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Assessing Energy Savings: A Comparative Study of Reflective Roof Coatings in Four US Climate Zones

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High albedo roof coatings are designed with the specific aim of reflecting a greater proportion of solar radiation compared to traditional roofing materials, thereby lowering the solar energy absorption into the roof. In this article, we present the energy-saving potential of silicone, acrylic, and aluminum roof coatings using EnergyPlus. Two of the U.S. Department of Energy (DOE) prototype commercial buildings—standalone retail of area 2294 m^2 (24,692 ft^2) and strip-mall of area 2090 m^2 (22,500 ft^2)—across four cities namely Phoenix, Houston, Los Angeles, and Miami have been used to model the effects of different types of coatings. The performance with reflective coatings was compared with respect to a black roof having a solar reflectance of 5% and a thermal emittance of 90%. Furthermore, we quantified the capacity of reflective coatings to reduce rooftop temperatures. A sensitivity analysis was done to assess the impact of solar reflectance and thermal emittance on the ability of roof coatings to reduce surface temperatures, a key factor behind energy savings. A contour plot between these properties reveals that high values of both result in reduced cooling needs and a heating penalty which is insignificant when compared with cooling savings for cooling-dominant climates like Phoenix where the cooling demand significantly outweighs the heating demand, yielding significant energy savings. Additionally, the study investigates how the insulation thermal resistance of the roof relates to the energy savings resulting from the application of reflective coatings, particularly in terms of their effect on heating, ventilation, and air conditioning (HVAC) energy consumption. [DOI: 10.1115/1.4066069]

Keywords: roof albedo, cool roofs, roof coatings, urban heat island, energy savings, energy simulations, EnergyPlus, air conditioning, building energy modeling, cooling, energy efficiency

1 Introduction

The urban heat island phenomenon has become a significant environmental challenge in urban areas worldwide, significantly impacting energy consumption in buildings. Research indicates that every 1 °C drop in ambient air temperature can potentially reduce building energy use by about 5% [1,2]. On a hot summer afternoon, traditional low-reflectance surface roofs that absorb a huge amount of heat can have a temperature difference of up to 50 °C (90 °F) compared to the surrounding air [3]. The use of high-reflectance surfaces in urban areas is a cost-effective approach to reduce high temperatures in summer months. Studies have shown that cool roof coatings significantly impact roof surface temperatures, with results indicating a reduction of 4 °C on concrete tiles [4]. Furthermore, these coatings can achieve surface temperatures that are up to 15 °C lower compared to those with a dark-colored roof [4]. Given that approximately 50% of a building's thermal load is attributed to the roof [5], the potential for energy savings through the use of reflective coatings is substantial.

Based on the 2018 Commercial Buildings Energy Consumption Survey, approximately 5.9 million commercial buildings in the United States consumed 6.8 quadrillion British thermal units of energy, amounting to $141 billion in energy costs [6]. The use of air conditioners and electric fans for cooling purposes currently contributes to approximately 20% of the overall electricity consumption in buildings worldwide. This increasing demand for space cooling not only poses significant challenges to electricity systems in numerous countries but also contributes to an increase in carbon emissions [7].

To save energy from space cooling, cool roof materials have gained a lot of interest in past years. Reflective roof coatings have emerged as an economically viable option for reducing building's heating, ventilation, and air conditioning (HVAC) energy consumption, contributing to sustainability. Two critical properties, solar reflectance and thermal emittance, play an important role in the design of these reflective coatings. The solar reflectance is the

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ability of a material to reflect a portion of solar irradiation back into the atmosphere while thermal emittance is the ability to release absorbed heat into the atmosphere in the form of long-wavelength thermal radiation.

