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Performance Evaluation of High-Rise Buildings Integrated with Colored Radiative Cooling Walls in a Hot and Humid Region

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Abstract: Radiative sky cooling is an appealing form of heat exchange between terrestrial objects and outer space through thermal radiation, which is attracting worldwide interest due to its nature as passive cooling, that is, cooling without consuming energy. Due to a recent breakthrough in material science, sub-ambient daytime radiative sky cooling has been effectively achieved, which has significantly stimulated research interest in this field. In view of the numerous radiative coolers being reported as having excellent spectral properties and cooling ability under sunlight, integrating these superb cooling materials into building skins is a promising route to implementing radiative sky cooling technology. To this end, this study deploys state-of-the-art colored radiative cooling coatings as a new retrofitting strategy for building walls, and then conducts a comprehensive performance evaluation by considering a high-rise building situated in the hot-humid city of Hong Kong. Potential benefits of implementing differently colored cooling wall strategies, including their performance regarding thermal insulation, energy savings, economic viability, and environmental sustainability, were thoroughly investigated. The obtained results elucidate that for the utilization of the porous P(VdF-HFP)-based bilayer wall, relative to the monolayer, the frequency of the wall temperature exceeding the surrounding environment on an annual basis can be further reduced by up to 4.8%, and the yearly savings in cooling electricity vary from 855.6 to 3105.6 kWh (0.4–1.5%) with an average of 1692.4 kWh. Besides this, the yearly savings in net electricity cost vary from 1412.5 to 5127.3 HKD and the reduction in carbon emissions ranges from 1544.4 to 5606.1 kg with an average of 3055.0 kg. In addition, discussions of the combination of the super-cool roof strategy with blue porous polymer-based cooling walls reveal that the achievable savings in terms of energy costs and reductions in carbon emissions are 1.6 and 2.2 times more than either the application of the super-cool roof or porous polymer bilayer walls alone, respectively. This research offers new understandings of the deployment of colored cooling coatings on vertical building façades in hot and humid regions, which can considerably facilitate the realization of low-energy buildings in a passive approach for stakeholders.

Keywords: building energy; radiative cooling; colored cooling coating; building façade; hot and humid region

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1. Introduction

The building sector is a significant contributor to worldwide energy consumption and carbon emissions [1–3]. According to [4], it is responsible for 30% of final global energy usage and 28% of carbon emissions related to energy. In high-density cities like Hong Kong, there are numerous high-rise buildings across the city, and the building sector's share of carbon emissions can be over 60% [5]. Mitigating energy usage and limiting the release of greenhouse gases in the construction industry is crucial for achieving the sustainable development goals set by the International Energy Agency. By 2040, around 13% of the world's energy consumption and half of the world's carbon emissions in the building sector must be reduced [6]. In fact, for high-rise buildings with large vertical façade areas, in addition to ensuring their structural stability [7], the noticeable building heat gains from solar radiation through the opaque wall surfaces should be focused upon. The improvement of the thermal insulation capability of opaque wall surfaces is able to significantly enhance the whole-building energy performance [8–11]. As one of the new emerging renewable forms of energy utilization, radiative sky cooling technology, which significantly reflects the incoming solar radiation and fully uses the atmospheric window for heat dissipation from terrestrial objects into outer space, is one promising solution to achieve the goal of building energy savings and carbon reductions. To accelerate the deployment of radiative sky cooling technology in the building sector in Hong Kong, it is important to study its applications as a passive approach in high-rise buildings. Accordingly, this research can provide valuable insights into how radiative sky cooling can be effectively integrated into building walls to increase building energy-saving potential and reduce carbon emissions for sustainable development.

Radiative sky cooling refers to the process of releasing thermal energy into outer space through radiation [12–15]. To optimize this cooling ability, materials are fabricated to have high solar reflectivity, reflecting a broad range of incident sunlight, and high thermal emittance, ideally within the atmospheric transparency window from 8 to 13 μm, to improve heat dissipation [14]. Considerable advancements have been achieved in developing radiative coolers with spectral selectivity, including a precisely-engineered nanophotonic radiative cooler comprising seven layers of alternating HfO_2/SiO_2 [16] and metamaterials with glass polymers [17]. Moreover, researchers have developed other promising cooling materials based on polymers, such as a polymer coating ($P(VdF\text{-}HFP)_{HP}$) with hierarchical porous structures [18], a $PMMA_{HPA}$ porous film comprising nanopores [19], and scalable cooling coatings [20]. Other emerging cooling materials include structural cooling wood [21], polymeric aerogels [22], and aluminum oxide coated with silica [23]. However, it is noted that these high-reflective materials often appear overly white and produce glaring effects. With the development of radiative coolers that possess superior spectral properties and can obtain outstanding cooling performance during the daytime, radiative sky cooling technologies can be incorporated into numerous applications. For example, radiative coolers are able to enhance thermoelectric-based applications [24,25], and strengthen solar cell cooling for improved renewable system efficiency [26]. It is worth noting that of the different applications based on radiative sky cooling, incorporating innovative radiative cooling materials in building envelope systems is a viable and eco-friendly method of fulfilling a radiative cooling strategy integrated into buildings.

Given the unique building construction features of Hong Kong, where high-rise buildings are popular, integrating radiative cooling coatings into wall surfaces can effectively harness the application potential of a radiative cooling strategy integrated into buildings. However, currently, there is a lack of extensive research on cool walls incorporating radiative cooling materials. For retrofitting the envelope of walls, a significant consideration is avoiding glare and ensuring adequate visual comfort for occupants whilst preserving cooling effectiveness. Striking a balance among radiative cooling effects, visual comfort, and human aesthetics is crucial [27]. To address this issue, colored radiative coolers [28] are desirable as they absorb certain portions of visible spectra so as to display a particular color while also reflecting radiation in the near-to-short infrared ranges, which accounts for 51% of total solar energy [29]. To preserve surface color for the purpose of achieving visual comfort and aesthetics, colored cooling coatings are tailored to maintain visible light absorption. Nonetheless, these colored coolers must still have strong reflectivity within the near-infrared solar spectrum to minimize the absorption of solar heat, and simultaneously strong thermal emissivity in the mid-to-far-infrared wavelength range to effectively dissipate heat. Recent research has made progress in controlling the coloration of cooling coatings [30]. For example, Yalçın et al. [31] fabricated cooling coatings with the desired color by utilizing plain silver and plasmonic core–shell nanoparticles, with different coating colors achieved through adjusting the spectral positions of the surface plasmon resonance. Besides this, Xi et al. [32] demonstrated a cooling material with a metal–dielectric–metal structure to show specific colors, where the balance between color and cooling performance was explored. In addition, Zhai et al. [33] fabricated scalable, low-cost, and paint-format colored coatings using a simple preparation process with a facile solvothermal reaction. The reflectivity in near-infrared ranges and emissivity in the atmospheric transparency window of the colored coating were maximized to be 0.99 and 0.97, respectively, which could achieve 2.31 °C below ambient air during the daytime. Furthermore, Chen et al. [34] used the dielectric and plasmonic spheres with SiO_2 microspheres as the underlayer and plasmonic nanospheres for color in the top layer to develop bilayer-colored passive daytime radiative cooling coatings. The proposed colored coating shows better cooling performance than commercial white coatings, with fire resistance and storage stability as well. More recently, Zhao et al. [35] proposed a polymer-based colored film having composite opal photonic crystal structures, which demonstrates high emissivity within atmospheric transparency windows, achieving a temperature drop of 4.1 °C below surrounding air. Additionally, colored and paintable bilayer cooling coatings have been developed, where the top layer absorbs visible light for a specific color, while the lower layer reflects sunlight that has passed through the upper layer [29]. In summary, integrating colored radiative cooling coatings with wall surfaces offers a promising approach to applying radiative cooling strategies in high-rise buildings. Colored radiative coolers and cooling paints are desirable options that can selectively absorb visible light whilst preserving strong reflectance in the near-infrared solar spectrum and high thermal emittance in the mid-far-infrared wavelength.

