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Preparation and assessment of the potential energy savings of thermochromic and cool coatings considering inter-building effects

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Preparation and assessment of the potential energy savings of thermochromic and cool coatings considering inter-building effects

Abstract

Cool coatings show high solar reflectance and have been proposed to decrease the building energy demand by reducing solar heat gains. However, cool coatings may have a negative effect during cold seasons when solar gains would be beneficial. Thermochromic coatings, thanks to their ability to change their solar reflectance at different temperatures, have been proposed to reduce the heating penalties during colder seasons of traditional cool coatings. In this work, four different thermochromic pigments have been used to create façade paints. The solar reflectance and thermal emissivity of these paints have been evaluated experimentally. A significant change of 0.37 in the reflectance of the four paints was registered in the visible range. These products are hence compared with common cool coatings available on the market. In order to evaluate the potential energy savings of thermochromic paints, an office building in downtown Toronto (Ontario, Canada) and the surrounding area have been modeled in Energy Plus. Different scenarios have been simulated and compared among conventional, cool, and thermochromic coatings applied on the roof or on the building facades. The study also evaluates the different new coatings under several climate change scenarios. Overall results show that for the context of analysis, thermochromic paints can provide an 8.9% decrease in the cooling demand, while limiting the winter penalties to 1.7%, compared to the heating penalties of 2.6% resulted using cool coating. Despite the limited heating penalties, the annual energy demand for all the simulated scenarios is comparable. Similar results were also obtained when the inter-building effects were taken into account in the analyzed context. Finally, thermochromic paints proved to be more beneficial considering future climate conditions as Canada is projected to show significantly higher cooling energy demands.

Keywords: Urban heat island, cool materials, thermochromic paint, solar reflectance, inter-building effects.

1. Introduction

Global temperatures have been growing steadily during the last three decades due to the increasing emissions in the atmosphere of greenhouse gasses produced by human activities (Ritchie & Roser, 2017). Meanwhile, the current climate change mitigation strategies are not keeping up with the targets set in the Paris Agreement (Paris Agreement, 2016). In particular, as buildings account for 36% of global final energy use and 39% of energy-related carbon dioxide emissions (UN Environment, 2017), they are often indicated as the sector urgently needing solutions for a low-carbon future.

Improving the performance of the building envelope is a trending theme of research. The development of new building materials promises to represent a significant opportunity to reduce building energy demand and emissions (Ascione, 2017). Among new materials, reflective coatings represent a cost-effective and environmentally friendly alternative for building finishing. Characterized by a high solar reflectivity and thermal emissivity, cool coatings can reduce surface temperature leading to a reduction of the cooling demand (Synnefa et al., 2007; Synnefa & Santamouris, 2013; Hosseini & Akbari, 2014; Jandaghian and Berardi, 2020). Cool materials have demonstrated to bring substantial benefits, especially in hot climates. However, their static behavior becomes a limit in those climates with cold seasons and hot summer, where a dynamic response of the building envelope becomes critical (Wang et al., 2016).

As cool materials continuously reflect solar heat gains, these have may counterproductive effects during the cold season. Consequently, the demand for dynamic or responsive coatings, that could change their behavior according to environmental conditions, has emerged. In this context, thermochromic pigments have received increasing attention thanks to their variable thermo-optical properties that reversibly change accordingly to the temperature. This transformation allows thermochromic pigments to display a lighter and more reflective color during the hot periods of the year, and an absorbing behavior when the outdoor temperature decreases together with their solar reflectance (Karlessi & Santamouris, 2013).

Thermochromic coatings are already used in a variety of fields from packaging to clothing and medical products. A typical application in the building field of the thermochromic behavior is represented by thermochromic windows (Zheng et al., 2015; Yuanyuan et al., 2018). In these systems, the phase transition associated with a relevant change in the optical properties in the near-infrared range makes the thermochromic windows able to manage the solar heat gains dynamically. Similarly, thermochromic coatings could be adopted to control the heat gain of the opaque portion of the envelope, although a few studies on thermochromic coatings exist so far.

This study aims to compare both experimentally and numerically cool and thermochromic coatings; for this, the energy consumption variations of a building in a continental climate resulting from the application of different coatings are assessed. The research includes a laboratory characterization of thermo-optical properties including the solar reflectance, the thermal emissivity, and the solar reflectance index (SRI) of new cool and thermochromic paints. The following building-scale energy demand analysis is also conducted considering the inter-building effects. A final analysis focuses on the implication of climate change and the effectiveness of both cool and thermochromic paints over building energy demands under future climate scenarios.

2. Literature review

Exterior coatings influence the thermal behavior of the building envelope according to two parameters, the solar reflectance and the infrared emittance. While conventional dark-colored coatings usually have a low solar reflectance, cool coatings have a high solar reflectance and thermal emissivity. A coating with high solar reflectance decreases the absorption of incoming electromagnetic radiations. On the other hand, high thermal emittance allows a rapid dispersion of the absorbed heat, and a faster surface temperature decrease (Santamouris et al., 2011). The adoption of highly reflectivity materials is a promising mitigation technique for the urban heat island phenomenon since lower surface temperatures lead to less heat transfer to the ambient air (Synnefa et al., 2008, Wang et al., 2016). Haberl and Cho (2004) reported that cooling energy savings from the application of cool materials on residential and commercial buildings vary from 2% to 44%, while the peak cooling energy savings are between 3% and 35%, depending on building characteristics. Moreover, the reduced heat transfer leads to a lower temperature in the indoor environment and an increase in thermal comfort. In 2007, a study compared the behavior of a single-story building with a flat roof in 27 cities, and found that the adoption of a highly reflective roof with a solar reflectance of 0.85 caused a reduction of the maximum temperature between 1.2– 3.7°C and of the discomfort hours between 9% and 100% (Synnefa et al., 2007). However, the benefits of cool materials are higher when cool coatings are adopted in poorly insulated buildings (Fabiani et al., 2020). Together with lower surface temperatures, a higher solar reflectance of the roof coatings increases the lifetime of the roof as it would reduce the thermal fatigue and chemical degradation mechanisms (Pisello, 2017).

The effectiveness of cool coatings depends on the climatic conditions, as high albedo coatings are more effective in hot climates and at lower latitudes, where the building cooling load significantly exceeds the heating one. In fact, the reflection of the incoming radiation during the

heating periods and reduces free heat gain increases, even if the winter penalties are limited by lower sun angles, cloudier days, shorter daytime, and the chance of snow accumulation (Hosseini et al., 2014). In recent years, studies have investigated new coatings capable of adapting to different seasonal conditions and needs. Among the various solutions, thermochromic materials have gained significant attention. These products exhibit a relevant color change, accompanied by variations of their optical and thermal properties when exposed to a specific temperature. The temperature range at which the transformation occurs is called transition or switching temperature (Garshasbi & Santamouris, 2019). Temperature-sensitive optical properties allow to respond to different external environment changes: when thermochromic materials substitute a standard building coating, the new finishing could behave like a "conventional" cool roof during hot periods, while transitioning to a darker color during the cold seasons when they would absorb more solar radiation.

The current state of the art of thermochromic materials has been summarized by Garshasbi and Santamouris (2019) with specific attention to the possible application in the building sector. Currently, laboratory analysis has been conducted mainly on Leuco dyes (Zheng et al., 2015; Fabiani et al., 2019; Zhang & Zhai, 2019), which have a temperature transition consistent with the building sector and a low cost of production. Leuco dye thermochromic mechanism is a result of the interaction between three elements: color former, color developer, and co-solvent.

Measurements of the solar reflectance spectra of various thermochromic coatings have been carried out, and the results proved a significant change in the visible region, while a negligible effect has been recorded in the near-infrared one. Fabiani et al. (2019) used black microencapsulated leuco-based thermochromic pigments to produce a solvent-based coating with a solar reflective coefficient switch between 0.35 and 0.55 for the colored and non-colored phases, respectively. The optical properties of thermochromic coating are influenced by the concentration and size of the thermochromic pigment and by the concentration of the TiO_2 molecules (Zhang & Zhai, 2019). The introduction of TiO_2 particles in thermochromic paint increases the solar reflectance and the difference between the two phases (Zhang & Zhai, 2019; Xiong & Jianying, 2019).

Currently, the main downside of cool and thermochromic coatings is their aging (Morini et al., 2018). The primary degradation mechanism that reduces the thermochromic transformation is the UV radiation (Karlessi et al., 2009). Recently, Karlessi and Santamouris (2013) proved that a combination of UV and optical filters could limit the solar reflectance variation of the paint during both phases.

The potential energy saving of thermochromic coatings when applied to building envelopes is a relatively new field of investigation. Just a few studies have investigated the benefits of this technology by modeling prototype buildings using energy modeling (Zheng et al., 2015; Jianying & Xiong, 2019; Park & Krarti, 2016). Different procedures have been adopted to simulate the dynamic behavior of thermochromic paints. Park and Krarti (2016) used two reflectivity values for two periods: a solar reflectivity of 0.55 during the cooling period and a reduced 0.30 value during the heating period. Similarly, Zheng et al. (2015) performed an analysis on a small box; the reflectance of the coating was monthly selected based on the average air temperature, if the temperature was higher than 25°C, the coating was assumed to be in its colorless phase for the entire month. Jianying and Xiong (2019) performed a more precise analysis: the dynamic optical properties of thermochromic paints were modeled using the energy management system (EMS) in EnergyPlus, so it changed accordingly to the surface temperature. Jianying and Xiong (2019) investigated the energy consumption in seven cities representing the different U.S. climate zones confirming that thermochromic paints are especially effective in regions with high cooling and heating demands, like Chicago or Portland. Compared to a conventional roof, cool coatings and thermochromic coatings mixed with TiO_2 reduced the annual cooling electricity demand by 8.9–23.3 kWh/m^2 and 2.9–15.1 kWh/m^2 respectively, which corresponded to a decrease between the 17.2 to 54.5% and 11.1 to 39.4% of the cooling demand. However, when the heating loads were taken into account, the thermochromic coatings guaranteed the best performance.

