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Investigating the energy saving potential of thermochromic coatings on building envelopes

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HIGHLIGHTS

- Thermochromic (TC) coatings provide heating and cooling savings in buildings.
- 5 building types and 3 climates were studied.
- TC coating properties were optimized according to building types and climates.
- Temperature-based control of TC coatings leads to heating penalties in winters.

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ABSTRACT

Thermochromic (TC) materials can switch solar absorptance (α) based on temperature stimuli. When coatings with TC properties are applied on building envelope surfaces, the amount of solar heat gains can be controlled to reduce the heating and cooling demand of buildings. To date, limited research has been conducted in investigating optimal TC coating properties for application on opaque building envelopes in various scenarios.

In this research, a method to model TC coatings using building performance simulation (BPS) tools has been developed and coupled with python to optimize solar absorption states (α) and switching temperatures and reduce the annual heating and cooling demand. The simulation-based approach has been employed to perform early-stage exploration studies on multiple building types and climates to support material R&D in developing optimized coatings for target applications and assess the potential energy savings.

The results indicate that the optimum TC properties are unique to climate and building types. TC coatings with high switching temperatures result in larger energy savings for scenarios with high heating demands, while TC coatings with low switching temperatures produce larger energy savings in scenarios with high cooling demands. Similarly, increasing the high solar absorption (α_{high}) to 1 increases the heating savings, while reducing the low solar absorption (α_{low}) to 0 results in higher cooling savings. Furthermore, it was found that solar irradiance causes temperature spikes triggering the TC coatings to unnecessarily switch from high to low absorptance state in winters leading to heating penalties. Replacing optimal static with TC coatings on terraced houses in the Spanish climate with a 2:3 heating to cooling demand ratio results in 2 to 13% energy savings.

1. Introduction

With considerable research focused on reducing building energy consumption, it is critical to develop economic technical strategies for large-scale refurbishment of existing buildings, as these buildings will make up a substantial share of the 2050 building stock [1]. Buildings in the EU consume 40% of the total energy produced, of which 40% is used for space heating and cooling, with heat exchanges through building envelopes being a major contributor [2,3]. Reducing this energy consumption is paramount in meeting the sustainability goals set for the

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built environment. Therefore, it is essential to investigate and develop innovative building envelope materials and use advanced building performance simulation to accelerate and steer material development [4,5].

Solar energy in the form of shortwave (near infra-red and visible) radiation plays a major role in the energy balance of buildings. During winters solar heat gains reduce the heating demand, while during summers it is beneficial to reflect incoming solar irradiance to prevent overheating inside buildings. Depending on the climate, maximizing or minimizing solar gains can significantly reduce the heating or cooling demand in buildings [1]. Recent research has led to the development of coatings capable of absorbing different amounts of shortwave radiation (0.3–2.5 μm), referred to here as solar absorptance (α) which varies between 0 and 1, with 1 being complete absorption of solar irradiance and vice versa.

The application of static low solar absorptance coatings on building envelopes to reduce solar heat gains in buildings has been thoroughly researched. These so-called cool coatings reflect incoming solar irradiance, which leads to lower surface temperatures and a reduction of conductive heat flow into the building [6]. Several experiments have been carried out to measure the decrease in cooling demand realized from reducing the roof solar absorptance from conventional values in both residential and commercial buildings. Typical solar absorptance values for conventional envelope materials are between 0.70 and 0.80, respectively [3]. Reducing the roof solar absorptance ($\Delta\alpha$reduced) by 0.55 for several residential buildings in Florida and Sacramento exhibited a 2%-80% reduction in cooling energy compared to conventional roofs [7,8]. Similar studies carried out on commercial buildings with $\Delta\alpha reduced = 0.4 - 0.5$ resulted in cooling energy reduction during summer periods ranging from 2–52% for retail stores, 17–32% for schools, 17% for offices, 26% for museums, 13–18% for medical clinics, 39% for hospices and 4% for cold storages [9–13].

With the widescale adoption of building performance simulations (BPS) tools in research, several studies have explored the annual impact of applying cool coatings in different climates, building constructions, and building types. Akbari et al. [14] simulated single-story residential and commercial buildings with $\Delta\alpha$reduced $= 0.3 - 0.45$ for 11 US cities. The cooling energy savings compared to conventional coatings for residential and commercial buildings varied between 6–17% and 3–9% respectively, however during the winters, the decreased solar absorption resulted in 0–5% and 0–14% increase in the heating energy. This study was later expanded by Akbari et al. [10] to include 240 US cities which revealed that the cooling savings from the application of cool coatings increase in warmer climates and the heating penalties increase in colder climates. The cooling energy savings caused by cool coatings are dependent on the climate, building insulation level, building type, and solar absorptance value [3,10,15].

To mitigate these heating penalties, recent research has been focused on developing dynamic solar control coatings capable of switching between two (high and low) solar absorptance states corresponding to the thermal energy demand of the building [3,16]. Currently, four main types of dynamic solar control exist, photochromic, electrochromic, directional reflecting materials (DRM), and thermochromic. Photochromic coatings are colored when exposed to ultraviolet irradiance but appear pale in the dark [17]. Electrochromic coatings change solar absorptance values as a response to a variation in a voltage field [18]. However, their potential application on opaque building envelopes has largely been unexplored [19]. DRM coatings have corrugated tilted surfaces that allow for a seasonal control on the amount of solar heat flow into a building. An elevated reflectance side reflects solar irradiance in summers, while, a ground facing absorption side absorbs solar irradiance in winters [20]. Simulation studies conducted by Park et al. [21] and Testa et al. [22] showed that replacing cool coatings with bi-directional coatings (Î ± low = 0.45, Î ± high = 0.70) resulted in a source energy reduction of 0.9%, 4.9%, 11% (New Orleans, St. Paul, Baltimore) for residential buildings and 0.1% to 3.9% (New Orleans, St. Paul) for commercial buildings. The research suggested that coatings with temporal switching between solar absorptance states could further increase energy savings by working effectively during periods with fluctuating heating and cooling demands.

Thermochromic (TC) coatings are a dynamic solar control coating, with temperature-based temporal switching from high solar absorptance at low temperatures to low solar absorptance at high temperatures. Despite the intuitive potential of the technology, thus far, limited research has been carried out to quantify the magnitude of impact and potential of these coatings. Gray [16] studied the application of chromogenic polymer-based TC coating; these coatings change color from black to transparent at higher temperatures resulting in Î ± low = 0.45, Î ± high = 0.70. Whole-building simulations revealed less than 1% additional energy savings compared to cool coatings, with warm climates showing the least potential for TC coating application. More recently, the combined use of pigment-based TC coated roofs (Î ± low = 0.74, Î ± high = 0.82) and phase change material (PCM) layered walls showed promising results in various Chinese cities, simulation studies found a reduction of 19% in total energy savings and 4% in CO_2 emission reduction compared to traditional envelopes [23]. Researchers have also analyzed the potential of using TC coatings on roofs as an adaptive measure for mitigating urban heat islands [24,25]. Micro-encapsulated leuco-based TC pigments were used to develop advanced solvent-based coatings and applied over cool roofs. The pigments transition from black to translucent at 20 °C resulting in a TC coating ($\alpha_{low} = 0.45$, $\alpha_{high} = 0.85$). The coating exhibited a 5.8% reduction in heating demand, and a 1.25% increment in the cooling demand compared to a cool coating (Î ± = 0.45) while providing similar urban heat mitigation benefits. Simulation studies of real ($\alpha_{low} = 0.1$, $\alpha_{high} = 0.45$) and theoretical ($\alpha_{low} = 0.1$, $\alpha_{high} = 0.8$) thermal responsive coatings resulted in energy savings ranging between 8 and 15% while increasing indoor thermal comfort [26].

Another possible material for such a concept would be vanadium oxide (VO_2), which has received considerable attention in the last decades [27–30]. The unique properties of this material result in a transition between high and low near-infrared (NIR) absorption, depending on temperature. The facade aesthetics remain unaltered as the absorption transition predominantly occurs in the part of the spectrum invisible to the human eye. The switching temperature dictating the high and low absorption can be altered by cation doping of VO_2 using tungsten (W^{6+}) or magnesium (Mg^{2+}) [28,29]. Without doping, VO_2 has a typical switching temperature of 68 °C, which lowers down to room temperature or lower with doping levels up to 7% [27,30].

TC coatings have the potential to reduce heating penalties in winters while exhibiting low cooling demand in summers. This has led the scientific community to explore novel TC materials and integrating them with specific material bases to develop coatings capable of different switching temperatures and spectral absorption [31]. For example, using TC pigments of different colors or varying the thickness of TC coatings containing VO_2 and TiO_2, different low (α_{low}) and high (α_{high}) solar absorptance states can be achieved, but the maximum switching range between α_{low} and α_{high} was limited to 43% [17,32].

Despite these efforts, there is currently a limited understanding of the causal relationships between TC properties and their effect on building performance. Because of the differences in scale between nanometer and building-level, and because the effects on the latter scale are very context-dependent and application-specific, it is difficult to derive general guidelines [33]. Consequently, research into material development for TC devices for building envelopes has received limited guidance regarding optimal solar absorptance properties and switching temperatures [34].