Although extensive progress has been achieved on fabricating radiative cooling materials, there is as yet no comprehensive performance evaluation utilizing the colored radiative cooling coatings as a new retrofitting strategy for wall surfaces of high-rise buildings. Particularly for the metropolis Hong Kong, which is situated in a hot-humid climate region characterized by numerous high-rise buildings, the cooling electricity from air-conditioning systems accounts for over 32% of the entire-building electricity consumption for space cooling, and thus developing a passive cooling strategy by focusing on the improvement of building envelope systems, especially for the vertical façade systems, could be of overriding importance for building energy savings and realizing building sustainability. To fill the above research gaps, based on existing progress in the development of scalable and low-cost colored radiative cooling materials, this study aims to conduct a thorough performance evaluation of the coatings' applications in the vertical façade systems of a high-rise building, considering the hot-humid climate characteristics of Hong Kong. The main novelty of this study is highlighted as follows: First, state-of-the-art colored cooling coatings, which could be fabricated at a large scale and low cost, are adopted as a new retrofitting strategy for exterior wall surfaces. Second, based on comprehensive numerical evaluations of a typical high-rise building model integrated with the new cooling wall systems, its corresponding thermal performance, cooling electricity conservation, net cost saving, and carbon-neutral potential induced by the cooling wall strategy will be fully explored. Third, comparative analyses between super-cool roofs and colored cooling walls will be conducted and the potential benefits of the combination scheme will be fully investigated. The results provide useful insights into the passive realization of low-energy buildings. Accordingly, the structure of the paper is as follows: Section 2 will elaborate the details of the research methodology, including the adopted high-rise building model, climate characteristics of Hong Kong and spectral properties of the colored radiative cooling walls. An analysis of the results will be given in detail in Section 3, where comprehensive evaluations of thermal, energy, economic and environmental performance induced by varying colored cooling wall approaches in a high-rise building under hot and humid conditions will be conducted. Section 4 will further discuss the effects of a combination of colored cooling walls with a super-cool roof strategy on overall building performance, followed by the conclusions in Section 5.

2. Research Methodology

2.1. High-Rise Building Model

In order to conduct a performance evaluation of the application of colored radiative cooling walls on high-rise buildings, a 10-story high-rise apartment as shown in Figure 1 was adopted in this study. The building model was retrieved from [36] and is in compliance with ASHRAE Standard 90.1 [37]. The standard-compliant high-rise building model that has a window-to-wall ratio of 30% and encompasses a total building area of 7836.5 m^2, where the net conditioned area is 7059.9 m^2. The determination of thermal zones is in accordance with the layout in each floor, which includes a total of 8 air-conditioned apartments with a non-air-conditioned corridor in the center. Therefore, there are 8 thermal zones in each floor and a total of 80 thermal zones for the entire building. Regarding the fuel type to maintain indoor thermal comfort, since Hong Kong situated in a hot-humid region has no need of heating service, only cooling from air-conditioning systems using electricity is considered in this study. Specifically, the thermostat setpoint for HVAC control is 24 °C for cooling. For high-rise buildings, the wall surface accounts for a large proportion of incoming solar irradiance. Thus, the integration of colored cooling coatings can not only reduce the solar heat gain through the vertical façade system, but also avoid the glaring effects caused by strong super-white solar reflective materials. To this end, this study will focus on the retrofitting of wall surfaces by adopting paintable radiative cooling coatings with different colors which can be easily applied to building exterior walls. It is noted that the wall structure is composed of an exterior stucco layer, middle gypsum board, insulation layer, and interior gypsum board layer, which results in a U-factor of 0.384 W/(m^2·K). The baseline thermal performances of building envelopes in Hong Kong, including the roof, walls, and windows, are in compliance with the design standard for the energy efficiency of public buildings of China [38]. To conduct simulations on thermal and energy performance of the studied building prototype, EnergyPlus [39] was adopted in this study, which is a comprehensive program for simulating energy usage for whole buildings and can accurately address the mass and energy equilibrium of buildings and thus predict the HVAC energy consumption in response to varying building envelope properties [40,41]. Besides this, variations in the spectral properties of building envelopes can be input into EnergyPlus for the investigation of the impacts of radiative cooling walls on overall building performance. The reliability of EnergyPlus in performing building simulation has been validated with the mean bias error being less than 3.2% [40]. Thus, the accuracy of simulation results from this research is ensured. It is worth noting that the building performance induced by the proposed colored cooling wall strategies can change in accordance with varying practical building types, but the high-rise building prototype adopted in this study is representative of typical local building features in Hong Kong and can fully satisfy the purpose of this investigation.

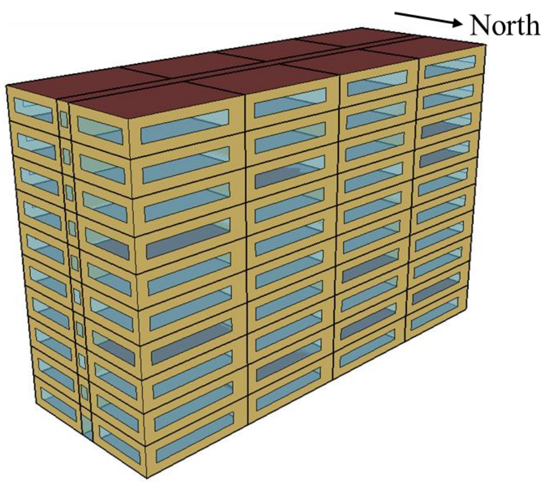
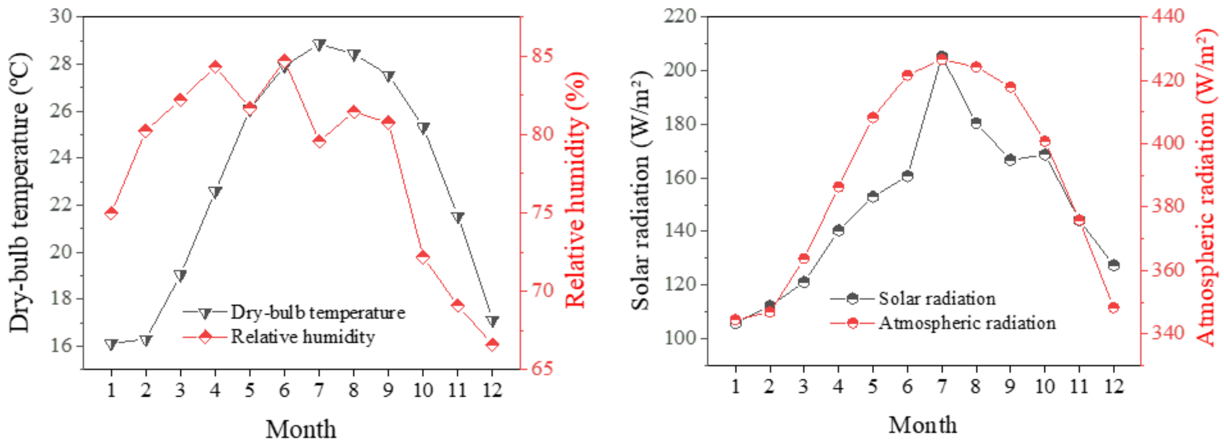


Figure 1. The ten-story high-rise building model.