3. Methodology

3.1 Laboratory characterization

3.1.1 Sample development

Four cool coatings, developed by two companies Kool Seal and Lanco, were selected and evaluated. The coatings were applied to brick squared samples (5x5 cm) in two layers, as represented in Fig. 1.

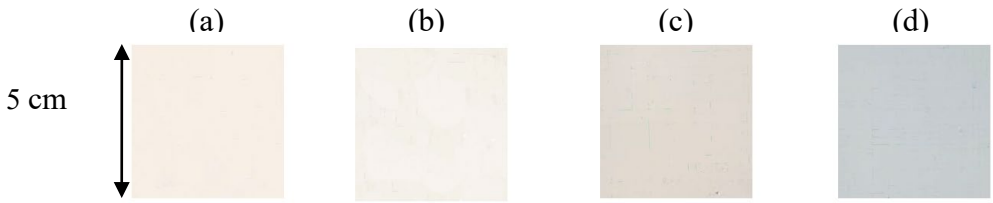

Figure 1. Cool paint samples considered in this study: (a) Kool Seal Premium, (b) Kool Seal RV, (c) ultra siliconizer, and (d) urethanizer.

To design a thermochromic paint, four microencapsulated leuco dyes thermochromic in powder form were purchased from different companies (Table 1). The paints were created using two components: an acrylic water-based base paint, characterized by a high concentration of TiO_2 molecules (14%), and the thermochromic powder mixed in different concentrations to assess different levels of the thermochromic effect. Three types of coating have been prepared for each thermochromic product, using three concentrations of the powder: 5%, 10%, and 15%. Different amount of thermochromic particles have been tested to evaluate their impact on the solar reflectance value during the colored and non-colored phase. The components were stirred manually to avoid the damaging of the microcapsule. Two hands of the thermochromic paints have been applied to each brick as done for the cool paints.

Table 1. Characteristics of the thermochromic considered in this study.

Product	Company	Color	Transition temperature	Particle Size
Thermochromic Red RT-31BF	Kelly Chemical Corporation	red	31°C	10 ± 2 µm
Thermochromic Black LT-31BF	Kelly Chemical Corporation	black	31°C	10 µm (max)
Chromicolor® MS Powder LF Grade	Matsui Shikiso Chemical Co.	magenta	25°C	2-4 µm (average)
Thermochromic Powder BPA Free_Red 31	LCR Hallcrest	red	31°C	<6 µm (97%)

Each thermochromic paint proved to have different behaviors. All samples were simultaneously exposed to the same environmental condition inside a climatic chamber which was programmed to raise the temperature from 26°C to 34°C at 1°C temperature steps. Each temperature set-point was maintained for 30 minutes after which a manual evaluation of the color change of the specimens was performed using a color palette. The color transformation resulted to be gradual for some products like Kelly Powder, while others, like Mastui, showed a more rapid transformation.

All the tested paints proved to be highly reactive to the transition temperature when heated. The percentage of thermochromic powder had no impact on the temperature and duration of the thermochromic transition. However, the higher percentages of thermochromic particles led to more saturated colors, as evident in Fig. 2.

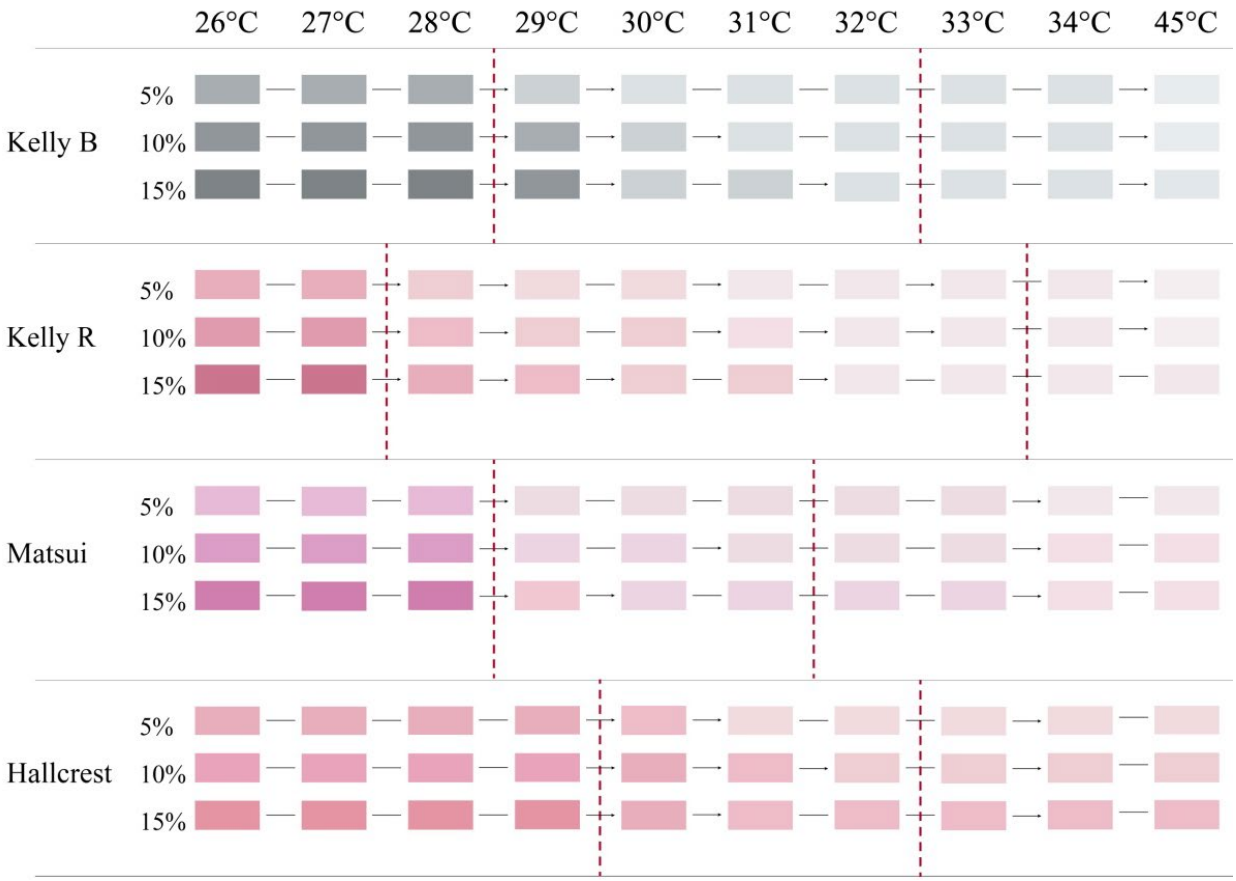

Figure 2. Thermochromic transition temperature and transition range comparison. The red dotted lines identify the temperature thresholds at which the thermochromic transformation occurs.

The measurements of the recovery time, e.g., the time required to return to the colored phase, proved that the inverse transition was slowed for all products. All samples were simultaneously exposed to the same lab conditions (air temperature of 23 °C and relative humidity of 20%), and the process was considered concluded when the color of the previously heated samples was the same as the reference ones already placed in the lab. The sample with the shortest recovery time (15 minutes) was the one developed with the black Kelly Powders; while the paint developed with the Hallcrest red powder required 40 minutes to recover fully.

3.1.2 Optical characterization

Two thermo-optical properties were evaluated, the solar reflectance (ASTM E903-12) and the thermal emittance (ASTM E1933-14). The resulting values have been used as input data to calculate the solar reflectance index (SRI) in compliance with the (ASTM E1980-11).

The total solar reflectance of the samples was tested using the Cary 5000 UV-Vis-NIR spectrophotometer coupled with an internal diffuse reflectance accessory (DRA) consisting of a 110 mm diameter integrating sphere (DRAs). The instrument was calibrated using a

Polytetrafluoroethylene (PTFE) disk, provided by the Agilent Company. Once the spectral reflectance was obtained, the solar reflectance was computed using the 100 selected ordinates derived from Tables G173 of ASTM E903 (2012).

The visible reflectance was measured in a similar way by selecting all the ordinates from the Tables G173 of ASTM E903 (2012) included between visible range boundaries. The solar reflectance of the colored and colorless phase of the thermochromic paints was measured separately. A hot plate was used to heat the coated bricks to 40 °C to make sure that the paints would have remained uncolored throughout the entire measurement period. The surface temperature was monitored using thermocouples. Similarly, to evaluate the solar reflectance of the colored phase, the samples were cooled down to 15 °C.