The main contribution of the present article lies in the identification of optimal properties and the corresponding quantification of the energy-saving potential of TC coatings in opaque building envelopes, with the aim of supporting efficient R&D planning and priority-setting for TC materials. A model has been developed to simulate the novel thermochromic coatings using BPS tools which have been coupled with programming software to create a unique simulation framework for optimizing the switching temperature and solar absorptance properties of TC coatings for various buildings and climate scenarios. Three different building types, terraced houses, retail stores, and office blocks are combined with three different climates to form building and climate scenarios to investigate. Each scenario is simulated with static coatings to investigate the influence of varying solar absorptance values on heat transfer within the facade and the resulting impact on the annual heating and cooling demand. Optimal solar absorptance values are identified based on the aggregate heating and cooling demand for each scenario. The operation of a typical TC coating is benchmarked against two static coatings of similar solar absorptance, to identify the potential and limitation of the TC coating. Currently, TC coatings can be designed with many different low (α_{low}) and high (α_{high}) solar absorptance values but the switching range between states is limited. By using building performance simulation (BPS) as a virtual laboratory, a large range of switching temperatures and low (α_{low}) and high (α_{high}) solar absorptance values are investigated to form trends that can aid material R&D in developing coatings optimized for target applications. The energy savings from both current state of the art (SOTA) and theoretical optimal TC coatings are compared against optimal static coatings on a case-to-case basis to identify promising applications and appropriate coatings are selected for the specific building and climate scenarios.

2. Approach

2.1. Simulation methodology

2.1.1. Modeling thermochromic coatings

In this research, EnergyPlus has been used for whole building simulations. EnergyPlus was developed by the Lawrence Berkeley National Laboratory and the U.S Department of Energy [35]. As BPS tools lack built-in models to simulate adaptive building envelope technologies [4], the Energy Management System (EMS) in EnergyPlus was used to adjust the solar absorptance of building envelopes according to surface temperatures at each timestep [35,36]. Using surface temperature as EMS sensors and if-else logics, at each timestep, the control algorithm actuates the “Surface Property Thermal Absorptance” to a high or low value for each building envelope element depending on whether the sensor value is lower or higher than the switching temperature, respectively. The switching between the high and low value is assumed to be automatic and instantaneous. The simulation of adaptive building envelope technologies requires a fundamental approach to the numerical solution of building surface constructions. Therefore, the fully implicit first-order conduction finite difference (condFD) method has been used to simulate varying properties and conditions in the envelope [37,38]. The calculation nodes are placed at each surface layer to predict surface temperatures required in studying thermochromic coatings. The EMS modeling approach has been successfully validated to simulate thermotropic glazing in buildings [39] and this approach has been used for simulating adaptive façade elements in previous researches [5,40].

2.1.2. Simulation architecture

Recent research suggests that there is no “one solution fits all” when it comes to selecting the optimal coating for an application [41]. Therefore, a simulation framework that couples BPS with EPPy was developed to optimize thermochromic coating parameters for each building and climate scenarios. Eppy is a scripting language in python for editing EnergyPlus input files [42]. Using Eppy various coating properties (such as solar absorptance) were varied and EnergyPlus was used to carry out whole building simulations (Fig. 1). The resulting annual heating and cooling demands were compared in python to determine optimal properties. The static solar absorptance value of building envelopes was varied between 0 and 1 and the optimal value was selected to serve as benchmarks. Later, TC coating was simulated on these building envelopes, and its properties were optimized sequentially. As the switching temperature of VO_2 based TC coatings can be varied through cation doping, determining optimum switching temperatures is a critical metric for the material developer. Therefore, the switching temperature was varied between 10 and 50 °C to select the optimal temperature. In the second phase, the low and high solar absorptance states of the TC coating were varied simultaneously. The resulting total heating and cooling demands for TC and static coatings were compared to determine the most suitable coating for each building climate scenario. The methodology allows for optimizing both static and TC coatings properties for various applications and evaluate their respective energy demands.

2.2. Description of building and climate scenarios

To investigate how building types and climates influence the energy-saving potential of solar control coatings, three distinct building types are explored in this research: a terraced house/row dwelling, an office block, and a retail store. These buildings are simulated in three climates according to the Köppen climate classification: Oceanic (Cfb) (Amsterdam, Netherlands), Dry-summer subtropical (Csa) (Seville, Spain), and Humid subtropical (Cfa) (Milan, Italy). The terraced house model is based on Dutch construction standards (ISSO, 2010), the office building is a lightweight, highly insulated construction based on the IEA reference office building [43,44], and the retail store is based on the U.S. Dept of Energy commercial reference buildings [45]. To research the impact of insulation levels on the energy potential of TC coatings, three different thermal resistance (Rc) values typical for residential buildings from the regions under investigation were studied, these have been described in Table 1 [44,46,47]. A detailed description of the various characteristics of these buildings has been provided in Table 2.

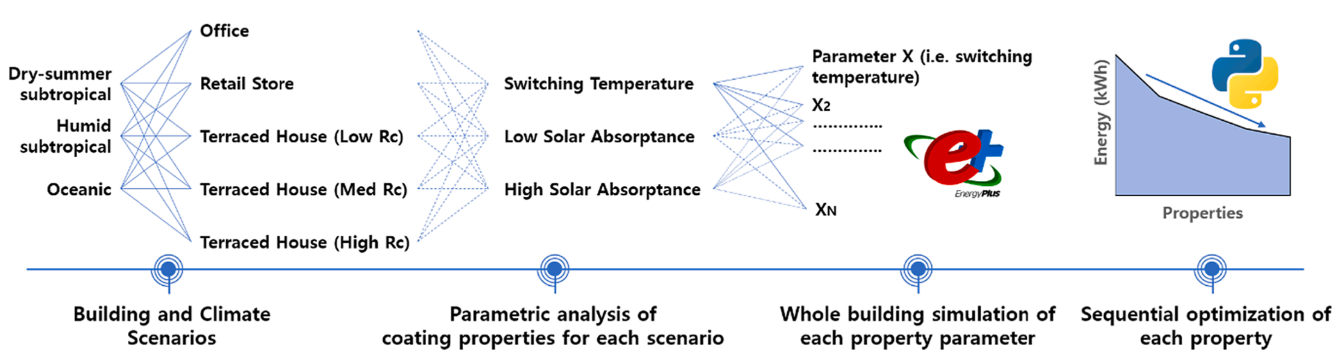


Fig. 1. Simulation and optimization architecture of 3 thermochromic properties (switching temperature, low and high solar absorptance states) for 3 climates and 5 building types.

Table 1
Typical Rc values of various building types and constructions arranged according to Netherlands, Italy, Spain (NL, ITL, ESP) respectively.

Rc (m^2·k/W)	Terraced House			Office	Retail Store
	High Rc	**Med Rc**	**Low Rc**		
	NL, ITL, ESP	*NL, ITL, ESP*	*NL, ITL, ESP*	*NL, ITL, ESP*	*NL, ITL, ESP*
Exterior Wall	4.8, 0.9, 1.1	1.4, 0.4, 0.4	0.3, 0.4, 0.3	2.3, 0.5, 0.9	0.9, 0.2, 0.2
Exterior Roof	2.4, 1, 1.9	0.8, 0.5, 0.6	0.5, 0.3, 0.4	2.3, 0.4, 0.9	1.1, 0.1, 0.1
Exterior Floor	2.2, 0.4, 1.1	0.5, 0.3, 0.1	0.2, 0.2, 0.1	2.3, 0.4, 0.9	2.2, 2.2, 2.2
Exterior Window	0.6, 0.3, 0.3	0.2, 0.2, 0.2	0.2, 0.2, 0.2	0.7, 0.7, 0.7	0.2, 0.2, 0.2

3. Results

3.1. Static solar absorptance coatings

Thermochromic coatings are benchmarked against static coatings to assess their energy-saving potential; however, it is essential to determine the optimum static coating for each building and climate scenario for accurate benchmarking. In this section, static coatings are optimized based on annual heating and cooling demand.

3.1.1. Effect of static solar absorptance on the sensible heat balance of buildings

The solar absorptance of an external surface determines the amount of solar energy in the form of shortwave radiation that is absorbed by that surface. The optimum amount of solar radiation to be absorbed annually varies based on the climate and building types. The solar absorptance value of the opaque building envelope (hatched area in Table 3) of each climate and building scenario was varied (α = 0, 0.25, 0.5, 0.75, and 1.0). The annual heat balance for the low Rc terraced house in Italy (Fig. 2) illustrates, that buildings with higher solar absorptance values experienced larger net thermal flux through conduction (ConductionPos and CondutionNeg in Fig. 2). This leads to a proportional decrease in the heating demand and an increase in the cooling demand.