2.2. Climate Characteristics of Hong Kong

In this study, the high-rise apartment is situated in a hot and humid city Hong Kong, where the monthly weather profiles are exhibited in Figure 2. It is noted that the meteorological data were retrieved from EnergyPlus weather database [42]. Hong Kong has a subtropical climate characterized by hot-humid summers and mild winters. The local climate is significantly impacted by the East Asian monsoon, bringing warm and moisture-laden air from the southern region during the summer season and cooler, drier air from the north during the winter. Basically, Hong Kong is hot and humid throughout a year with an annually averaged dry-bulb temperature of 23.1 °C and a relative humidity of 78.2%. The summer months are characterized by high humidity, with relative humidity often exceeding 80%. Besides this, the annually averaged solar radiation is 148.8 W/m^2 and the incident atmospheric infrared radiation is 388.7 W/m^2. Since Hong Kong suffers from serious heat stress, especially during summer seasons, implementing passive radiative cooling strategies on envelope systems can yield benefits and achieve energy savings in buildings. It should be mentioned that since Hong Kong has a generally hot climate throughout a year, cooling energy only is provided from the air-conditioning system with no need of a heating service for the thermal comfort of occupants. Thus, applications of radiative cooling envelope approaches will not incur building heating-energy penalties, which may need to be considered in other regions with cold climates during winter periods. While it is noted that although radiative cooling is suitable for hot-climate regions like Hong Kong, radiative cooling performance can be compromised due to the presence of high humidity and substantial atmospheric infrared radiation, leading to its diminished effectiveness. Hence, it is essential to evaluate the colored radiative cooling walls' effect on overall building performance by considering the typical climate data throughout a year in Hong Kong, so as to determine the feasibility and potential benefits of the proposed passive cooling approach for building sustainability.



(**a**) (**b**)

Figure 2. Monthly averaged weather profiles in Hong Kong. (**a**) Monthly dry-bulb temperature and relative humidity. (**b**) Monthly solar and atmospheric infrared radiation.

2.3. Colored Radiative Cooling Walls

Although it is widely acknowledged that the rapid advancement of radiative cooling materials has enabled superb cooling performance under direct sunlight, the concomitant strong glaring effects due to high solar reflectance can noticeably increase the visual discomfort of pedestrians for vertical façade applications. Therefore, wall surface thermal improvement should consider the appropriate balance between the cooling performance and the visual comfort. To this end, it is of great necessity to develop colored radiative cooling coatings that absorb visible light from 0.4 to 0.74 μm to preserve a certain color, whilst maintaining high reflection in the near-to-short infrared spectrum from 0.74 to

2.5 μm, which accounts for nearly 51% of solar heat. Aiming to achieve the above purpose, Chen et al. [29] developed bilayer colored radiative cooling coatings utilizing the porous P(VdF-HFP) polymer as the non-absorbing sun-scattering underlayer combined with a top layer with colorants to absorb visible light for color preservation. Besides this, a TiO_2-based underlayer was also fabricated for comparative analyses. By controlling different colorants of the top layer, four types of colored bilayer radiative cooling coatings were developed, including black, blue, red and yellow, which demonstrate different properties of solar reflectivity and thermal emissivity in different wavelength ranges, as shown in Table 1, where a monolayer coating with the same color is also exhibited for comparison. The full spectral properties include the reflectance values in the visible wavelength range from 0.4 to 0.74 μm, the near-to-short infrared wavelengths from 0.74 to 2.5 μm as well as the broadband solar spectrum range (0.4–2.5 μm), and the infrared emittance values in wavelengths from 5 to 15 μm. The different colors of the coatings are controlled by the parameter of visible light reflectance R_{vis}, which can affect the coating's solar heat absorption and thus its achievable cooling performance. The coatings can be handily applied in a paintable format directly onto the exterior wall surface to achieve the desired improvement through retrofitting. Since Hong Kong only has cooling loads, the higher coverage ratio of the radiative cooling coatings applied on walls can more effectively decrease the building heat gains through façade systems, thus reducing cooling loads and achieving higher energy-saving potential. In this regard, all the opaque wall surfaces are coated with the proposed colored radiative cooling coatings to maximize the building cooling energy-saving capability. Utilizing the proposed colored radiative cooling coating can provide an efficient approach to achieve a harmonious balance between visual comfort and the cooling effectiveness of building façades.

Table 1. Spectral properties of colored coatings, including reflectance values in visible spectrum (R_{vis}), near-to-short infrared (R_{NIR}), whole solar spectrum (R_{solar}), and broadband thermal emittance (ε) [29].

Color	Coating Type	R_{vis}	R_{NIR}	R_{solar}	ε
Black	Porous bilayer	0.07	0.81	0.44	0.95
	TiO_2-based bilayer	0.06	0.73	0.39	0.95
	Monolayer	0.05	0.30	0.17	0.96
Blue	Porous bilayer	0.17	0.63	0.40	0.95
	TiO_2-based bilayer	0.17	0.58	0.37	0.95
	Monolayer	0.15	0.43	0.29	0.95
Red	Porous bilayer	0.39	0.84	0.61	0.95
	TiO_2-based bilayer	0.38	0.79	0.58	0.95
	Monolayer	0.35	0.74	0.54	0.96
Yellow	Porous bilayer	0.59	0.86	0.72	0.95
	TiO_2-based bilayer	0.58	0.80	0.69	0.96
	Monolayer	0.54	0.69	0.61	0.96