To measure the thermal emissivity, the Haida Climatic Test Chamber HD E702 was used together with a Fluke Ti450 PRO Infrared Camera. The tests were performed according to the ASTM E1933 (2014) following the noncontact thermometer method. As a surface-modifying material, a black tape characterized by an emissivity of 0.95 was attached to each sample. To heat the paints uniformly, all the samples were placed inside the climatic test chamber at a controlled temperature of 40 °C (10 °C higher than the transition temperature and 18-23 °C more elevated than the ambient temperature) for approximately 25 minutes. The images were taken at a distance of 50 cm in a controlled lab environment with an air temperature of 23 °C and a relative humidity of 20%. The infrared images were processed using the SmartView 4.3 software to calculate the actual thermal emissivity, following the methodology reported in other recent studies (Soudian et al., 2020).

3.2 Simulations

3.2.1 Case study

The thermochromic coatings were also assessed on a case study building. For this scope, one educational building located in downtown Toronto (Ontario, Canada) was selected. The reasoning for this selection was the desire to assess thermochromic coatings in a continental climate with high heating and cooling loads; moreover, the selection of an office building allowed to consider better the impact that solar gains have on such a typology of buildings, whose energy load is mainly influenced during daytime hours. Finally, the selection was done for one building of the Ryerson University as this is currently in the process of being retrofitted and there is interest in assessing the impact of the color of the finishing layers over the present and future building energy demand.

The model was simulated using the CWEC 2016 weather file provided by Environment Canada. The building energy model was reconstructed from the architectural and mechanical drawings, kindly provided by Thom Partnership architectural firm. An ideal load air system object was designed to simulate a hypothetical HVAC system that provides an unlimited amount of air at a specific temperature when the set-points specified in the schedules were not met. The characteristics of the building energy model are reported in Table 2.

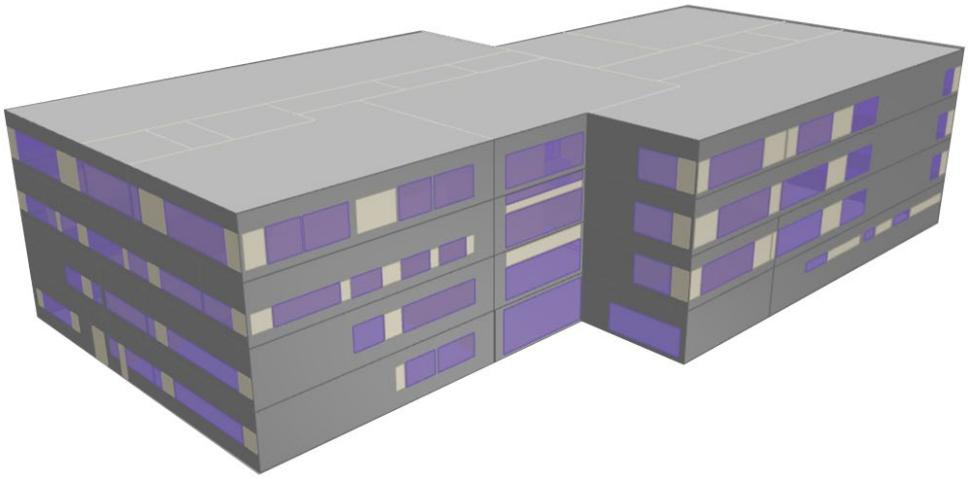

Figure 3. Energy model of the case study building designed with Honeybee.

Table 2. Main building characteristics of the educational building of Ryerson University.

General parameter	value	Envelope	U-Value [W/m^{2}K]
building floor area / conditioned	6300 m² / 6000 m²	Roof	0.37
gross wall area / roof area	2900 m² / 1800 m²	exterior wall	1.18
window to wall ratio	23%	ground floor	0.63
N° of thermal zones	62	windows	3.95
N° of conditioned zones	54	spandrel panels	6.67

3.2.2 Energy demand analysis

The results obtained by the laboratory tests have been used as input data to simulate the potential energy savings that could be achieved if the thermochromic paints are applied on the envelope of the case-study building. The possible aging and shorter life expectancy of thermochromic pigment in the outdoor environment was neglected.

Four types of analysis have been conducted, as summarized in Table 3. Out of the thermochromic paints created and tested, only the most performing sample was simulated. The paint produced with the Black LT-31BF Kelly powder with a 15% concentration proved to be

the one characterized by the largest solar reflectance difference between the two phases. Moreover, it is the paint with the lowest solar reflectance during its dark stage, leading to probable lower heating penalties.

Three different coatings have been compared: conventional low reflective paint, cool paint, and thermochromic paint. Four scenarios have been investigated: firstly, the current situation has been analyzed, where both horizontal and vertical surfaces have been coated with conventional low reflecting paint; afterward, the roof has been covered with cool and thermochromic paints; finally, the effects of thermochromic paints applied on the walls have been simulated.

Table 3. Type of analysis for the several investigated scenarios.

	Energy consumption	Parametric	Context	Climate change
Roof	1) Conventional 2) Cool 3) TCM lab paint	TCM	1) Conventional 2) Cool 3) TCM lab paint	1) Conventional 2) Cool 3) TCM lab paint
Façade	1) Conventional 4) TCM lab paint	-	1) Conventional 4) TCM lab paint	1) Conventional 4) TCM lab paint

Thermochromic paints were simulated in Energy Plus using the Energy Management System (EMS) components. This allowed to change the value of the material properties during the simulations dynamically. The thermo-optical properties of the paints are reported in Table 4.

Table 4. Thermo-optical properties of the different coatings used as input for the simulation.

	Solar absorptance	Visible absorptance
Conventional	0.8	0.8
Cool	0.2	0.2
Thermochromic	0.4 for $T \leq 28°C$ F(T) linear for $28°C \leq T \leq 32°C$ 0.2 for $T \geq 32°C$	0.63 for $T \leq 28°C$ F(T) linear for $28°C \leq T \leq 32°C$ 0.26 for $T \geq 32°C$

3.2.3 Parametric analysis

A parametric investigation of the thermo-optical properties to optimize the performance of the thermochromic coatings was also performed. Two parameters were manipulated to investigate

the dynamic behavior of thermochromic coating: the visible absorptance that characterized both phases, and the transition temperature.

The visible absorptance is the only thermo-optical parameter that changes accordingly to the outdoor temperature, while no variation has been observed during the laboratory tests and in previous studies (Zheng et al., 2015; Fabiani et al., 2019; Zhang & Zhai, 2019) in the near-infrared and ultraviolet range of the solar spectrum. The total solar absorptance value has been calculated considering the solar radiation distribution in the electromagnetic spectrum; more precisely, the visible radiations (45%), the ultraviolet radiations (5%), and the near-infrared radiations (Synnefa and Santamouris, 2013). To describe the dynamic behavior of the paint, a 0.3 visible absorptance variation has been considered, according to the results obtained in previous studies and from the spectrophotometer analysis. Therefore, the visible solar absorptance of the paint during the two different phases can be described as follows:

$$VIS_{abs,Coloreless} = VIS_{abs,Colored} - 0.3 \quad (1)$$

The other parameters selected for this investigation is the transition temperature, while the transition temperature range has been kept constant to a 4 °C.

$$Solar\ Absorptance_{dark} < T_{trans}\ ;\ Solar\ Absorptance_{light} > T_{trans} + 4 \quad (2)$$

In total, 30 different thermochromic paints have been simulated on the roof of the building. The number of different scenarios is the result of the combination of six different transition temperatures (T_{trans} = 15 °C, 18 °C, 21 °C, 24 °C, 27 °C, and 30 °C) and five visible absorptance values ($VIS_{abs,Colored}$ = 0.5, 0.6, 0.7, 0.8, and 0.9).

3.2.4 Context analysis

The introduction of the surrounding constructions around the case study building has been evaluated. Since the incident solar radiation heavily influences the behavior of the thermochromic paint, it is necessary to evaluate their performance if the context is introduced. The floor plans of the surrounding buildings have been reconstructed using the available Open Street Map data.

3.2.5 Climate change impact

To assess the impact of climate change on the heating and cooling demand of the case study building and understanding the corresponding consequences on the studied paints, a cross-comparison analysis was performed, and the four scenarios have been investigated using future weather files. In this study, future weather files created by Berardi and Jafarpur (2020) using the WeatherShift™ tools were adopted. The WeatherShift™ tools use the imposed offset method to

statistically downscale Global Climate Models for future weather file generation establishing a correlation between Global Climate Models and historical local weather data. The worst-case emission scenario (RCP8.5), which considers a rise of the emission throughout the 21st century, and the period of 2056–2075 projection timeframe have been used to create the future weather file.

4. Results

4.1 Laboratory characterization

The spectrophotometer measurements conducted on the four cool paints are illustrated in Fig. 4; each line has been obtained as an average of the two measurements carried out on the two sample sets. All the four coatings show a high total reflectance since the reflectance coefficient is relevant both in the visible and near-infrared range where the majority of the solar spectrum is concentrated. The sample with the lowest solar reflectance is the Lyanco Urethanizer. Table 5 summarizes the solar and visible reflectance value measured. All products showed a thermal emissivity of approximately 0.9, meaning that the paint can emit the absorbed radiation quite easily in this specific portion of the spectrum.

The thermal emissivity and the solar reflectance values, together with a convective coefficient assumed to be 12 W/m^2K (i.e., a common wind condition), allow the calculation of the SRI values of the four products. Since all the tested paints have a similar thermal emittance, the most influential parameter is the solar reflectance. The Ultra Siliconizer has the highest solar reflectance index (110), followed by two Kool Seal products (Kool Seal RV 108 and Kool Seal 105), while the lowest value was recorded for the Urethnizer paint (102). All the samples show an index higher than 100 since the solar reflectance of all the paints is larger than the white reference surface (0.8).