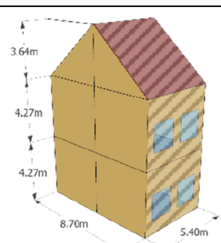
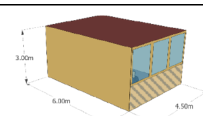
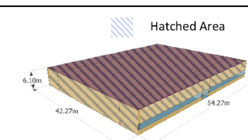
3.1.2. Impact of solar absorptance on the heating and cooling demand

To investigate the correlations between conduction and solar energy absorbed at the external surface, an annual hourly analysis of conduction, heating, and cooling values for static coatings Î ± = 0 and Î ± = 1 is conducted (Fig. 3). A high solar absorptance (Î ± = 1) coating captures larger solar energy, which in turn increases heat flow through conduction. The amount of conduction proportionally influences the heating and cooling demand of the building. Higher conduction (Conduction In) into the building decreases the amount of heating required in winters but increases the cooling requirement in summers. A low solar absorptance (Î ± = 0) coating reflects all incoming solar irradiance and thus has lower thermal conduction into the building (Conduction In) which therefore reduces the cooling demand during summers but increases the heating demand during winters. The increase in heating demand caused by low solar absorptance coatings is commonly referred to as heating penalties (Fig. 3).

3.1.3. Optimizing static solar absorptance coating

Due to the static nature of these coatings, their potential to control solar heat gains is limited. In this section, the performance of these coatings is evaluated in terms of the annual heating and cooling demand. The building and climate scenarios have a unique heating and cooling ratio, which determines whether cumulatively it is beneficial to reduce the heating or the cooling demand (Fig. 4). Scenarios with a higher cooling demand benefit from low solar absorptance coatings. The cooling energy savings in these scenarios are larger in magnitude when

Table 2
Model description of terraced house, office block, retails store.

	Terraced House	Office	Retail Store
Building Shape			
Total Floor	140	27	2294
Hatched Area (m^2)	129	5.4	3388
Window to Wall Ratio	27%	60%	7%
Floors	2	1	1
Zones	5	1	5
Envelope			
Exterior Walls	Brick/Air/Insulation/Brick/Plaster	Aluminum/Insulation/Plaster	Stucco/Concrete/Insulation/Plaster
Roof	Bitumen/Insulation/Concrete	Concrete/Insulation/Screed/Carpet	Roof Membrane/Insulation/Metal Decking
Floor	Carpet/Screed/Concrete/Insulation	Carpet/Screed/Insulation/Concrete	Concrete/Insulation
Adiabatic Features	Load bearing sidewalls	Roof, Floor, Side, and back walls	N/A
Infiltration (ACH)	0.20	0.15	0.27
Ventilation (L/s·m^2)	0.50	0.83	1.37
Internal Gains			
People (W/person)	85	70	120
Lights (W/m^2)	15.0	10.9	16.6
Equipment (W/m^2)	7.5	7.0	5.2
Shading	N/A	70% shading when solar radiation on external facade > 120 W/m^2	N/A

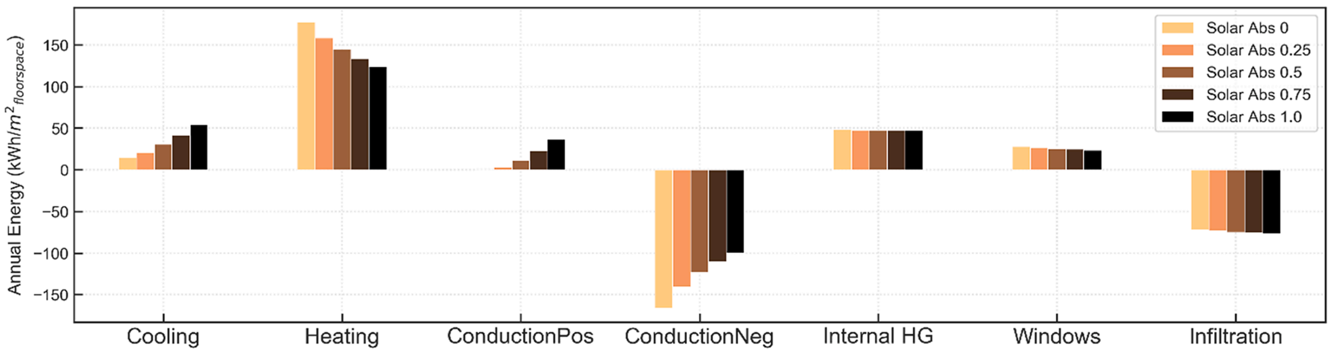


Fig. 2. Annual sensible heat balance of low Rc terraced house in Italy for α = 0, 0.25, 0.5, 0.75, 1.0.

compared to the heating penalties and therefore result in the reduction of the total annual energy demand, (e.g. office buildings, Fig. 4). However, for scenarios with higher heating demand, high solar absorptance coatings offer larger energy savings, as heating savings outweigh cooling penalties, (e.g. terraced houses in the Netherlands, Fig. 4).

Fig. 5 expresses the additional energy savings achieved from applying various static solar absorptance coatings benchmarked against the worst-performing static coating. The optimum static solar absorptance values (αopt) for each scenario are reported in the legend. Scenarios in which the bulk portion of the total energy demand consists of either heating or cooling follow a linear energy savings trend, implying that α_{opt} lies at extreme solar absorptance values. This research focused on the sun-exposed perimeter zones of office buildings. The thermal conditioning demand for these zones is cooling dominated, therefore shifting from a dark coating (α = 1) to cool coating (α_{opt} = 0) results in an annual energy saving of 2 kWh/m^2 to 12 kWh/m^2 of floor area (NL, ITL, ES, Fig. 5E). The energy demand for terraced houses in the Netherlands is predominantly heating based because of the colder climate, therefore, replacing cool coating (α = 0) with a dark coating (α_{opt} = 1) can result in an energy-saving of 6 kWh/m^2 to 48 kWh/m^2, (High Rc, Med Rc, Low Rc, Fig. 5C).

Scenarios with heating and cooling demands of equivalent magnitude follow a parabolic curve, which suggests that the α_{opt} lie in-between α = 0 and α = 1. As the heating demand is higher than the cooling demand, the optimal solar absorptance values for the terraced houses in Italy are also high (α_{opt} = 0.5–0.75). Replacing cool coatings (α = 0) with these optimal static coatings result in energy savings of 4 kWh/m^2 to 22 kWh/m^2 (High Rc, Med Rc, Low Rc, Fig. 5B). On the other hand, the terraced houses in Spain have a higher cooling than heating demand and therefore, the optimal solar absorptance values are low (α_{opt} = 0.0–0.25). By replacing dark coatings (α = 1) with α_{opt} results in energy savings ranging between 19 kWh/m^2 to 27 kWh/m^2 (High Rc, Med Rc, Low Rc, Fig. 5D). Due to the large exposed surface area of retail stores, external climates have a major influence on the heating and cooling demand ratio, the optimal static coatings for retail stores are dependent on the regional climate (α_{opt} = 1 NL, 0.5 ITL, 0 ES). In these cases, the application of dynamic coatings such as TC coatings seems promising in reducing both the heating and cooling demands.

3.2. Thermochromic coatings

3.2.1. Analyzing the behavior of the thermochromic coatings on building envelope

In this section, the dynamic solar control properties of TC coatings are examined to assess their effectiveness in reducing both the cooling and heating demand of a building. Fig. 6 compares the impact that a TC

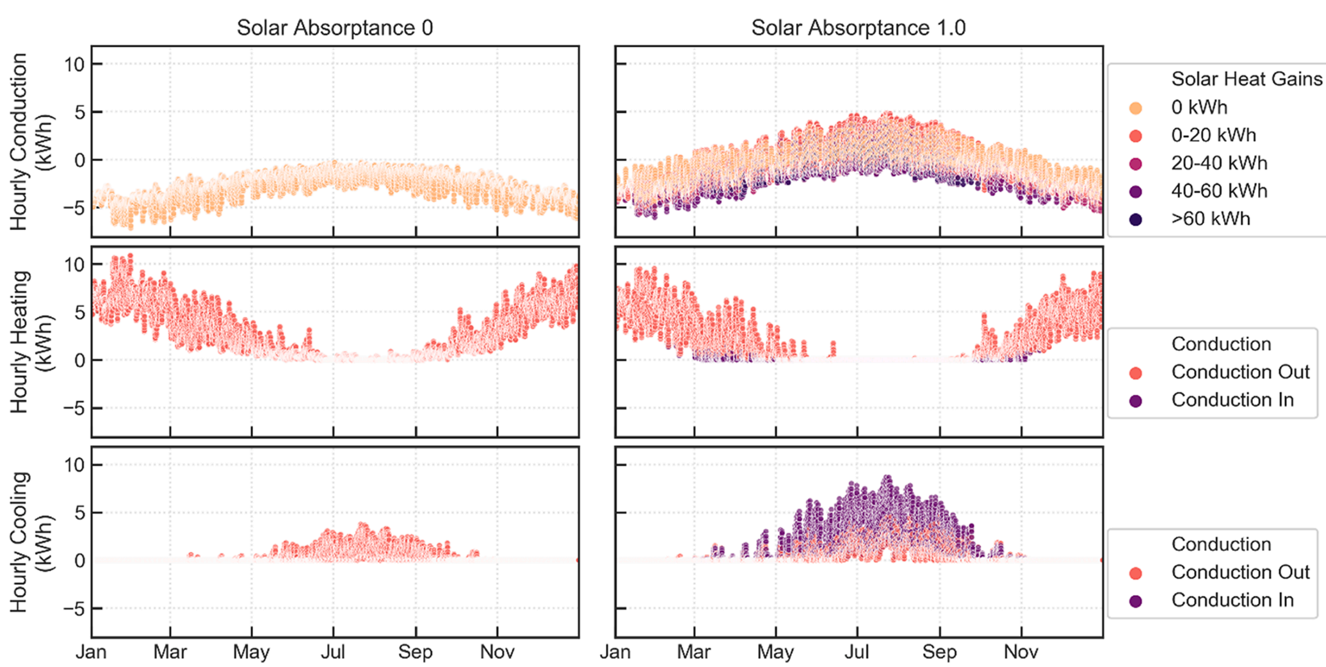


Fig. 3. A comparison of the hourly distribution of Conduction in, Heating and Cooling concerning solar irradiance and conduction respectively for Î± = 0 and Î± = 1, low Rc terraced house in Italy.