3. Results

3.1. Cooling Wall Thermal Performance

The reduction in wall surface temperatures is an effective indicator to validate the cooling performance of the proposed colored cooling coatings applied on wall surfaces [41]. Accordingly, the temperatures of one of the south-facing walls were collected throughout a year for four types of colored bilayer radiative cooling coatings, including black, blue, red and yellow. To make for a fair comparison, the 8760 hourly-based annual data have been statistically analyzed by utilizing the cumulative distribution function (CDF) and probability density function (PDF) methods, which can exhibit temperature distributions and the occurrence rate of differently colored cooling walls relative to the ambient temperatures, as shown in Figure 3. Compared to the original monolayer wall with the same color, the utilization of the TiO_2-based bilayer and porous P(VdF-HFP)-based bilayer can effectively decrease wall temperatures. Particularly for the black wall, the occurrence frequencies of wall temperatures higher than those of the ambient air are 53.3%, 50.5% and 49.5% for the monolayer, TiO_2-based bilayer, and porous P(VdF-HFP)-based bilayer, respectively, demonstrating the efficacy of employing these coatings in sustaining wall cooling performance. In the same vein, in terms of the yellow wall, the monolayer has an occurrence rate of wall temperatures 44.5% higher than ambient air, while by contrast, the corresponding occurrence rate decreases to 41.3% and 39.7% for the TiO_2-based bilayer and porous P(VdF-HFP)-based bilayer coatings, respectively. In fact, both the monolayer and bilayer coatings with the same color have the similar visible-light reflectance, and the above cooler surfaces induced by the colored cooling coatings are mainly caused by the increased reflectance values in the near-to-short infrared wavelength ranges. It is noted that wall surfaces facing different orientations can exhibit some disparities in their surface thermal performance. For instance, the comparative analyses between the south and north walls on the second floor painted with the yellow cooling coating show annual average surface temperatures of 23.7 and 22.8 °C, respectively, indicating the south wall receives more incident solar radiation and thus higher solar heat gains. The above results indicate that the application of colored radiative cooling coatings is able to promisingly reduce surface heat gains and thus maintain a cooler wall surface temperature whilst still preserving the same color. With passively cooled building façades, the cooling energy consumption to maintain indoor thermal comfort can be reduced accordingly. It is worth mentioning that using colored radiative cooling walls can effectively decrease heat gains through walls. Using the colored cooling coatings on wall surfaces, the overall thermal transfer values through walls can be effectively controlled to ensure the equivalent or even better thermal performance as compared to that induced by thick wall insulation layers. As a result, from the perspective of thermal regulation, less building wall insulation will be used when introducing the colored cooling wall strategies, and the thermal insulation layers in wall structures can be accordingly reduced so as to decrease the building construction cost.

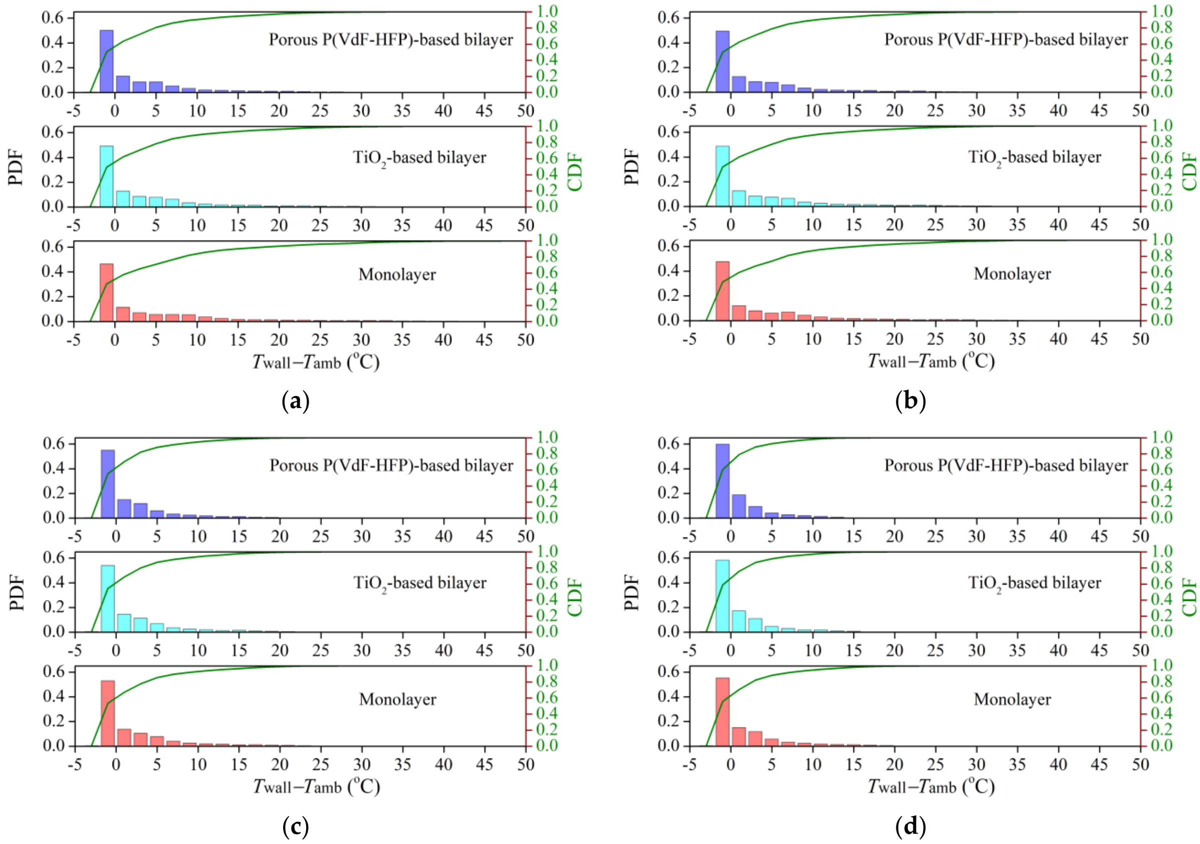


Figure 3. Statistical thermal analyses of differently colored walls relative to the ambient temperatures (**a**) Black wall. (**b**) Blue wall. (**c**) Red wall. (**d**) Yellow wall.

3.2. Energy-Saving Potential

The annual cooling electricity consumption from air-conditioning systems in order to ensure the thermal comfort of occupants induced by differently colored cooling walls in Hong Kong is shown in Figure 4. As is evident from the figure, under the same color, the monolayer wall corresponds to the highest cooling electricity consumption, due to the highest solar heat-absorption rate, followed in turn by the TiO_2-based and porous P(VdF-HFP)-based bilayer walls, respectively. Among the four colors, the yellow wall with the highest solar reflectance values to minimize the solar heat absorption exhibits the lowest cooling electricity consumption. In response to different wall colors, the cooling electricity consumption varies from 734.6 to 753.2 GJ, 731.1 to 744.9 GJ, and 729.7 to 743.4 GJ for the monolayer, TiO_2-based bilayer, and porous P(VdF-HFP)-based bilayer coatings, respectively. Besides this, to elucidate the energy-saving potential of the new colored radiative cooling coatings, the annual savings in cooling electricity and corresponding saving rates were specifically calculated relative to the monolayer under the same color, and the results are exhibited in Figure 5. It is clear that compared to the monolayer wall, the yearly electricity saving ranges from 394.4 to 2455.6 kWh/yr with an average of 1213.2 kWh/yr for TiO_2-based bilayer wall, and from 855.6 to 3105.6 kWh/yr with an average of 1692.4 kWh/yr for the porous P(VdF-HFP)-based bilayer wall. Regarding the four different surface colors, the black and red walls show the highest and lowest annual cooling electricity saving rates, respectively, varying from 0.2% to 1.2% and from 0.4% to 1.5% for the TiO_2-based bilayer and the porous P(VdF-HFP)-based bilayer walls, respectively. Compared to the TiO_2-based bilayer wall, the porous P(VdF-HFP)-based bilayer wall shows higher reflectance values in both the wavelength ranges of the near-to-short infrared and solar spectrum, thus achieving comparatively higher cooling electricity-saving potential among different colors. Hence, the utilization of the P(VdF-HFP)-based bilayer cooling wall is able to considerably reduce the building cooling energy consumption in accordance with the different surface colors.