Table 5. Cool paint solar and visible reflectance results comparison.

	Solar R%			Visible R%		
	Set A	Set B	*average*	Set A	Set B	*average*
Ultra Siliconizer	0.88	0.87	*0.87*	0.91	0.90	*0.91*
Urethanizer	0.84	0.80	*0.82*	0.83	0.81	*0.82*
Kool Seal	0.84	0.84	*0.84*	0.89	0.88	*0.88*
Kool Seal RV	0.88	0.83	*0.86*	0.91	0.87	*0.89*

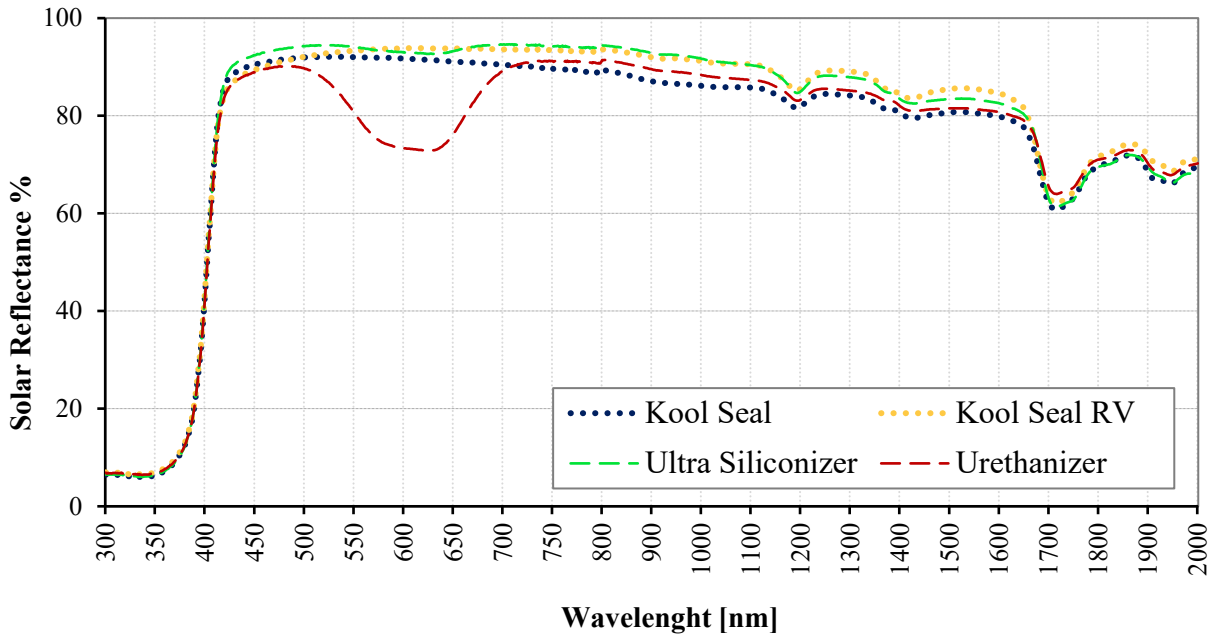

Figure 4. Solar reflectance spectrum for the four cool paints considered in this study.

Thermochromic paint proved to be highly reflective, too. However, the thermochromic transformation proved to affect the visible reflectance of the paint, modifying the total solar reflectance accordingly to the sample temperature. Small differences were observed in the NIR and UV regions: short wave radiations are absorbed by the samples, while the vast majority of the long wavelengths are reflected even when the samples are colored, as illustrated in Fig.5. The percentage of thermochromic particles influenced the color saturation and thus the reflectivity of the paint. A higher amount of particle inserted in the mix led to a lower visible reflectance, especially during the colored phase.

The paints Hallcrest and KEL_R have a similar trend, both characterized by a peak in the red region of the visible range (600 nm), the samples, in fact, have a similar color. The black specimens (KEL_B) have no specific peak; these samples achieve lower values of solar and visible reflectance since the black powder absorbed more radiation compared to red pigments.

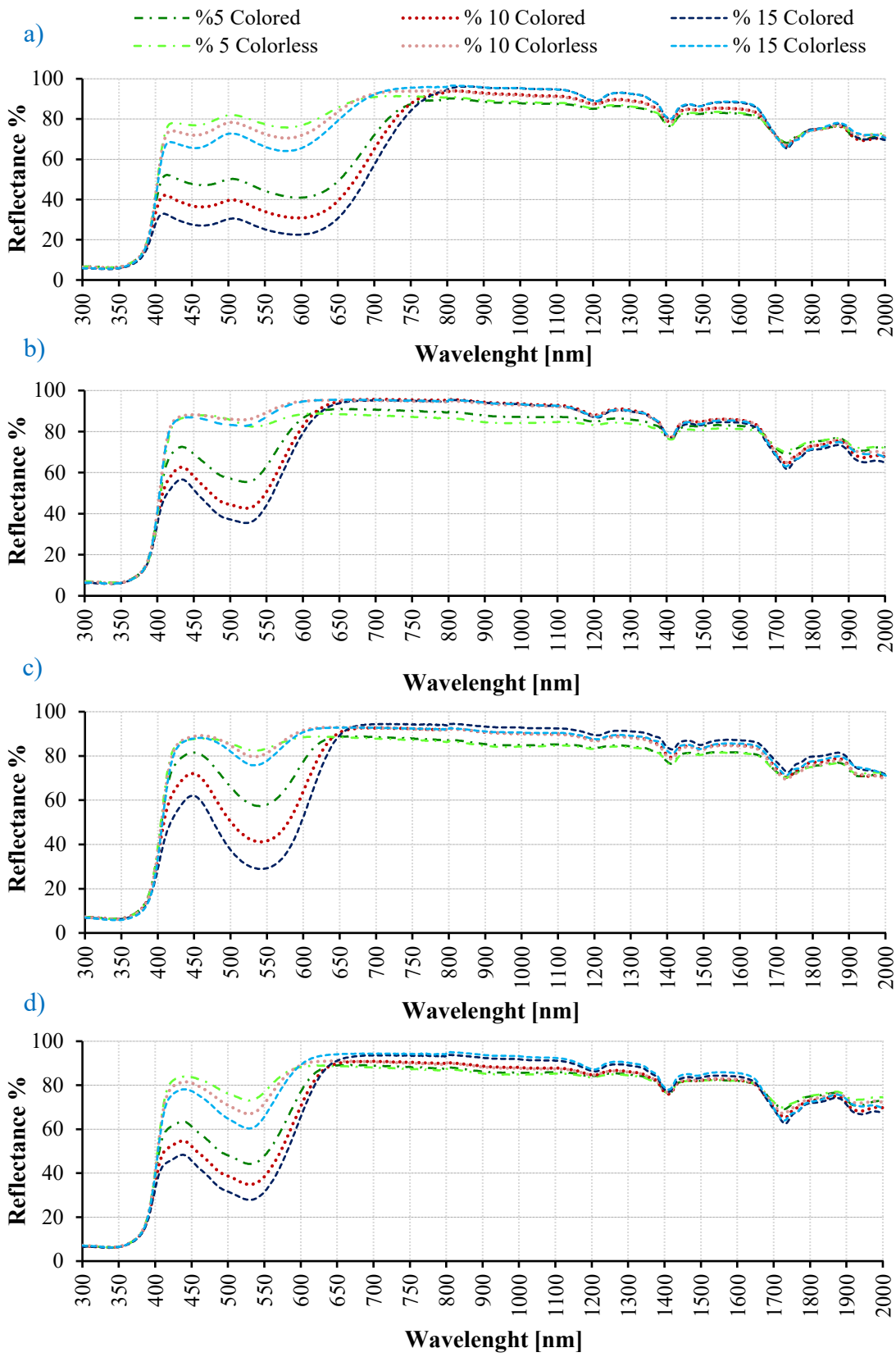

Figure 5. Thermochromic total solar reflectance spectrum for the four thermochromic coatings considered in this study: a) Kelly_B; b) Kelly_R; c) Matsui; and d) Hallcrest.

Among the developed samples, the paint produced using the highest concentration of the Kelly Black powder achieved the highest solar reflectance difference between the two phases (Table 6). A visible reflectance variation of 0.37 has led to a change of the total solar reflectance of 0.2. All the samples reached a high level of reflectance during the colorless phase due to the high percentage (14%) of TiO_2 contained in the base solution.

Table 4. Solar and visible reflectance of thermochromic samples, colored and colorless phase: comparison between the different percentages of thermochromic powder.

Product	Phase	TCM concentration	Solar R%	Visible R%	ΔR% Solar	ΔR% Visible
KELLY_B	Colored	5%	66	54	/	/
		10%	63	45	/	/
		15%	60	37	/	/
	Colorless	5%	81	80	+15	+26
		10%	81	78	+18	+33
		15%	80	74	+20	+37
KELLY_R	Colored	5%	78	75	/	/
		10%	77	71	/	/
		15%	75	67	/	/
	Colorless	5%	85	88	+7	+13
		10%	87	89	+9	+18
		15%	86	88	+11	+21
MATSUI	Colored	5%	77	75	/	/
		10%	75	68	/	/
		15%	72	62	/	/
	Colorless	5%	81	84	+5	+9
		10%	84	86	+9	+18
		15%	84	85	+12	+23
LCR	Colored	5%	73	68	/	/
		10%	72	64	/	/
		15%	71	61	/	/
	Colorless	5%	80	82	+5	+9
		10%	81	81	+9	+18
		15%	82	80	+12	+23

All the products have comparable thermal emittance values (0.9), and no significant differences have been registered between paints with different concentrations of thermochromic. All the solar reflectance indexes were mainly influenced by the variation of the solar reflectance value (Table 7). In the colorless phase, all the samples show a value higher than 100 since the solar reflectance of all the paints is larger than the reference surface. High values have been obtained even for the colorless phase of each sample. Even if these values are comparable to the one registered for the cool coating is essential to remind that there is a higher concentration of TiO_2 particle in the thermochromic samples compared to the cool ones. Moreover, the values obtained by the thermochromic samples are representable of a basic and simple receipt, while the tested cool coatings are products entirely developed, with more components mixed.