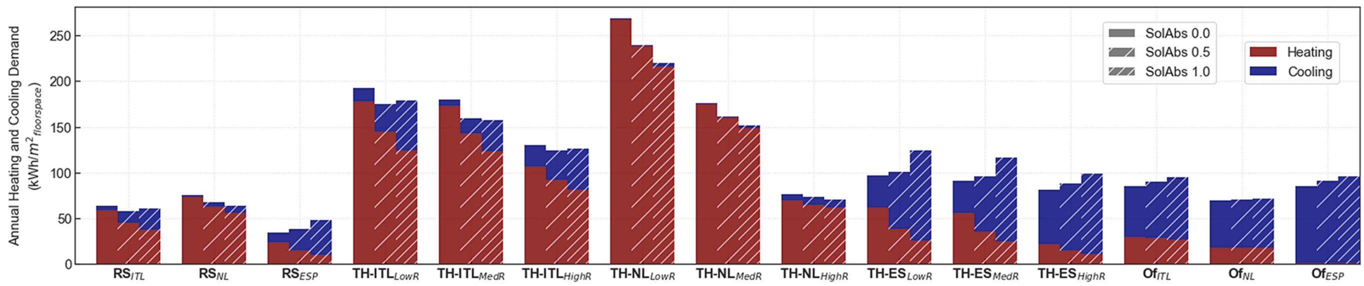


Fig. 4. Heating and Cooling Breakdown (kWh per square meter floor area) for solar absorptance (SolAbs α = 0, 0.5 and 1), Of = Office building, RS = Retail store, TH = Terraced House, ITL = Italy, ESP = Spain, NL = Netherlands, Low Rc, Med Rc, High Rc).

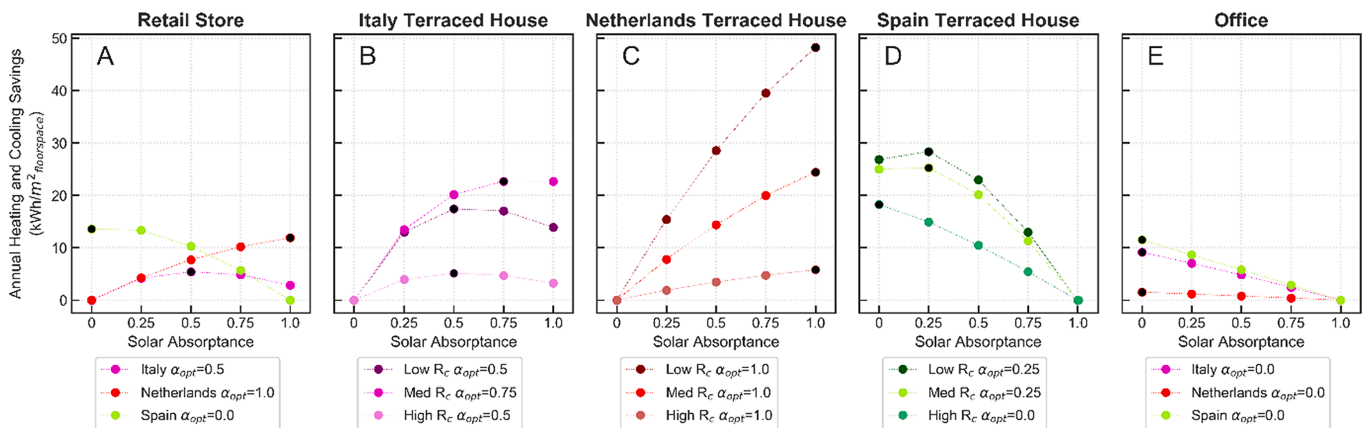


Fig. 5. Additional energy-saving (kWh per square meter floor area) from various static solar absorptance coatings benchmarked against the worst-performing coating.

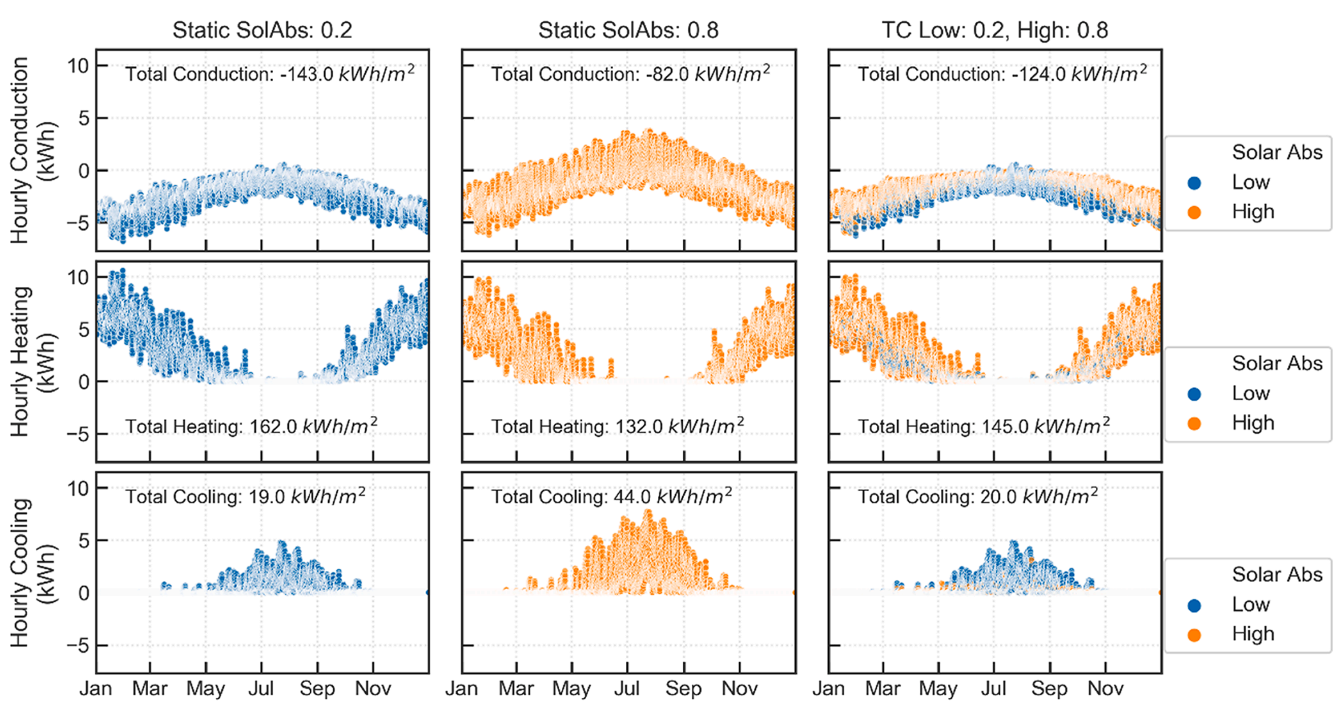


Fig. 6. A comparison of the hourly distribution of conduction in, heating and cooling with respect to solar absorptance states for static coatings Î ± = 0.2 and Î ± = 0.8, and TC coating (Î ± low = 0.2, Î ± high = 0.8), low Rc terraced house, Italy.

coating (α_{low} = 0.2, α_{high} = 0.8, switching temperature = 20 °C), a cool coating (α_{low} = 0.2) and a dark coating (α_{high} = 0.8) have on the conduction, heating and cooling demand of a low Rc terraced house, in Italy. During winters, the TC coating switches to high solar absorptance reducing the conductive heat losses of the building which leads to a decrease in the heating demand. In summers, the TC coating switches to a low solar absorptance state, reflecting incoming solar irradiance and reducing conduction into the building, which consequently reduces the cooling load (Fig. 6). However, the hourly analysis of the heating and cooling demand shows instances during which the coating state is contradicting the building's energy demand. In winters, direct solar irradiance on the south facade causes the daytime surface temperatures (T_{D_sur}) to rise above the switching temperature, which results in the coating switching to a low solar absorptance state and reflect desirable solar heat gains. Fig. 7 plots T_{D_sur}, switching temperature against the daily heating and cooling demand for north and south zones. The T_{D_sur} of the southern facade has a flatter annual profile, which is frequently higher than the switching temperature in winters. Therefore, the temperature-based control of TC coating has limited success in regulating solar heat gains in winters, leading to heating penalties. On the other hand, the parabolic profile of T_{D_sur} of the northern facade allows for better seasonal segregation and improved solar heat gain regulation. In both cases, TC coating succeeds in effectively reducing the cooling demand, but heating penalties from the southern facade limit its potential of reducing the heating demand, as apparent in the total values reported in Fig. 6.