Since cooling loads vary seasonally, to further investigate the distributive characteristics in response to different months, the monthly cooling energy savings of differently colored cooling walls are demonstrated in Figure 6 and the corresponding saving rates are illustrated in Figure 7. As is evident, for both the TiO_2-based bilayer and porous P(VdF-HFP)-based bilayer coatings, the monthly cooling electricity savings are distributed unevenly throughout a year. Basically, the hot summer months, when there is a higher demand for cooling energy, correspond to higher cooling electricity savings induced by the proposed passive wall cooling strategies. Specifically, the peak monthly cooling energy saving rate in Hong Kong varies in response to different surface colors, mainly occurring in the months from May to November with the monthly peak saving rates varying from 12% to 18%. The higher monthly energy saving rates in summer months are due to the higher cooling loads from air-conditioning systems in these hot periods. The increased heat-insulation capability of the colored cooling walls can effectively reduce the building heat gains through envelope systems, thus decreasing cooling electricity consumption. It is obvious that among the four colored cooling walls, retrofitting the black wall with the porous P(VdF-HFP)-based bilayer coating can yield the most prominent monthly cooling electricity savings, ranging from 61.2 to 409.9 kWh/month. By comparison, the red wall shows the least energy saving capability, with monthly saving rates varying from 11.5 to 115.9 kWh/month for the porous P(VdF-HFP)-based bilayer coating. The above results reveal that the application of the colored cooling wall shows more potential in harvesting the cooling electricity saving in hot-month periods when cooling loads are high, which makes the implementation of the colored cooling wall more attractive for stakeholders.

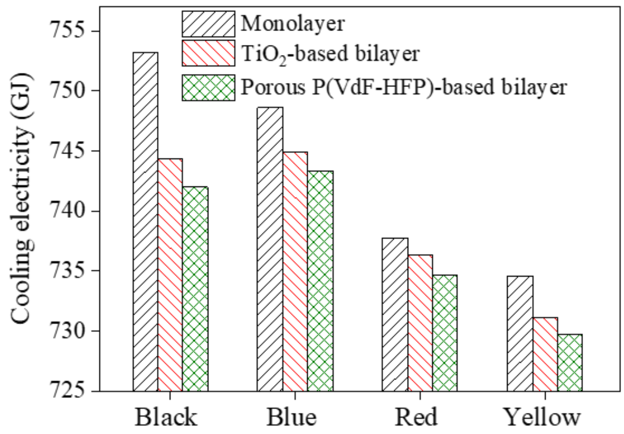


Figure 4. Cooling electricity consumption induced by differently colored cooling walls.

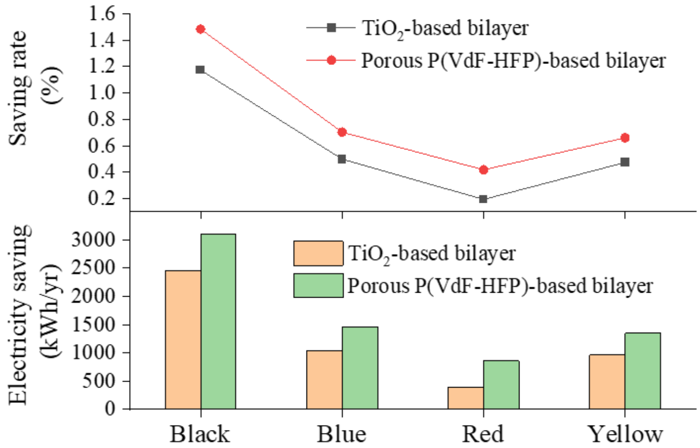


Figure 5. Cooling electricity saving relative to the monolayer wall with the same color.

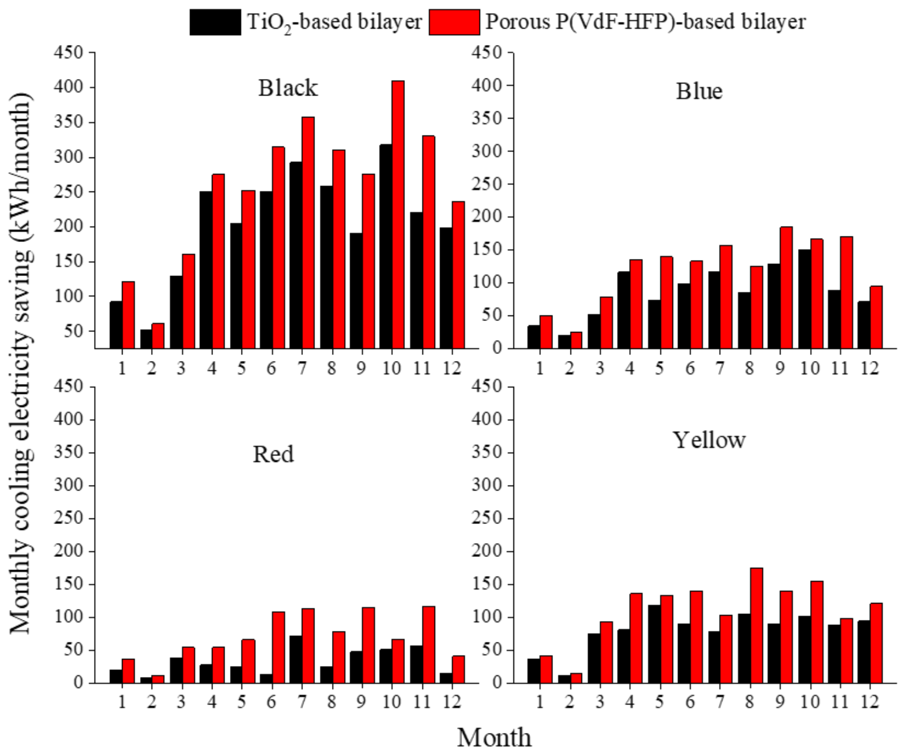


Figure 6. Monthly cooling energy saving distribution of differently colored cooling walls.

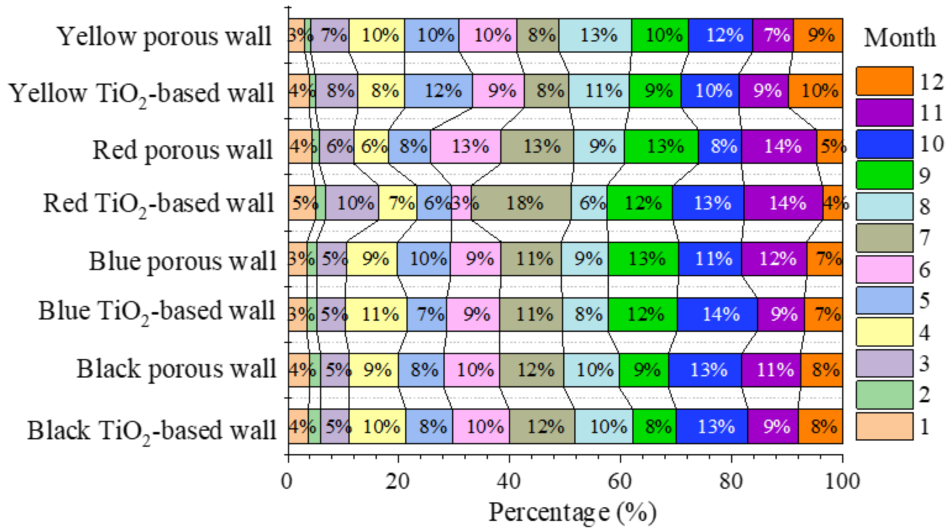


Figure 7. Percentage of monthly cooling energy saving distribution of differently colored cooling walls.