Table 5. SRI value of the thermochromic samples: evaluation of the impact of various percentage of the thermochromic in the coating.

SRI	5% colored	10% colored	15% colored	5% colorless	10% colorless	15% colorless
Kelly_B	81	77	73	101	102	100
Kelly_R	97	96	93	107	110	108
Matsui	96	93	89	101	106	106
Hallcrest	90	89	88	100	102	103

4.2 Simulation analysis

4.2.1 Energy consumption analysis

Initially, the model has been tested without the implementation of an HVAC to understand the effect of the different paints on the indoor air temperature. This was necessary to evaluate the actual indoor temperature, avoiding the air condition system to bring the temperature to the prefixed set points. Two thermal zones have been studied: a zone located on the top floor of the building, at direct contact with the roof, and a zone located on the first floor of the building. Both spaces have the same orientation (northwest) and a comparable dimension and window to wall ratio to obtain a reliable data comparison. Two periods were investigated: three summer days, 1/08-3/08, and three winter days, 1/01-3/01.

The results demonstrated that the adoption of the reflective coatings on the building roof mainly impacts the zone air temperature of the beneath rooms, while negligible effects are obtained for the areas located two or more levels beneath. The traditional coating leads to the highest indoor air temperature due to its high absorptance, while the reflective roofs provide significant indoor air temperature reduction, especially in the summer period.

When the upper floor was considered, thermochromic paints applied on walls decreased the indoor air temperature of almost 0.8 °C during winter, while during three summer days, the value was more than doubled, being 1.75°C. The low U-value of the building leads to a more relevant impact on the indoor air temperature. The adoption of reflective paint on the roof, instead, induces a decrease of the room temperature, but the effect is less pronounced: an average reduction of 0.5 °C and 0.3 °C was obtained for the cool and thermochromic coatings during the winter analysis period, while a 1.3 °C and 1.6 °C reduction was obtained during the summer period respectively.

The indoor temperatures differences are a consequence of the different amounts of heat transfer through the building envelope, which are directly linked to the exterior surface temperature and their respective variations. Two comparisons have been performed: thermochromic walls have been compared to conventional high absorbing walls, while a conventional (dark) roof has been compared to a cool and a thermochromic one. An HVAC system has also been introduced to stabilize the indoor temperatures between 18 °C and 26 °C using different schedules. Figure 6 illustrates the exterior surface temperature trends and their relation to outdoor air temperature and incident solar radiation, comparing the effects obtained by thermochromic paint and conventional paint during the three hottest days of summer.

Each façade temperature trend shows a peak during a different period of the day accordingly to the orientation; as expected, the peak for the east-facing wall occurs during the early hours of the day (9:00-10:00 am), while the west-oriented one during the afternoon (5:00-6:00 pm), and no clear peaks is measured for the north-facing surface.

The increased reflectance of the wall, due to the application of the thermochromic paint, has decreased the peak temperature otherwise reached using conventional coatings. Excluding the north wall, for the other three surfaces, an overall temperature reduction is achieved throughout the whole day. In particular, during the hottest day (1/08), the south façade peak temperature has shifted from 45.9 °C to 31.9 °C at 2:00 pm, for the east one from 44.5 °C to 30.5 °C at 9:30 am. The south-west oriented wall is the one where the higher benefit is achieved: the difference between the thermochromic and the conventional high absorbing wall simulations has reached a maximum of approximately 23 °C (from 54.5 °C to 31.0 °C) at 5:30 pm.

Solar radiation plays a key role since the outdoor temperature is not particularly elevated. During the last day displayed in the graphs, the weak direct solar radiation and low diffuse solar radiation, probably caused by a clouded sky, leads to a very limited surface temperatures difference between the two scenarios since the thermochromic transformation does not occur (Fig. 6).

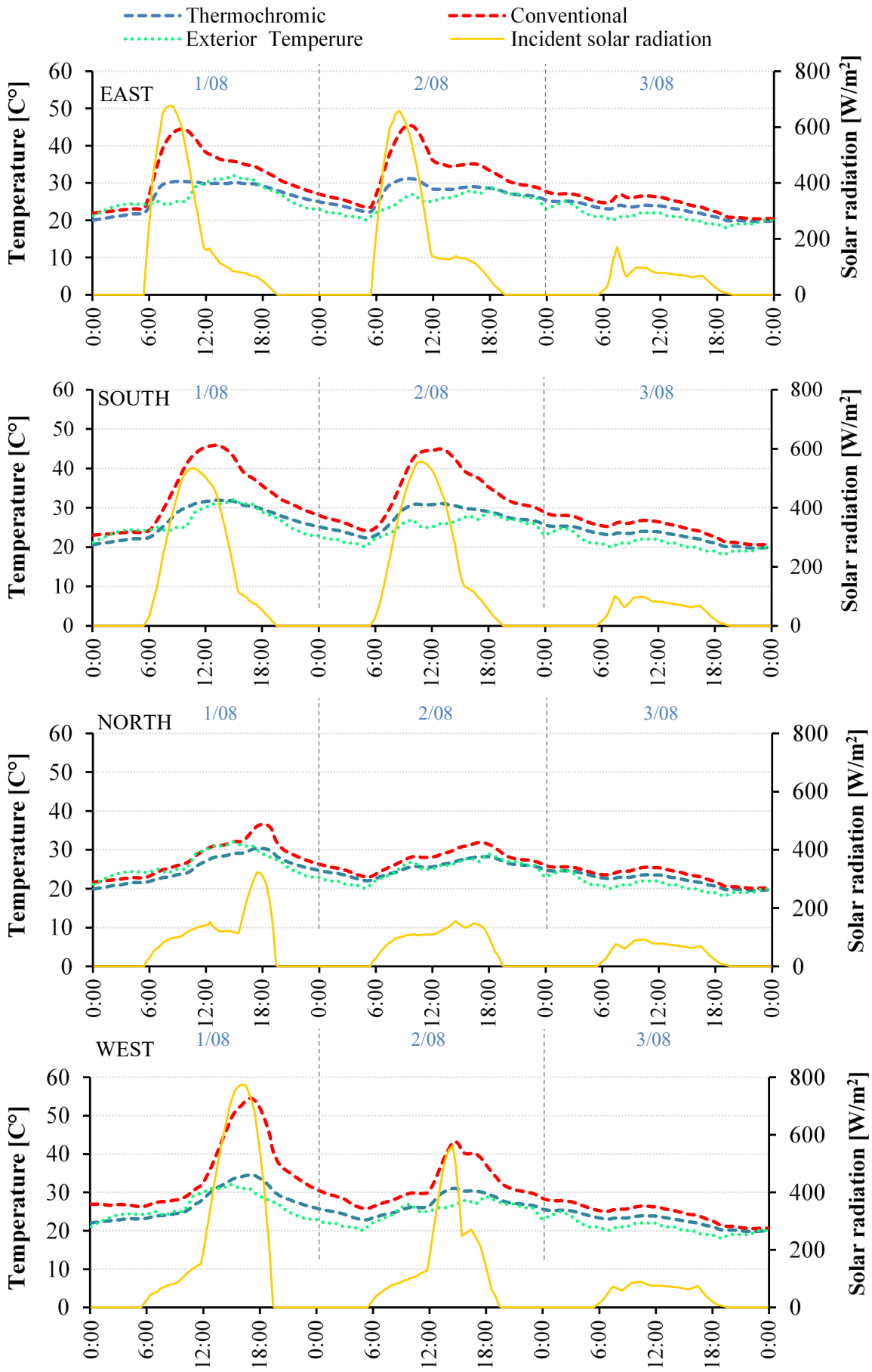

Figure 6. Wall surface temperatures comparison during three summer days (1st-3rd August).

The benefits achieved are even more significant on the roof since it is the surface that receives the most considerable amount of solar radiation. Both thermochromic and cool material achieved a significant surface temperature reduction: the peak is reduced from 62.5 °C to 37 °C. Thermochromic and cool paint achieve similar results since the solar reflectivity of the two solutions are similar. Small differences are observed during the early hours of the day when the thermochromic transformation has not occurred yet. The thermochromic paint completely shifts to the colorless phase after the solar radiation heats the surface for approximately one hour, between 6:00 and 7:00 am. During the 3rd of August, the drastic decrease of the direct radiation incident, coupled with relatively warm air temperature (max 20 °C), caused the surface to be not hot enough so that the thermochromic transformation could occur (Fig. 7).