3.2.2. *Optimizing the switching temperature of thermochromic coatings*

The switching temperature of a TC coating controls the total annual duration the coating spends in each of its solar absorptance states. This impact can be evaluated by analyzing the hourly heating and cooling demand for various switching temperatures (Fig. 8). By increasing the switching temperature, the coating is constrained to remain at the high solar absorptance state for a longer duration throughout the year. This increases solar absorption, reducing the heating demand and increasing the cooling demand. While decreasing the switching temperature prioritizes the reduction of the cooling demand. Depending on the heating and cooling demand of each scenario, an optimum trade-off between energy savings and penalties exist, which leads to scenario-specific switching temperature optima.

The switching temperature was varied between 10 and 50 °C at 5 °C intervals and the optimum (Topt) was determined based on the lowest total heating and cooling demand for each scenario and reported in the legend of Fig. 9. Like static coating optimization, 2 distinct trends were observed, a linear and a parabolic trend. A linear trend illustrates that an optimization between heating and cooling savings is irrelevant, as the bulk of the thermal conditioning load consists of either heating or cooling. Therefore, the lowest annual energy demand occurred with T_{opt} calibrated to reduce that demand. These extreme values of T_{opt} suggest static coatings are more appropriate for such applications. Office buildings benefited from low switching temperatures ($T_{opt:}$ 10, 15 °C) aimed to reduce the cooling demand, while terraced houses in the Netherlands benefited from high switching temperatures ($T_{opt:}$ 50 °C) aimed at reducing the heating demand. On the other hand, scenarios with heating and cooling demand of relatively equivalent magnitude follow a parabolic trend with the optimum switching temperature between 15 and 35 °C. This ensured an appropriate amount of switching between states to minimize both heating and cooling demands.

3.2.3. *Energy savings from various low and high solar absorptance states of thermochromic coatings*

The low absorptance state (α_{low}) and high solar absorptance state (α_{high}) of the TC coatings determine the amount of solar radiation is absorbed in those states, this subsequently affects the annual heating and cooling demand. Therefore, parametric analysis was performed by varying the α_{low} and α_{high} between 0 and 1 with 0.25 intervals, resulting in 15 low and high state configurations for each scenario. The heat maps in Figs. 10–14 show the resulting total annual heating and cooling demand per square meter of floor space for each low and high solar absorptance configuration for all the building and climate scenarios. Each box corresponds to the total heating and cooling demand of a specific α_{low} (x-axis) and α_{high} (y-axis) configuration, simulated at switching temperature (Topt) identified in the previous section. The diagonal boxes represent static coatings as the low and high solar absorptance values are identical $\alpha_{low} = \alpha_{high}$. These heat maps aid in selecting optimum α_{low} and α_{high} for given switching ranges and building and climate scenarios, and simultaneously compare energy savings between static and TC coatings.

The oceanic climate of the Netherlands mostly causes heating demand, almost 90% of the total energy demand. Dark coatings (α = high) absorb higher solar energy to reduce this heating demand and subsequently coating with $\alpha = 1$ has the lowest total heating and cooling

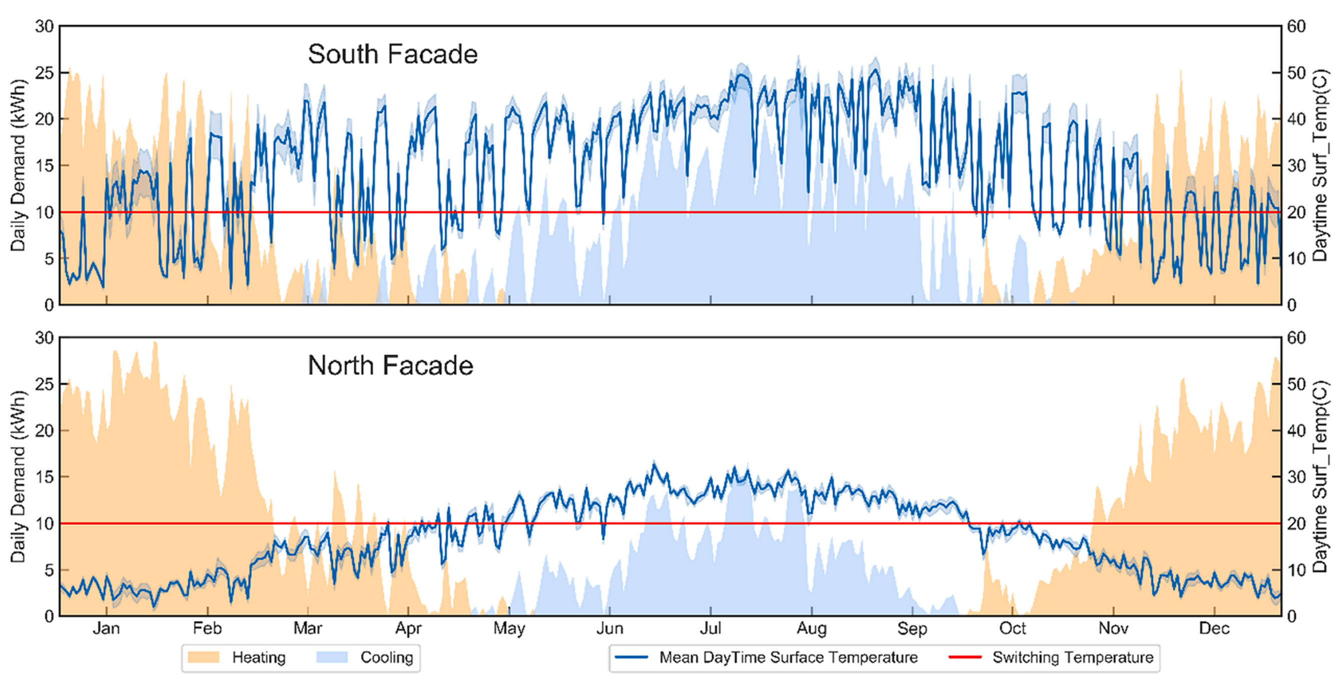


Fig. 7. Daily mean minimum and maximum daytime surface temperature of the south and north-facing facade plotted against the daily heating and cooling demand, TC coating (Î ± low = 0.2, Î ± high = 0.8, 20 °C switching temperature), low Rc terraced house, Italy.

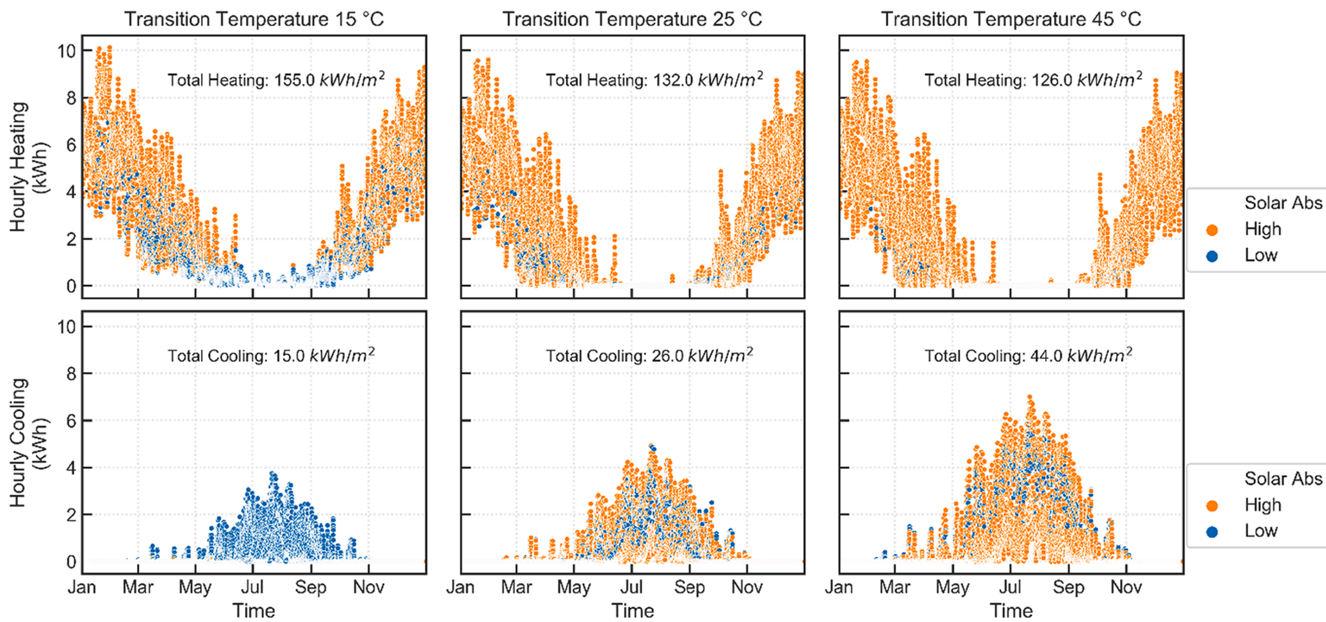


Fig. 8. Effect of various switching temperature on the number of state transitions, heating and cooling demand of a low Rc terraced house in Italy.