3.3. Economic and Environmental Evaluation

As one of the important aspects of performance evaluation, the building economic and environmental analyses, which are conducted based on the previous results of energy savings, can elucidate the building energy cost savings and carbon-emission reductions induced by the proposed colored cooling wall strategies. To assess the economic feasibility of the application strategy of the proposed colored cooling walls, considering the energy-saving potential in Section 3.2 together with the unit price rate of electricity for buildings with 1.651 HKD/kWh in Hong Kong [43], the annual net cost savings in cooling electricity consumption were fully evaluated with the results exhibited in Figure 8. As is evident for a high-rise building, compared to the monolayer wall, the further utilization of a TiO_2-based bilayer coating and the porous P(VdF-HFP)-based bilayer coating is able to noticeably bring the economic benefits for the entire building. The annual savings in net electricity cost range from 651.2 to 4054.1 HKD/yr for the TiO_2-based bilayer coating and from 1412.5 to 5127.3 HKD/yr for the porous P(VdF-HFP)-based bilayer coating in response to different surface colors. Since the increased solar reflectance through using the P(VdF-HFP)-based bilayer coating as compared to the monolayer coating is 0.27, 0.11, 0.07, and 0.11 for the black, blue, red and yellow walls, respectively, the highest and lowest cost savings in cooling electricity turn out to be the black and red wall, respectively. These results elucidate the potential energy-saving benefits in accordance with the passive cooling wall strategies in the hot-humid region of Hong Kong, which can provide reference guidance for stakeholders in implementing this promising technology.

Carbon reduction is a crucial parameter to validate the potential for achieving carbon neutrality by implementing the proposed colored cooling coatings on walls. Considering the carbon emission factor of 0.57 kg CO_2/kWh in Hong Kong [44] and the electricity site-to-source conversion factor of 3.167 as well as the cooling energy saving performance, the annual net avoided CO_2 emissions relative to the monolayer with the same color are shown in Figure 9. Both the TiO_2-based bilayer coating and porous P(VdF-HFP)-based bilayer coating show promising carbon-reduction potential. In particular, the yearly carbon-emission reduction ranges from 712.0 to 4432.7 kg/yr with an average of 2190.0 kg/yr for the TiO_2-based bilayer wall and from 1544.4 to 5606.1 kg/yr with an average of 3055.0 kg/yr for the porous P(VdF-HFP)-based bilayer wall. In the same vein, the black and red cooling walls, which, respectively, exhibit the highest and lowest electricity saving potential, show the largest and smallest carbon reduction capability, respectively. Compared to the TiO_2-based bilayer coating, the development of the porous P(VdF-HFP)-based bilayer coating exhibits more carbon-reduction capability, with extra net reductions in CO_2 emissions ranging from 687.0 to 1173.4 kg/yr and an average of 865.0 kg/yr.

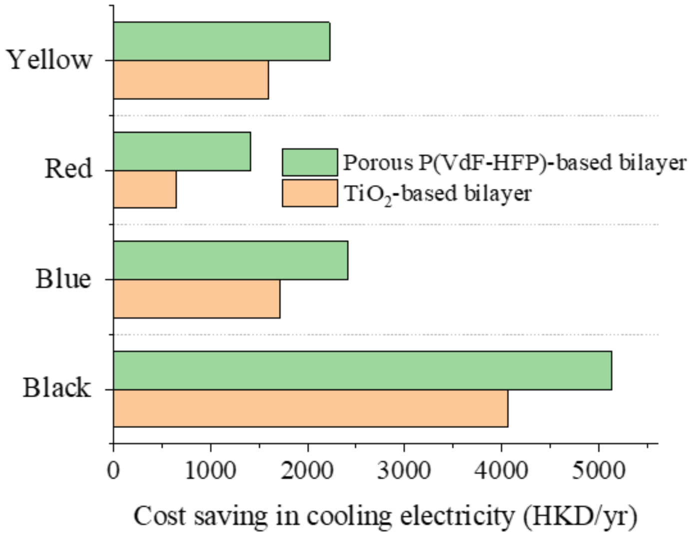


Figure 8. Net cost saving in cooling electricity induced by colored cooling walls relative to the monolayer.

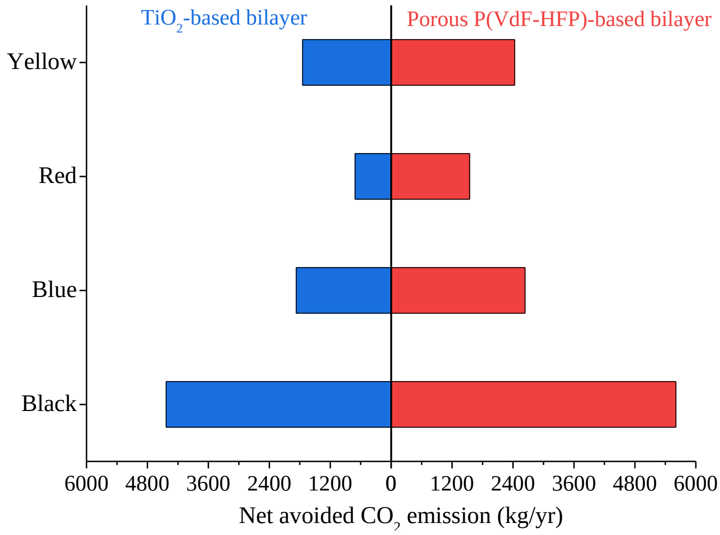


Figure 9. Net avoided CO_2 emission relative to the monolayer.