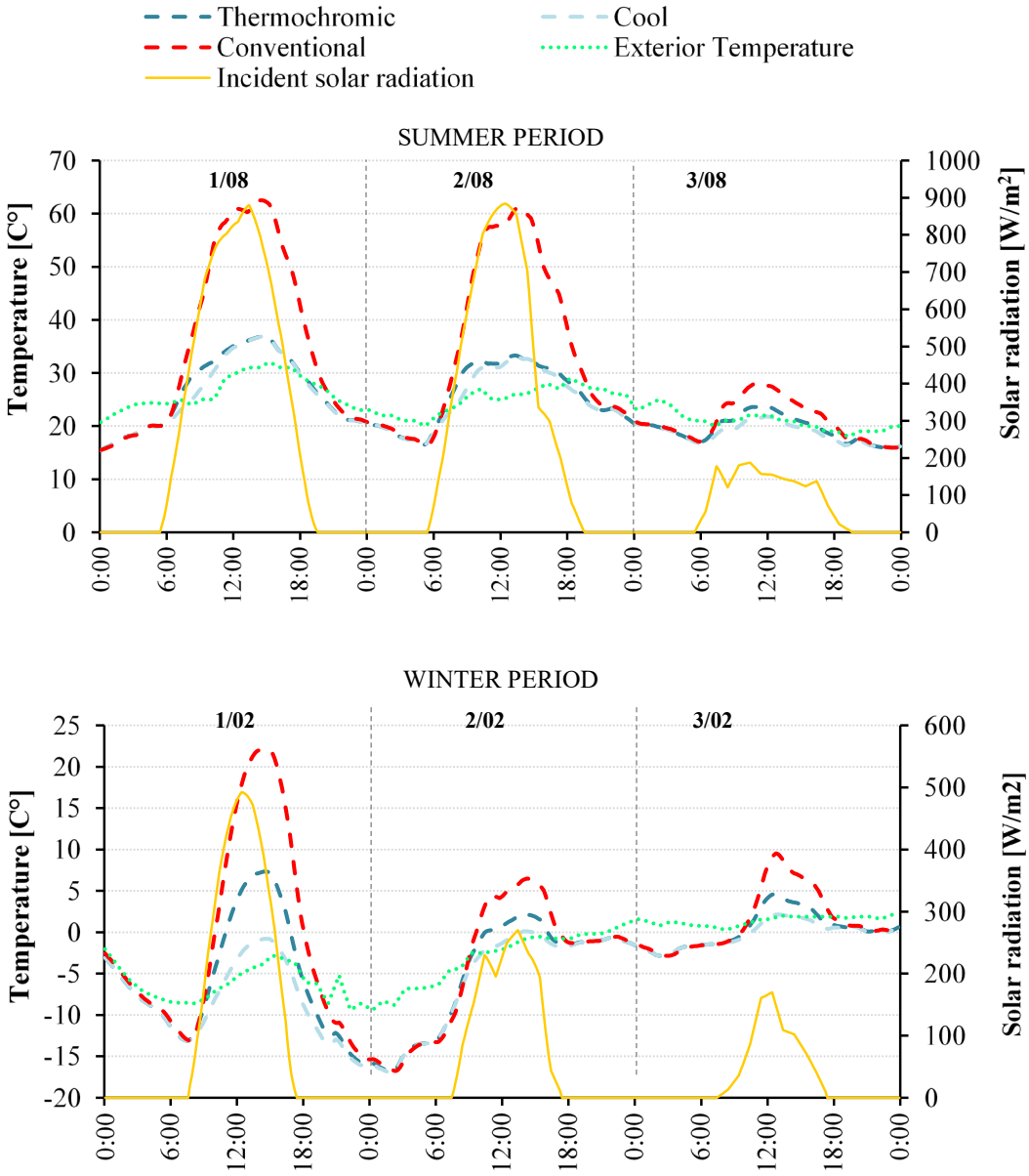

Figure 7. Roof surface temperatures comparison during three summer (1st-3rd August) and winter days (1st-3rd February).

The opposite trend has been observed during three typical winter days: as expected, cool and thermochromic surfaces lead to lower surface temperatures; however, the differences are less pronounced compared to the summer days, especially during the coldest day when the outdoor temperature is the main factor influencing the surface temperature.

The annual energy consumptions highlighted some limits of the simulated reflective paints. Since the climate of Toronto is heating dominated, the high solar reflectance of the thermochromic during its colored phase reduces the benefits obtained during the cooling period, where the incoming solar radiation is partially reflected. Cooling days are considerably lower compared to the ones where the heating system is working; moreover, since the outside temperatures are not particularly elevated even during summer, a limited amount of energy is requested to cool down the building (Table 8).

Table 6. Cooling benefits and heating penalties of the four different scenarios.

	EUI for conventional roofing [kWh/m^2]	Δ Cool roof	Δ TCM roof	Δ TCM wall
Cooling Load	17.8	-11.0%	-8.9%	-14.2%
Heating Load	73.7	+2.6%	+1.7%	+4.4%
Total	91.5	0%	-0.4%	+0.8%

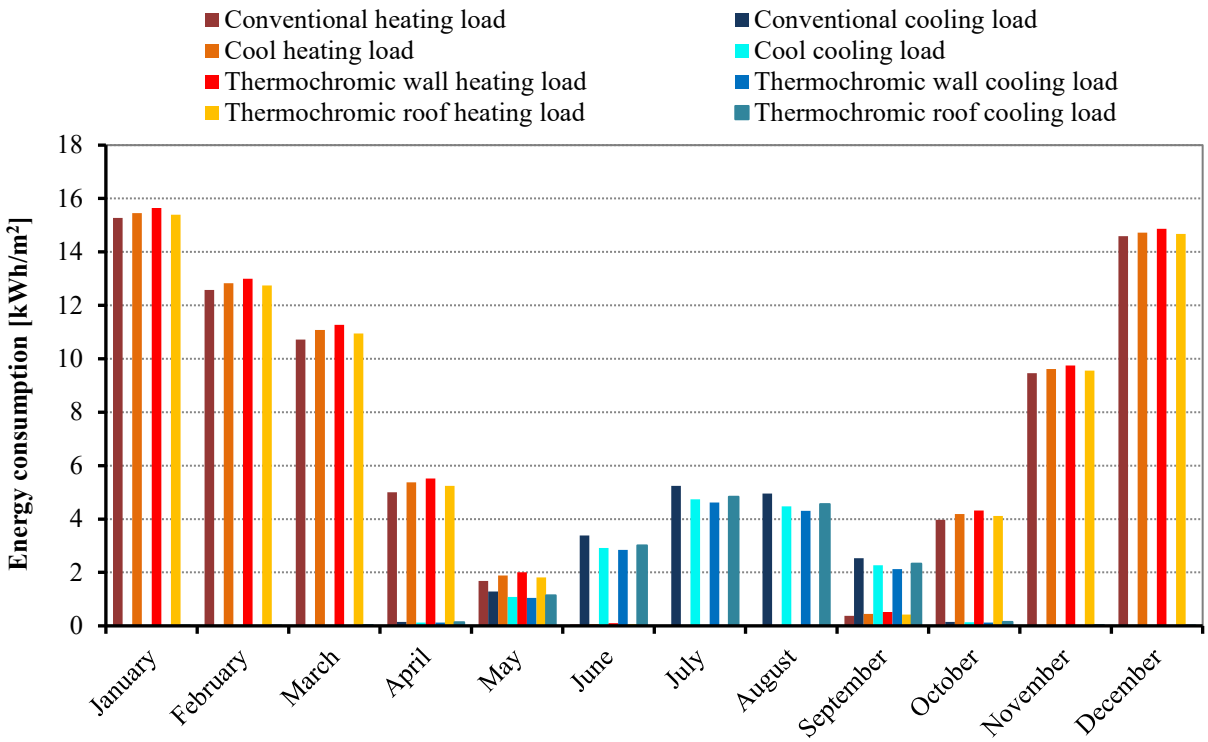

Figure 8. Monthly energy consumption comparison: conventional, cool roof, thermochromic wall, thermochromic roof.

Even if the overall energy consumptions are not significantly reduced, it is clear that, for this specific building, the adoption of a thermochromic roof is preferable compared to a cool or a conventional roof. The higher absorptance of the thermochromic paint contained the heating penalties to 1.7% during the cold season, while the thermochromic transformation allows a 9% reduction of the cooling energy demand during the summer months. Cool roofs are less efficient compared to the previous solution as a consequence of their static behavior, even though the cooling savings are higher (-11%), the higher heating demand (+2.6%) nullifies the benefits. Thermochromic walls are not a suitable alternative to conventional paint. Since the heating consumptions are responsible for almost 80% of the total energy demand, the reduction of the potential solar heat gain caused by the higher reflectance of thermochromic paints compared to conventional high absorbing coatings has led to relevant heating penalties during the winter season (+4.4%). The heating penalties are larger compared to the scenario where thermochromic paint is applied on the roof since façades cover a larger portion of the building envelope; therefore, a higher amount of radiation is reflected, and less heat is transfer into the building.

4.2.2 Parametric analysis

The results show that the thermochromic paint with the lowest solar absorptance, 0.5, and a temperature transition of 18°C is the preferable solution. This solution maximizes the cooling benefits, thanks to the high solar reflectance and the low transition temperature, which allows the paint to reach its colorless phase more frequently.