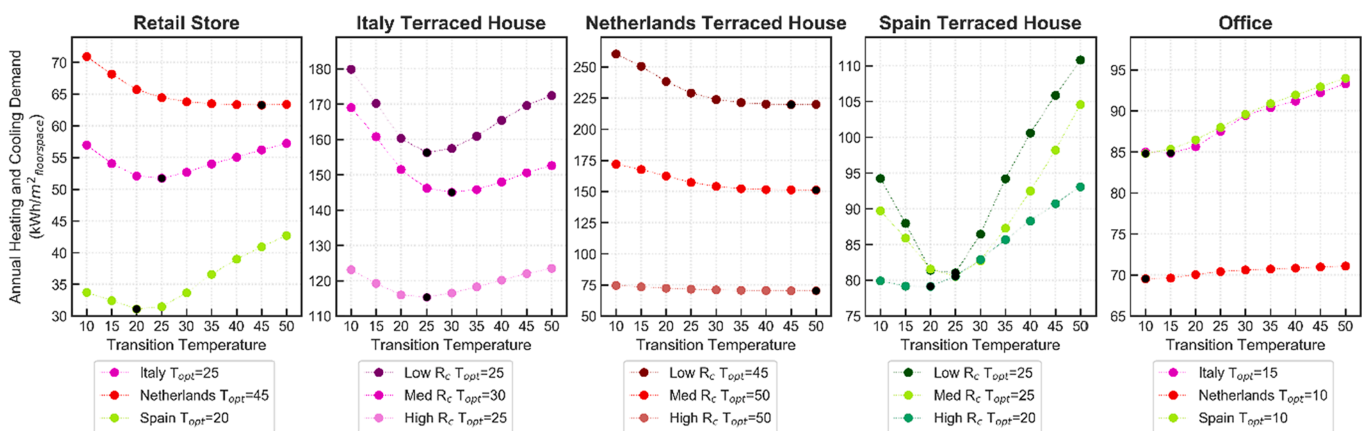


Fig. 9. Total annual heating and cooling demand (kWh per square meter floor area) of all scenarios with a TC coating of varying switching temperatures.

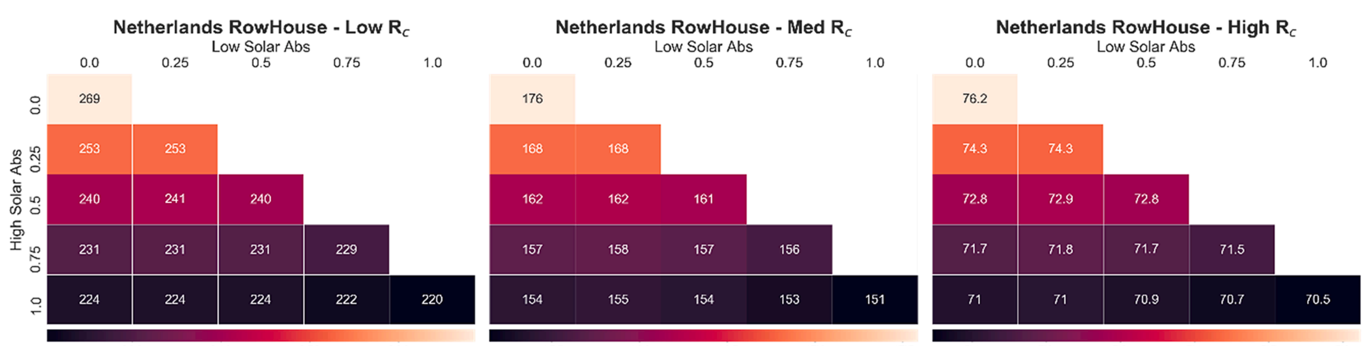


Fig. 10. Total heating and cooling demand (kWh per square meter floor area) with varying low and high solar absorptance states for terraced houses, the Netherlands.

demand. TC coatings switch from high to low solar absorptance during summers to reduce the cooling demand, however, high surface temperatures in winters cause TC coatings to incur heating penalties. The large difference in magnitude between the heating and cooling demand amplifies the heating penalties in comparison to the cooling savings. Thus, reducing α_{low} of TC coatings from 1 to 0 (along the x-axis) resulted in an increase in heating penalties and the total heating and cooling demand, as depicted in Fig. 10. The increase in insulation from low Rc to high Rc reduced the impact external coatings had on the total energy demand, however, the general energy-saving trend from various

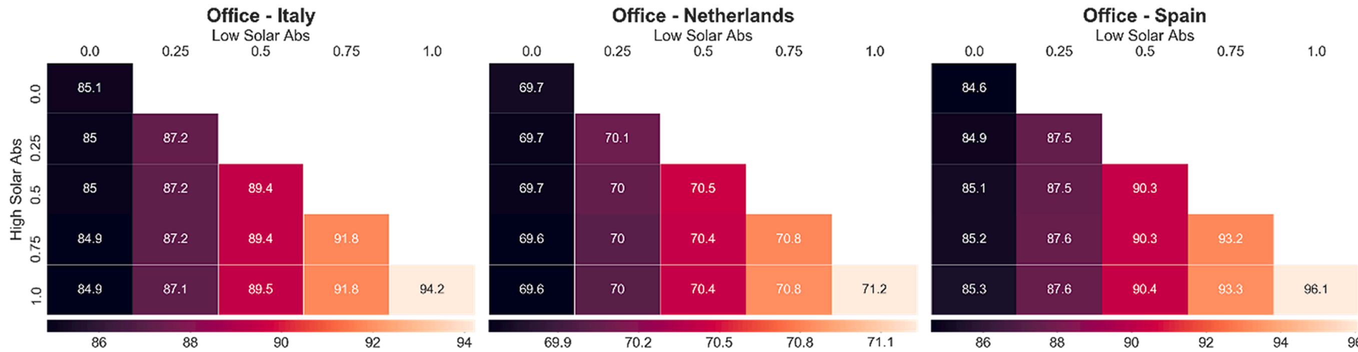


Fig. 11. Total heating and cooling demand (kWh per square meter floor area) with varying low and high solar absorptance states for office blocks.

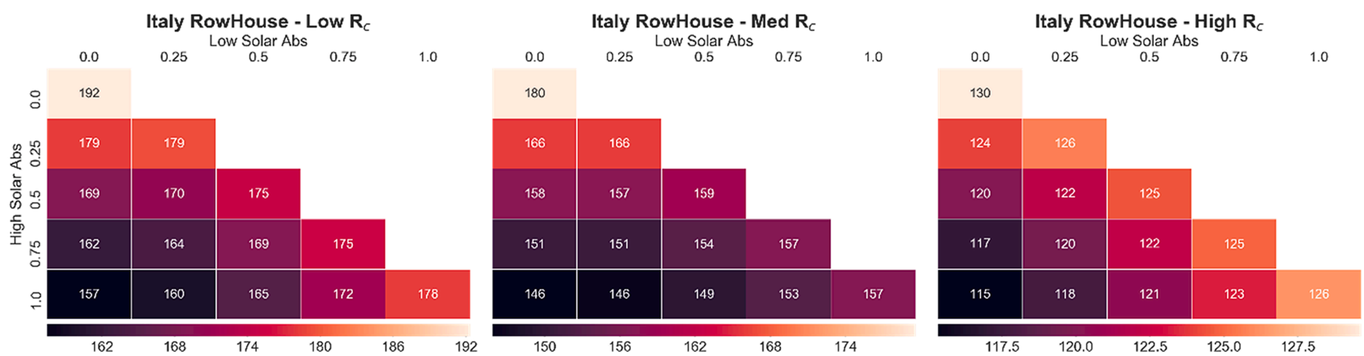


Fig. 12. Total heating and cooling demand (kWh per square meter floor area) with varying low and high solar absorptance states for a terraced house, Italy.

