Abu Dhabi, from 14.7 to 17.4 °C, also in the upper floor. In general, the use of thermochromic paints allowed maximum indoor temperature reductions from 2.2 to 11 °C, when compared to dark coatings. Additionally, minimum indoor temperature increments from 0.8 to 2.7 °C were achieved, when compared to white paints.

In terms of energy use, when operating the building in the conditioned mode to keep the indoor temperature between 20 and 25 °C, thermochromic paints led to energy savings of up to 48%, 39%, and 8%, comparably to common white paints, and up to 20%, 26%, and 50.6% when compared to common black paints, for Porto, Madrid, and Abu Dhabi, respectively.

Regarding the effect of thermal insulation, it decreased ca. 50% of the building energy demand. The impact of thermochromic paints in terms of energy savings is 2%–8% higher in buildings without thermal insulation than insulated buildings.

It was also possible to conclude that the use of thermochromic paints has a more evident impact in temperate climates. The seasonal temperature variation must be significant to justify the need for a dynamic response of the surface by changing its optical properties and color.

Overall, these virtual simulation results confirmed that thermochromic paints can deliver benefits both in summer mode as in winter, unlike cool paints, which provide summer benefits but have a penalty in winter. Nevertheless, these outcomes require future confirmation by physical tests in a real scenario. Additionally, the chemical composition of the paint/coating is essential for understanding the final performance of these materials. Further developments on the chemical formulation of such paints to ensure longevity and cost reductions should thus be encouraged.

Glossary/Nomenclature/Abbreviations

List of Acronyms

BD1	Building configuration without thermal insulation
BD2	Thermal insulated building configuration
BP	Black paint
COP	Coefficient of performance
EER	Energy efficiency ratio
EPS	Expanded Polystyrene
GHG	Greenhouse gases
HVAC	Heating, ventilation and air-conditioning
LT	Linear transition
ST	Step transition
TSR	Total solar reflectance
WP	White paint

Notation and Glossary

E_{Heating}	final energy demand for heating (MWh·y^{-1})
E_{Cooling}	final energy demand for cooling (MWh·y^{-1})
E_{Total}	total final energy demand for air conditioning (MWh·y^{-1})
T_{Max}	week average daily maximum indoor temperature, (°C)
T_{min}	week average daily minimum indoor temperature (°C)
α	absorptivity
ε	emissivity

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