4. Discussion

Although the above results fully elucidate the potential benefits of colored cooling walls in contributing to building sustainability, it is noted that roofs, which are the major recipient of incoming solar irradiance, also account for large amounts of building heat gain, especially for the top floor. In this regard, this section further discusses the impacts of the integration of a super-cool roof with blue-colored cooling walls on the overall performance of buildings in terms of energy efficiency, economic viability, and environmental impact. It is noted that the super-cool roof is coated by a hierarchically porous polymer ($P(VdF\text{-}HFP)_{HP}$)-based super-white coating with excellent spectral properties for daytime radiative cooling [18,45]. Specifically, the radiative cooling coating equipped with a solar reflectivity of 0.98 and a thermal emissivity of 0.97 is scalable with low cost, which makes it feasible for applications at scale in buildings. It is noted that the baseline roof surface of the top floor in the building model has a solar absorptivity of 0.45 and thermal emissivity of 0.75. To illustrate the impacts of the super-cool roof on the energy performance in each floor, Figure 10 demonstrates the cooling electricity savings caused by the extra integration of the super-cool roof coating when compared to the scenarios without the super-cool roof coating. As can be seen from the figure, the additional integration of the super-cool roof only exerts impacts on the top three floors, where the top floor benefits the most in terms of the cooling energy saving, with around 5.6 GJ of electricity saved regardless of wall type. By comparison, the penultimate and antepenultimate floors of the building have much lower energy saving values of around 1.1 and 0.2 GJ, respectively. Hence, for high-rise buildings, the benefits derived from the super-cool roof strategy are mainly constrained on the top floors, and the low and middle floors are barely influenced by the cooling technique. However, from the energy-saving perspective of the entire building, such integration is also meaningful. Besides this, Figure 11 further depicts the annual cooling electricity saving rate of different passive combination strategies on each floor relative to the monolayer wall. For the 10th floor, the electricity saving rate caused by the single super-cool roof, the single porous polymer-based bilayer walls, and the combination of the cool roof and porous polymer-based walls is 7.2%, 0.6%, and 7.6%, respectively, and the above three values are 1.5%, 0.7%, and 2.0% for the ninth floor. As a result, a super-cool roof can achieve up to 12 times the energy saving rate compared to colored cooling walls for the top floor. However, the wall-retrofitting strategy can achieve almost evenly distributed energy saving rates on each floor, with an average of 0.5% and 0.7% for the TiO_2-based and the porous polymer-based bilayer walls, respectively.

The entire building's energy-saving potential, and the economic and environmental benefits derived from the further integration of the super-cool roof strategy when compared to the monolayer wall, are demonstrated in Figures 12 and 13, respectively. Compared to the wall-retrofitting strategies using colored cooling coatings on all vertical wall surfaces including the TiO_2 bilayer wall and the porous polymer bilayer wall, the super-cool roof with superb radiative cooling performance can yield more annual cooling electricity savings of 1975 kWh/yr, the value of which is 1036.1 kWh/yr and 1461.1 kWh/yr for the TiO_2 bilayer and the porous polymer bilayer walls, respectively. Hence, although the super-cool roof can only exert influence on the top floor, the corresponding whole-building energy saving can be more noticeable than the colored cooling walls, due to its excellent heat-dissipation capability for passive radiative cooling. However, it is noted that due to esthetical considerations, a compromise in cooling performance and visual comfort is necessary to achieve the appropriate purpose for wall cooling retrofitting. More promisingly, the combination of the super-cool roof with the porous polymer-based blue cooling wall is able to maximize energy-saving capability, with a yearly saving of over 3244.4 kWh/yr, which is 1.6 and 2.2 times more than the application of the super-cool roof or porous polymer bilayer walls alone, respectively. In addition, as can be seen from Figure 13, the combination of the colored cooling wall with the super-cool roof can considerably enhance the yearly net cost savings from 2412.3 to 5356.6 HKD/yr, and increase the carbon reduction from 2637.6 to 5856.8 kg/yr for the porous polymer bilayer wall.

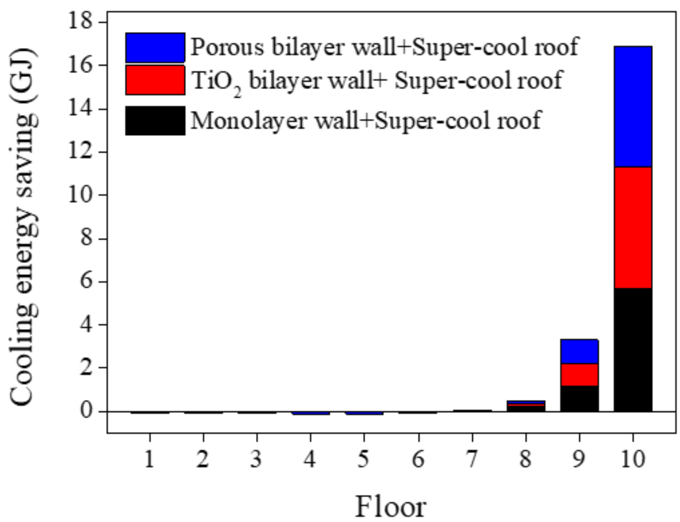


Figure 10. Super-cool-roof-induced cooling energy saving relative to the monolayer, TiO_2 bilayer, and porous P(VdF-HFP)-based bilayer walls without combining the super-cool roof.

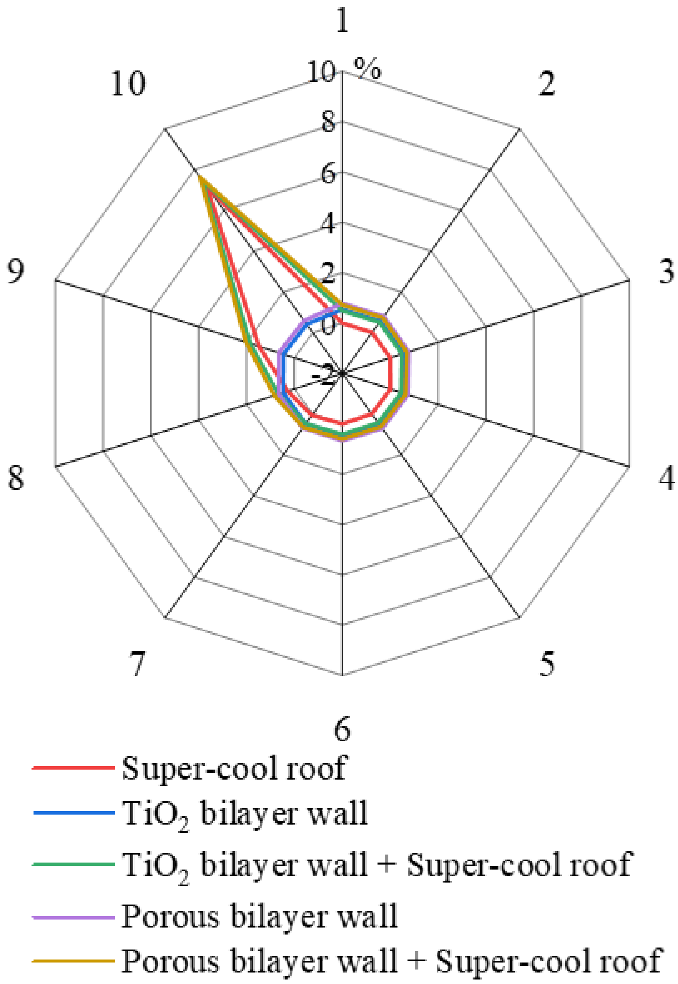


Figure 11. Yearly cooling electricity saving rate in each floor relative to the monolayer wall.