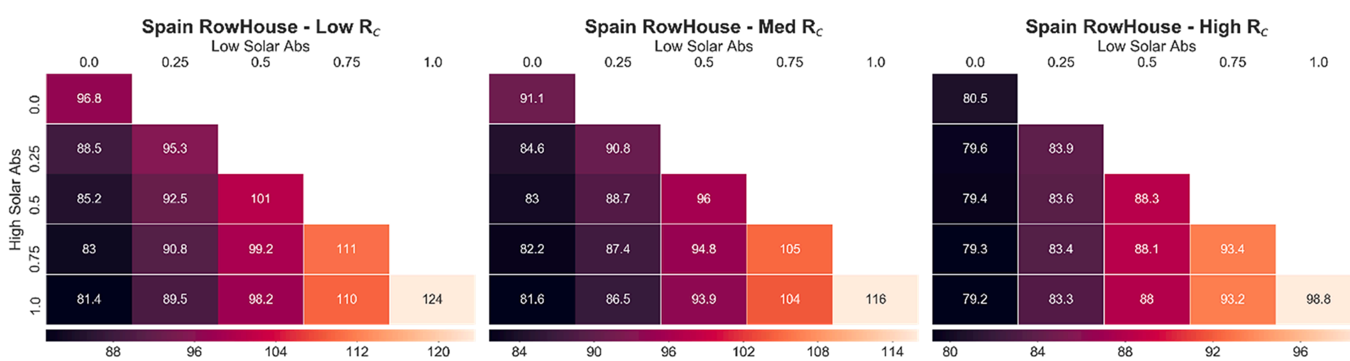


Fig. 13. Total heating and cooling demand (kWh per square meter floor area) with varying low and high solar absorptance states for terraced houses, Spain.

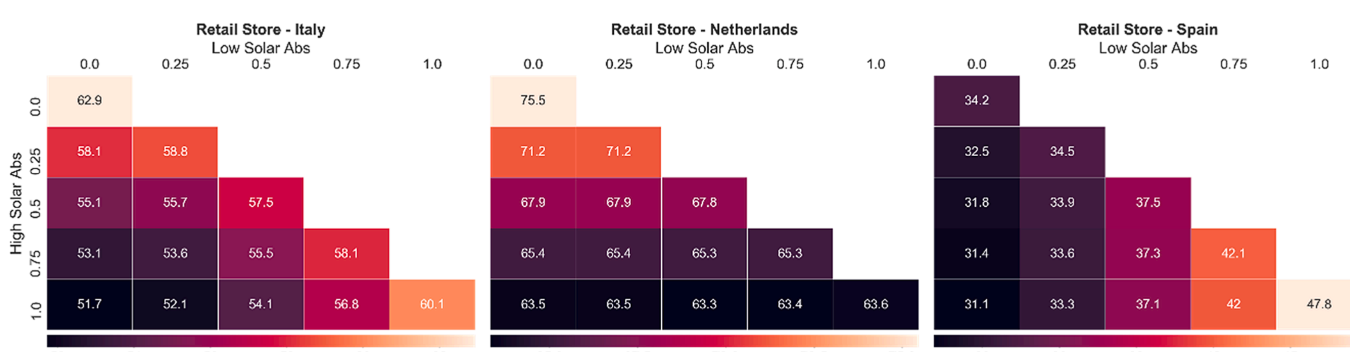


Fig. 14. Total heating and cooling demand (kWh per square meter floor area) with varying low and high solar absorptance states for Retail Store.

coatings remained the same.

Thick insulation and small facade surface area limit the impact external conditions such as climate have on the total heating and cooling demand of the office buildings. Therefore, most of the thermal load consists of the cooling energy needed to dissipate internal heat gains and solar heat gains through the windows. TC coatings with $\alpha_{low} = 0$ resulted in the lowest total energy demand, however, increasing α_{high} from 0 to 1 (along the y-axis in Fig. 11) in an attempt to facilitate heating savings results in negligible increment in the total energy savings, this is because the heating demand accounts for a small fraction of the total heating and cooling demand.

The humid subtropical climate in Italy results in an almost 80 to 20% heating and cooling ratio. Therefore, coating configurations with α_{high} fixed at 1 resulted in the lowest energy demands. As the cooling demand forms 20% of the total energy demand, TC coatings offer higher energy savings than static coatings. By switching to α_{low} in summers TC attain cooling savings that are larger than the heating penalties leading to a decrease in the total energy consumption. As a result, decreasing Î ± low of TC coatings from 1 to 0 results in a decline in the total energy demand, as can be seen along the x-axis of Fig. 12.

The dry-summer subtropical climate of Spain results in an almost 35 to 65% heating and cooling ratio. The high cooling demand favors the application of TC coatings with α_{low} at 0, which resulted in the lowest energy demands. Like the terraced house in Italy, Spanish terraced houses also benefit from the application of TC coatings. As increasing α_{high} from 0 to 1 resulted in additional heating savings, which reduced the total heating and cool demand, as depicted along the y-axis in Fig. 13. As TC coatings are more effective at reducing the cooling demand, these coatings offer higher savings in this scenario. The impact of TC and static coatings was reduced as the building envelope insulation level was increased.

Due to large building envelopes, the thermal conditioning demand of retail stores is largely dependent on the local climate. In the case of the retail store in the Netherlands, most of the thermal demand is heating, thus TC coatings with α_{high} at 1 produced the lowest total energy demand. However, reducing the α_{low} of TC coatings from 1 to 0 resulted in only marginal savings. The application of TC coatings on retail stores in Spain and Italy resulted in energy savings. As the retail stores in Spain have higher cooling demand, TC coatings with α_{low} at 0 resulted in higher energy savings, which increased as the α_{high} was increased from 0 to 1 along the y-axis. As the retail stores in Italy have a higher heating demand, TC coatings with α_{high} at 1 ($\alpha_{high} = 1$) obtained higher energy savings which increased when the α_{low} was lowered from 1 to 0 along the x-axis (Fig. 14).

3.3. *Comparison of optimal static and thermochromic coatings*

A shift from static to TC coatings is only beneficial if additional energy savings can be attained compared to the optimal static coating. Fig. 15 shows the additional energy savings obtained by TC coatings of various solar absorptance states (x-axis) benchmarked against optimal static coatings. Based on section 3.1.3, for each scenario the α_{low} and α_{high} which resulted in the lowest energy demand were fixed while the other solar absorptance state was varied to assess the energy savings linked to increasing the switching range between solar absorptance states of TC coatings. For the office buildings and terraced houses in Spain α_{low} was fixed at 0 (Fig. 15D and E), on the other hand, α_{high} for the terraced house in Italy and the Netherlands was fixed at 1, (Fig. 15B and C). For the retail store, the fixed solar absorptance values varied with the region and have been indicated in the legend (Fig. 15A).

In scenarios where either heating or cooling demand formed the majority part of the thermal conditioning demand, such as office buildings (all climates) and terraced houses in the Netherlands, the application of TC coating led to either negligible energy savings or energy penalties when compared to the optimal static coatings (Fig. 15C and E). Increasing the switching range between α_{low} and α_{high} of the TC coatings resulted in higher energy penalties. Thus, it exhibited little or no value in moving to TC coatings. However, TC coatings achieve higher energy savings in scenarios with more equitable heating and cooling demand, such as terraced houses and retail stores in Spain and Italy (Fig. 15A, B and D). The energy savings increased were directly related to the switching range between α_{low} and α_{high} of TC coatings. The highest savings occurred at the maximum switching range of 100%, between $\alpha_{low} = 0$ and $\alpha_{high} = 1$.

4. Discussion

R&D activities in the field of building envelope technologies typically include experimentation and prototyping. This research, however, has highlighted the use of BPS as a virtual laboratory to perform exploration studies of novel materials and technologies to support the decision-making process of innovative product development. By conducting early-stage studies with BPS, future R&D activities can be focused towards high-potential avenues, reducing the resources and time required for product deployment [33]. By using Fig. 8 and Figures 10–14, material R&D can extract the optimum switching temperatures and low and high solar absorptance states to focus development for their target application. Currently, TC coatings under development have limited switching ranges and the optimal low and high solar absorptance states (α_{low} and α_{high}) for a given switching range vary with application. Summarizing the results from this research, optimal properties and additional energy savings compared to static coatings for two TC coatings have been presented in Table 3, a SOTA optimal TC coating with a 50% switching range and a theoretical optimal TC coating with a 100% switching range. The optimum α_{low} and α_{high} values for the SOTA TC coating vary for the specific application, for example, the optimum α_{low} and α_{high} values of the SOTA TC coating developed for a terraced house in Italy with higher heating demand are 0.25 and 0.75 respectively, while, the optimum α_{low} and α_{high} values for a similar TC coating developed for a terraced house in Spain with higher

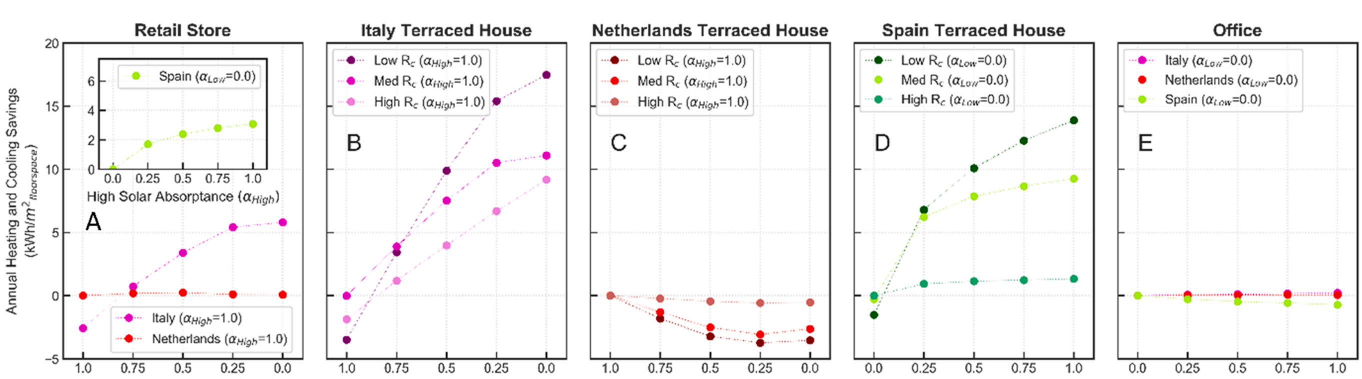


Fig. 15. Energy-saving (kWh per square meter floor area) of TC coatings of various solar absorptance states, benchmarked against the optimal static coatings.