- Colored: Visible absorptance = 0.5
- Colorless: Visible absorptance = 0.5-0.2 = 0.3

Figure 9 illustrates how the best-case scenario slowly shifts from maximizing the cooling benefits when the reflectivity is higher, to the reduction of the heating penalties as the solar absorptance increases. A turning point is observed around the 21°C transition temperature. For high transition temperature, a low reflective paint is preferable: since the thermochromic transformation rarely occurs, a higher absorptance guarantees the limitation of heating penalties. A higher reflectivity is suitable when the transition temperature is lower since the thermochromic transition comes into play more frequently. While the solar absorptance has a more significant impact on the energy consumption above the turning point, below the 21°C, the differences are less significant since the heating demand has a more substantial effect on the overall energy consumptions. However, the improvements obtained by changing the transition and solar absorption are not substantial; the difference between the worst and best-case scenarios is less

than 1%. The relatively low improvement is a consequence of the negligible effect of the thermochromic paint achieved on the lowest floors of the building.

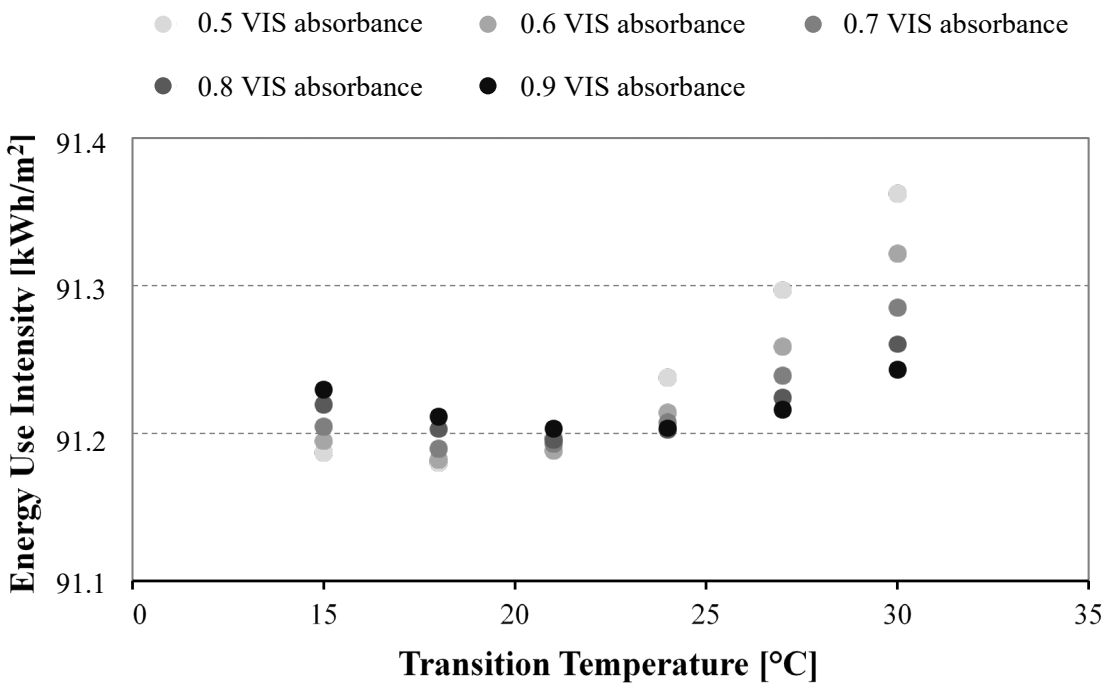

Figure 9. Parametric analysis results: annual energy use intensity comparison resulting from the different combinations of transition temperature and visible absorptance.

The best performing scenario of the parametric analysis (T_{trans} =18°C; solar absorptance$_{colored}$ = 0.35; solar absorptance$_{colorless}$ = 0.21) has been compared to the lab paint created including the Black LT-31BF Kelly powder with a 15% concentration in the mixture (T_{trans} =28°C; solar absorptance$_{colored}$ = 0.40; solar absorptance$_{colorless}$ = 0.20). The solar reflectance of the two simulated paints is similar during both phases, even if the lab paint is slightly more absorptive when colored. The main difference is the transition temperature at which occurs the thermochromic transformation. Therefore, the main variation registered between the two scenarios is that the thermochromic transformation occurs more frequently and earlier compare to the other scenario, as illustrated in Fig.10. The transformation begins approximately five hours before the thermochromic lab paint. Consequently, the registered roof surface temperatures are lower until the thermochromic lab paint reaches its colorless stage; even the peak temperature has been reduced by 0.5 °C. It is interesting to notice that the thermochromic transformation also occurs on the third day when the outdoor temperature and the amount of incident solar radiation is lower compared to the previous days. However, since the thermo-optical differences are limited, the total energy use intensity has not changed.

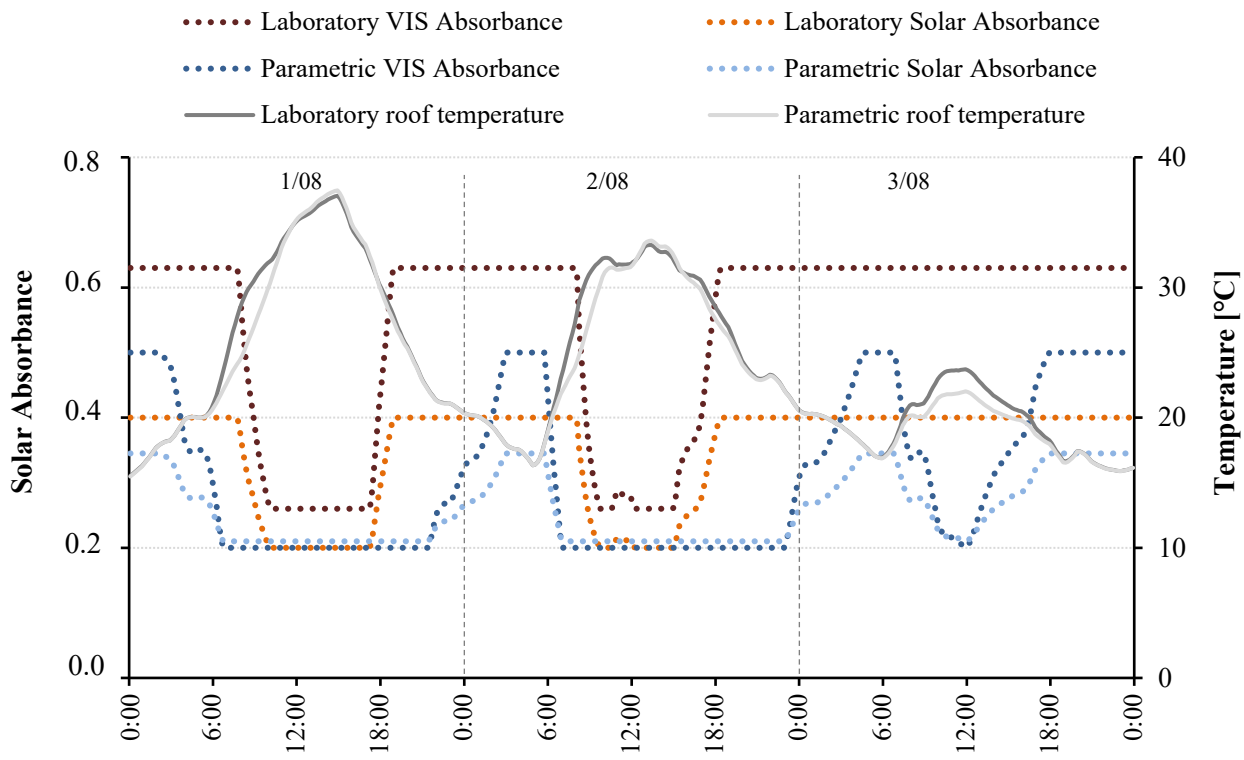

Figure 10. Roof surface temperature trends and thermo-optical properties: laboratory paint and best-case scenario of the parametric analysis during three summer days (1/08-3/08).

4.2.3 Context analysis

The solar radiation and shadows studies performed with Ladybug proved that the most affected areas are the north and the east oriented facades; a partial decrease of the radiation has also been registered on the east side of the roof and in the lowest zone of the south and west façades. The incident radiation on the east facade is reduced by approximately 500 kWh/m^2 throughout the entire year. Regarding the Energy Plus simulations, the focus has been pointed mainly on the east façade, where the most relevant variations of the thermochromic transformation could be registered.

The results reported a substantial reduction of the incident radiation, which has led to a significant decrease in the surface temperature. Previously, the maximum temperature reached by a facade covered with a conventional paint was approximately 45 °C, the introduction of shading elements has reduced the peak temperature of almost 15 °C. As a consequence, the application of thermochromic has been less effective, and the achieved temperature reduction has been less than 5 °C.

Table 9 summarizes the impact of the context on four surfaces having different orientations; more precisely, it describes the amount of time during which the thermochromic transformation

occurs. The context has an impact also on the roof; however, only a small portion is affected, and the effect is less relevant compared to the shading on the walls.

Table 7. Influence of the context on the thermochromic transformation.

		East	South	North	West	roof
Context	N° hours max R%	0	0	0	4	92
	% over the total period	0	0	0	0.05	1.05
	N° hours intermediate R%	13	343	10	298	711
	% over the total period	0.15	3.90	0.10	3.40	8.10
No Context	N° hours max R%	0	0	0	6	93
	% over the total period	0	0	0	0.07	1.05
	N° hours intermediate R%	212	378	30	353	721
	% over the total period	2.40	4.30	0.35	4.05	8.20

The context introduction increased the heating consumption by 9%, while the cooling demand has been reduced by 33% in the common case scenario, as a consequence of the less radiation incident on the building envelope\. The surrounding buildings offer a significant shading effect both on the wall and on the numerous windows characterized by a low U-value. It is interesting to notice that when the context is included, all the proposed reflective technologies are counterproductive: the adoption of reflective paint leads to an increase of the energy consumptions ranging from of 1.1% when the thermochromics are applied on the facade, to a 0.2% in the best case scenario when the thermochromics are used on the roof.