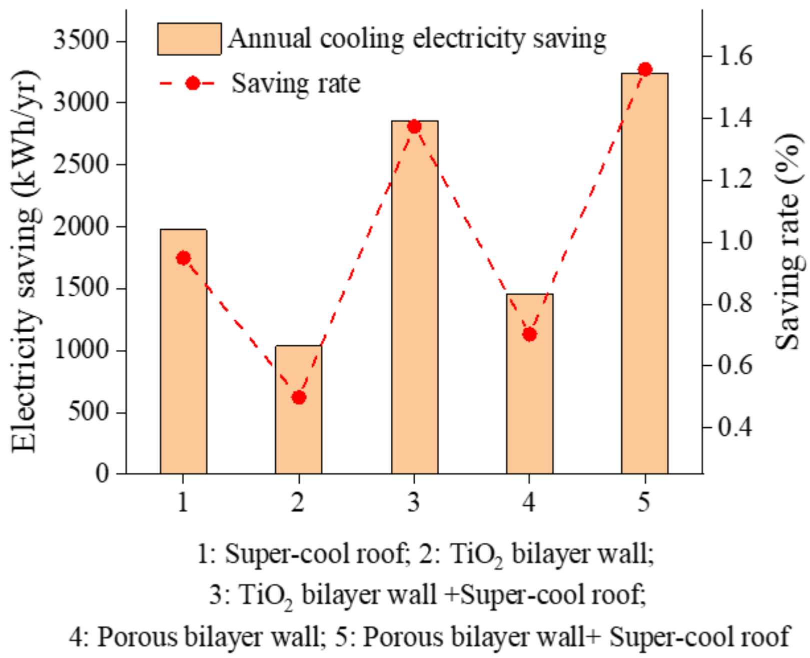


Figure 12. Yearly cooling electricity saving and saving rate relative to the monolayer wall.

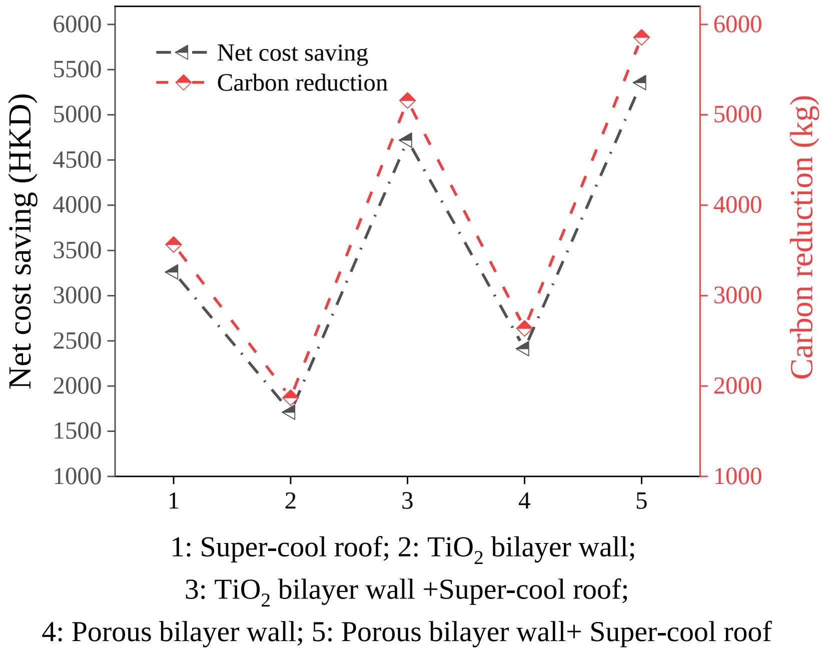


Figure 13. Annual net cost saving and carbon-emission reduction relative to the monolayer wall.

Although extensive benefits, including with regard to energy, economic, and environmental performance, induced by different-colored cooling walls or super-cool roofs in hot-humid Hong Kong have been fully investigated, it should be noted that the obtained results are derived from a 10-story high-rise building considering the local weather data in the typical meteorological year. Hence, the practical building performance associated with the proposed passive cooling strategies can change in accordance with real building prototypes, climate patterns, energy-price rates, and emission factors. But it can still be precisely evaluated by the proposed method in this study. In light of the rapid development of radiative sky cooling materials, which can be fabricated at a large scale and low cost, in future research the practical applications of implementing colored radiative cooling wall coatings together with super-cool roof paints on building envelope systems should be investigated so as to explore real-world potential benefits, based on the potential benefits obtained in this study as basic guidance for stakeholders. Besides this, considering the thermal interactions between neighboring buildings caused by the reflective cooling materials, the impacts of implementing radiative cooling coatings on vertical façades on practical building heat gains in densely built communities with high-rise buildings should be further studied, which could improve accuracy in predicting the energy-saving potential for a building community. More broadly, the potential mitigation of urban heat-island effects induced by the radiative-cooling-based building envelope systems in densely populated cities such as Hong Kong should be deeply investigated, as this is important to enhance the overall urban microclimate for residents.

5. Conclusions

In this study, a comprehensive evaluation has been fully conducted of overall building performance associated with colored radiative cooling walls in a high-rise building situated in a hot and humid region. Four colored bilayer radiative cooling coatings with satisfactory cooling performance were selected for investigation. Integrating the spectral properties of the colored radiative cooling coatings into a numerical high-rise building model, the corresponding building performance was quantified in terms of energy efficiency, economic viability, and environmental impact, and deeply elucidates the potential benefits of the implementation of colored radiative cooling walls in hot-humid Hong Kong. The results obtained reveal that the utilization of colored radiative cooling walls is able to efficiently reduce surface temperatures and thus inhibit building heat gain. Specifically, regarding the energy-saving potential relative to a monolayer wall, the yearly cooling electricity saving ranges from 855.6 to 3105.6 kWh/yr with an average of 1692.4 kWh/yr for the porous P(VdF-HFP)-based bilayer wall. The economic and carbon-reduction benefits induced by the colored cooling walls were evaluated based on the energy-saving potential together with the local unit price rate of electricity and the emission factor. Compared to a monolayer wall with the same color, the annual net savings in electricity cost range from 1412.5 to 5127.3 HKD/yr for the porous P(VdF-HFP)-based bilayer coating. Moreover, the annual reduction in carbon emissions ranges from 1544.4 to 5606.1 kg/yr with an average of 3055.0 kg/yr for the porous P(VdF-HFP)-based bilayer wall.

In addition, this study also specifically discusses the impacts of super-cool roof strategies on building energy performance on each floor, and explores the combination effects of colored cooling walls with the proposed super-cool roof. The results obtained indicate that implementing a super-cool roof strategy can lead to significant energy savings for the top floor of high-rise buildings. In fact, energy savings can be as high as 7.2%, which is 12 times higher than the energy saving rates achieved by colored cooling walls for the top floor. However, the wall-retrofitting strategy can achieve almost evenly distributed energy saving rates in each floor. Although the super-cool roof can only exert influence on the top floor, due to its excellent heat-dissipation capability for passive radiative cooling, the whole-building energy savings can be more noticeable than for the colored cooling walls. More promisingly, the combination of the super-cool roof with the blue porous polymer-based radiative cooling wall can maximize the energy-saving capability, with a yearly saving of over 3244.4 kWh/yr, which is 1.6 and 2.2 times more than the implementation of the super-cool roof or porous polymer bilayer walls alone, respectively.

In summary, this research attempts to assess the potential benefits of state-of-the-art colored radiative cooling coatings integrated into a high-rise building as an improved retrofitting strategy for wall surfaces. The results fully shed light on the building energy performance, net cost saving, and carbon-reduction potential caused by the implementation of colored cooling walls in a hot and humid region, which provide useful insights into the development of novel, radiative-cooling-assisted building façades to achieve sustainable and energy-efficient buildings.

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