Table 3
Summary table of additional energy savings (kWh per square meter floor area) from TC coatings of various low and high solar absorptance states ($\alpha_{low}/\alpha_{high}$).

	Heating: Cooling (%)	Topt (°C)	SOTA Optimal $\alpha_{low}/\alpha_{high}$ (50% Switching)	Energy Savings (TC- 50% vs. static αopt)	Energy Savings (TC vs. static αopt) Low:0 High:1
Retail Store					
Italy	77:23	25	L:0.5/H:1	3 kWh/7%	6 kWh/11%
Netherlands	93:7	35	L:0.5/H:1	0 kWh/0%	0 kWh/0%
Spain	37:63	20	L:0/H:0.5	2 kWh/10%	3 kWh/13%
Italy Terraced House					
Low Rc	83:17	30	L:0.25/H:0.75	10 kWh/6%	17 kWh/11%
Med Rc	89:11	35	L:0.5/H:1	8 kWh/5%	11 kWh/8%
High Rc	73:27	25	L:0.25/H:0.75	4 kWh/3%	9 kWh/8%
Netherlands Terraced House					
Low Rc	99:1	50	L:0.5/H:1	−3 kWh/−2%	−4 kWh/−2%
Med Rc	99:1	50	L:0.5/H:1	−3 kWh/−2%	−3 kWh/−2%
High Rc	88:12	50	L:0.5/H:1	0 kWh/−1%	−1 kWh/−1%
Spain Terraced House					
Low Rc	38:62	20	L:0/H:0.5	10 kWh/14%	14 kWh/19%
Med Rc	37:63	20	L:0/H:0.5	8 kWh/11%	9 kWh/13%
High Rc	16:84	15	L:0/H:0.5	1 kWh/2%	1 kWh/2%
Office					
Italy	31:69	10	L:0/H:0.5	0 kWh/0%	0 kWh/0%
Netherlands	25:75	15	L:0/H:0.5	0 kWh/0%	0 kWh/0%
Spain	1:99	10	L:0/H:0.5	0 kWh/−1%	−1 kWh/−1%

cooling demand are 0 and 0.5 respectively.

For skin load dominated buildings such as terraced houses and retail stores, the external climate is the largest influencer. Therefore, TC coatings applied to such buildings in climates with seasonal fluctuations (Dry-summer subtropical, Spain and Humid subtropical, Italy) resulted in additional energy savings compared to static coatings. TC coatings reduce both heating and cooling demand fields, while, static coatings reduce either heating or cooling and incur energy penalties in the other field. On the other hand, the influence of opaque surfaces in office buildings is low due to the small exposed surface area and thick insulation. Therefore, the application of TC coatings for this use case results in negligible energy savings. Fig. 15B and D show that higher insulation levels dampen the impact of external factors on internal conditions, this decreases the energy savings potential of TC coatings.

This research optimized a single switching temperature for the entire building meaning that a single switching temperature was used for both facades as well as roofs. Fig. 7 shows that such a practice leads to heating penalties in south-facing zones, which can be reduced through further optimization of the southern facade switching temperatures to compensate for higher surface temperatures. The time delay and temperature range required for complete switching were excluded for this study as these parameters vary with coating types. Furthermore, wind speed and direction directly impact convection which inversely affects surface temperatures, therefore, higher wind speeds reduce surface temperature allowing the TC coatings to remain in the high solar absorptance state for longer periods and vice versa. Total heating and cooling demand have been used as a key indicator in this research however, the conversion efficiencies related to their respective systems have been excluded from the focus. In cases without a cooling device, cooling demand can also serve as an approximate of the thermal discomfort in the space.

5. Conclusion

The work presented in this paper used BPS to identify optimal thermochromic (TC) coating properties and to investigate their energy-saving potential for a range of building and climate scenarios. Hourly analysis of TC coating operation revealed that the temperature-control is prone to excessive switching on the south facade. Solar irradiance on south-facing facades results in high surface temperatures which cause the TC coatings to switch from high to low solar absorptance. During winters, reflecting solar heat gains leads to heating penalties. As a result, the temperature-based control of TC coatings is more capable of modulating solar heat gain during summers than winters.

The switching temperature of a TC coating determines the number of switches between low and high solar absorptance states; therefore, it must be optimized for each intended application. Scenarios with higher heating demands benefit from high switching temperatures which cause the coating to remain at the high solar absorptance state for longer durations. This increases the solar energy absorption effectively reducing the heating demand (i.e. terraced houses in Italy, $T_{opt:}$ 25, 30, 35 °C, High Rc, Med Rc, Low Rc respectively). While, scenarios with high cooling demands benefit from low switching temperatures which promote an earlier transition to low solar absorptance states, reflecting solar heating and reducing the cooling demand (i.e. terraced houses in Spain $T_{opt:}$ 15, 20, 20 °C, High Rc, Med Rc, Low Rc respectively).

Low and high solar absorptance states of TC coatings determine the amount of solar radiation absorbed. Although TC coatings with α_{low} = 0 and α_{high} = 1 deliver the largest energy savings, current TC materials have limited switching ranges. However, material research is currently being performed to achieve different low and high solar absorptance states. Therefore, appropriately selecting these states based on the target application is essential in developing TC coatings that offer maximum energy savings. Generally, for scenarios with higher heating demand, TC coatings with high solar absorptance (α_{high}) fixed at 1 deliver higher savings. Lowering α_{low} on these scenarios results in additional cooling savings. However, in scenarios with higher cooling demands, low solar absorptance (α_{low}) fixed at 0 deliver higher energy savings, and increasing α_{high} provides additional saving on heating demand.

By benchmarking TC coatings against optimal static coatings, this research determined which scenarios would benefit from replacing static with TC coatings. Static coatings result in higher energy savings in scenarios where the thermal conditioning energy demand is largely composed of either heating or cooling. A static coating optimized to either absorb or reflect solar heat gains offer significant savings over their worst-performing static counterparts. For office building, cool coatings (Î± = 0) tuned to reduce the cooling demand resulted in annual energy savings of 1.7, 10, 12 kWh/m^2 of floor area (Netherlands, Italy, Spain respectively). While, for terraced houses in the Netherlands, dark coatings (Î± = 1) tuned to reduce the heating demand resulted in annual energy savings of 0.4, 2.2, 4.3 kWh/m^2 of floor area (High Rc, Med Rc, Low Rc respectively) compared to worst performing static coatings. TC Coatings offer higher energy where the heating and cooling demands are of a similar magnitude. For such applications, TC coatings manage energy savings from both heating and cooling demand fields, resulting in a lower cumulative annual energy demand when compared to optimal static coatings. For terraced houses in Italy, SOTA TC coatings with 50% switching (α_{low} = 0.25, α_{high} = 0.75; $T_{opt:}$ 25, 30, 35 °C) resulted in annual energy savings of 4, 8, 10 kWh/m^2 (High Rc, Med Rc, Low Rc respectively). While, TC coatings (α_{low} = 0, α_{high} = 0.5; $T_{opt:}$ 15, 20, 20 °C) resulted in annual energy savings of 1, 8, 10 kWh/m^2 (High Rc, Med Rc, Low Rc respectively) of floor space for terraced houses in Spain. From these results, it can be concluded that optimized TC or static coatings mainly have a significant effect on building with low to medium insulation levels.

TC coatings are a promising technology that can be used to control solar heat gains and improve energy efficiency in buildings with low insulation levels and high surface area to volume ratios, and in climates with high seasonal fluctuations. Finally, the heat maps (Figs. 10–14) produced in this research can be employed by material scientists as an aid to develop optimized TC coatings for specific applications and switching ranges.

CRediT authorship contribution statement

Afaq A. Butt: Methodology, Conceptualization, Software, Visualization, Writing - original draft. **Samuel B. de Vries:** Software, Writing - review & editing. **Roel C.G.M. Loonen:** Conceptualization, Supervision, Writing - review & editing. **Jan L.M. Hensen:** Supervision, Writing - review & editing. **Anthonie Stuiver:** Supervision, Writing - review & editing. **Jonathan E.J. van den Ham:** Supervision, Writing - review & editing. **Bart S.J.F. Erich:** Conceptualization, Supervision, Writing - review & editing.

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.

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