Table 8. Energy consumption comparison: context included.

	Conventional [kWh/m^2]	Cool roof	TCM roof	TCM wall
Cooling load	11.9	-12.5%	-10.1%	-12.3%
Heating load	80.3	+2.6%	+1.7%	+3.1%
Total	92.2	+0.6%	+0.2%	+1.1%

4.2.4 Climate change impact

The results highlighted a significant variation in the distribution of the energy demand of the building due to the mean temperature increase of 3.7–4.5 °C forecast by the future weather file. This increment has led to a doubling of the cooling consumption from 17.8 kWh/m^2 to 35.2 8 kWh/m^2 while the heating demand reduced by 20% from 73.7 kWh/m^2 to 58.6 kWh/m^2. Besides,

the total energy use intensity increased by approximately 2.5%, from 91.5 kWh/m^2 to 93.8 kWh/m^2.

Those changes have a significant impact on the effectiveness of reflective paints since their contributes become more relevant due to the increased necessity of reducing the cooling demand of the building, whose impact on the overall energy consumption has shifted from 20% to 38%. The cooling benefits achieved during the summer outweigh the heating penalties; thermochromic walls become the most effective solution guaranteeing a reduction of almost 11% of the cooling demand, leading to a reduction of the energy use intensity of 1.5%. Once again, thermochromic paints ensure lower energy consumptions compared to cool and conventional paints if applied on the roof: the cooling load is reduced by 6%, while the heating penalties are the lowest one 1.5%.

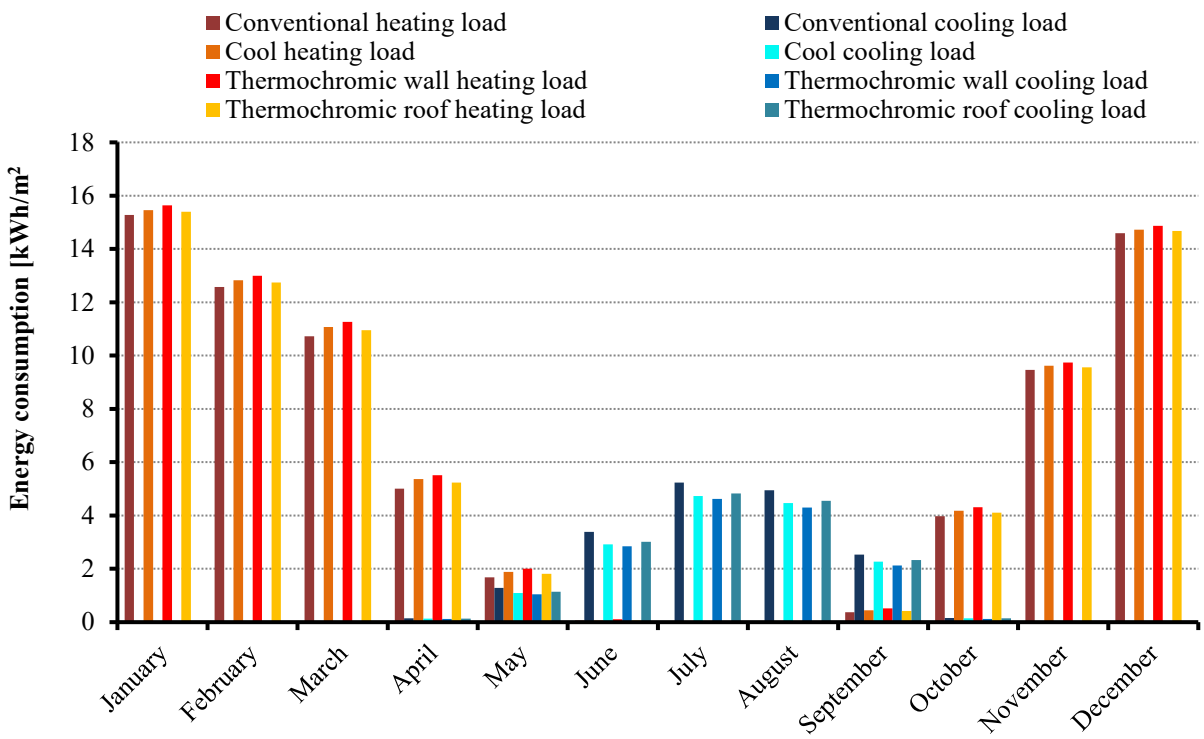

Figure 11. Monthly energy consumption comparison between four different scenarios: climate change impact.

Table 9. Energy consumption comparison: climate change impact.

	Conventional [kWh/m^2]	Cool roof	TCM roof	TCM wall
Cooling load	35.2	-7.0%	-6.1%	-10.7%
Heating load	58.8	+2.4%	+1.5%	+4.1%
Total	93.8	-1.2%	-1.3%	-1.5%

5. Discussion

The aim of this research was the investigation of the potential energy benefits resulting from the application of thermochromic paints as a strategy to control solar loads. The experimental tests highlighted the significant visible reflectance change occurring during the thermochromic transformation: among the twelve different investigated paints, the maximum variation recorded is 0.37, corresponding to a variation of the total solar reflectance of 0.20. Variations of the same order have been obtained in previous studies (Fabiani et al., 2019; Zhang & Zhai, 2019). The results testified the influence of the concentration of thermochromic particles on the total solar reflectance: a higher amount of thermochromic pigments decrease the reflectivity of the paint. A high solar reflectance characterizes the tested thermochromic paints in both phases due to the high percentage of TiO_2 particles included in the basic paint mixture. As already reported by Zhang & Zhai (2019) and Karlessi et al. (2009), TiO_2 particles are responsible for the increment of the solar reflectance of thermochromic paints. The same trend observed for solar reflectivity has been observed for the SRI values. However, the study results were limited by the basic receipt used for the preparation of the prototype thermochromic paint: additives that prevent the aging or improve the workability have not been introduced, and the purchased thermochromic powders are products that have not been specifically designed for outdoor applications.

The second step of the study was the evaluation of the potential decrease of the energy consumptions deriving from the adoption of thermochromic paints. Despite the reduction of the cooling demand, 11% and 9% achieved by cool and thermochromic paint when applied on the roof, the heating penalties deriving from the less heat absorbed during cold season balanced the overall energy consumptions of the building, even if thermochromic proved to be more performative confirming what has been observed by Jianying & Xiong (2019). The limited overall energy savings could be explained considering two factors: the long and severe winter climate in Toronto, and the peculiar characteristic of the case study building.

The situation was reversed when the future long-term changes in the outdoor climate conditions are considered, due to the higher mean air temperature, the cooling load was increased, and the heating one was reduced by 20%; as a consequence, reflective paints, in particular thermochromic, guarantee a decrease of the total energy use intensity between 1.3% and 1.5%. However, it must be specified that only one of the possible future scenarios has been simulated.

Contrary to previous studies, where only a single zone or small buildings were analyzed, the simulated case study had four levels, and its roof was sufficiently insulated (U-value = 0.37 W/m^2K). It is recognized that the effectiveness of reflective paints is limited to the zone just

below the roof, and the benefits are larger if the envelope is poorly insulated, as reported in a recent research conducted by Zhang et al. (2020) on a two-story and less insulated office.

To have a complete overview of all the environmental parameters and context influences, a factor that should be implemented and discussed in future studies, especially in cold climates, is the snow accumulation on the roof. Hosseini & Akbari (2014) simulated the snow accumulation considering the latter as an additional insulation layer characterized by specific solar reflectance value (0.8-0.9 for fresh snow, 0.3-0.4 porous dirty snow); the results proved that heating penalties for cool roofs are usually overestimated.

6. Conclusions

Thermochromic paints and cool paints, due to the high solar reflectance, proved to greatly reduce the temperature of the surface where they are applied. Besides the less heat transfer into the building, lower exterior temperatures are fundamental to prevent chemical degradation processes and thermal fatigue, increasing the lifetime of the envelope. Thermochromic paints reduced the roof peak temperature of approximately 25°C. On the facades, a decrease between 15°C -20°C has been registered, depending on the orientation of the wall. Those differences were largely reduced when the surrounding buildings have been introduced in the simulation domain, especially for the vertical facades. The inter-building effect limited the benefits achieved by thermochromic paints since the thermochromic transformation occurred less frequently. This aspect, coupled with a heating-dominated climate like Toronto, made reflective paints a counterproductive solution leading to an increment of the energy demand ranging from 0.2% to 1.1% when the thermochromic paint was applied on the roof and wall surfaces, respectively. Energy Plus proved to simulate thermochromic paints accurately. Nevertheless, this latter strictly related to the time step selected since the frequency of the update of the surface properties is linked to this parameter. Moreover, no component is currently available inside the software library itself, making the designing and setting process time-consuming. Future building energy simulations investigating different building typologies and climate conditions, especially more temperate zones, are also needed considering different climate change scenarios. At the same time, future laboratory tests should be focused on the limited change of the thermo-optical properties and the rapid aging of thermochromic coatings, as these issues limits a proper experimental verification of the benefits achievable resulted from the simulation analysis preventing thermochromic coatings from being a viable solution to cool products.

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