While there are concerns over potential heating penalties in winter climates, regions with predominantly cooling needs have shown significant energy savings from cool roof coatings. There are studies that review the potential of switchable roof reflectance technology to maintain energy savings without increasing heating load penalties [8]. Studies have demonstrated that reducing solar absorptance by 30% in high-rise buildings in Hong Kong can lead to a 12.6% decrease in annual cooling energy requirements [9]. Similarly, increasing roof reflectance in Miami and Dallas from 0.08 to 0.3 and 0.5 through cool roofing materials has been shown to reduce energy usage by 15% and 30%, respectively [10]. In Sydney, increasing the albedo fraction from 0.1 to 0.7 has the potential to decrease residential cooling requirements by 20%, with average peak cooling demands decreasing by 3.5% for every 0.1 increase in solar reflectance [11].

Over the years, roofing materials have been developed that have the ability to reflect both the visible and infrared spectrum of solar radiation [12–14]. A wide range of literature is available that evaluates the benefits and drawbacks of various cool roof methods across different climatic conditions [15,16]. A review of the comparison of the thermal performance of cool roofs suggests that on an average cool roof can save 15–35.7% energy across various climate zones [16].

However, the existing literature lacks sensitivity analysis regarding the radiative properties (solar reflectance and thermal emittance) and thermal insulation of buildings, which directly influence HVAC energy consumption. This study examines how variations in both the radiative properties and thermal insulation affect roof surface temperatures and the energy consumption of building HVAC systems. Although energy savings are calculated for multiple locations, this analysis primarily focuses on Phoenix, where the impact of cool roofs on reducing cooling energy demand is particularly pronounced due to the region's hot and arid climate.

2 Materials and Methods

EnergyPlus, a building energy simulation program developed by the U.S. Department of Energy (DOE), was employed in this study.[2] EnergyPlus offers advanced capabilities, integrating thermal zone conditions, HVAC system responses, and heat balance-based solutions for accurate energy consumption modeling. EnergyPlus builds on the most popular features and capabilities of BLAST and DOE-2 and includes many innovative simulation capabilities.

In this study, two of the DOE prototype commercial buildings namely standalone retail of area 2294 m^2 (24,692 ft^2) and strip-mall of area 2090 m^2 (22,500 ft^2) were used to model the effect of coatings [17]. Figures 1 and 2 below show the 3-D geometry of the standalone retail and strip-mall building, respectively. This study analyzes four different climatic conditions, viz., Phoenix, AZ (climate zone 2B), Houston, TX (climate zone 2A), Los Angeles, CA (climate zone 3B coast), and Miami, FL (climate zone 1A). Typical meteorological year (TMY) 3 weather files provided by EnergyPlus were used to set the weather conditions in the annual simulations carried out for all four cities in this study.

In order to validate our findings, we utilized another tool, namely the ORNL Cool Roof Calculator [18] developed by DOE's Oak Ridge National Laboratory. The calculator compares cooling and heating load savings for flat roofs with nonblack surfaces. Based on that we implemented specific modifications to both the buildings as follows:

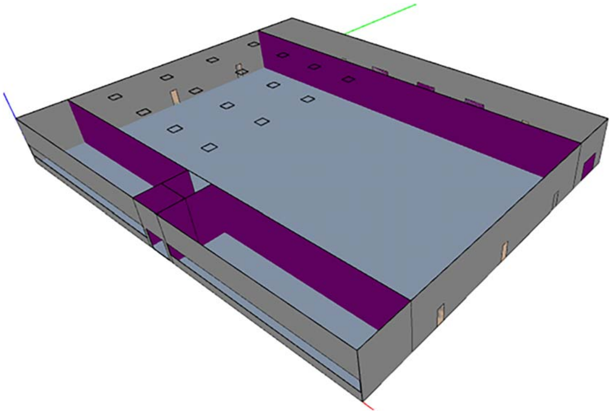
Fig. 1 Standalone retail building

(1) The R-value of the roof is adjusted to $1.76\ m^2\ K\ W^{-1}$ ($10\ h{\cdot}ft^2{\cdot}°F\ Btu^{-1}$) aligning with the average R-value provided by the ORNL Cool Roof Calculator. Additionally, the solar reflectance and thermal emittance of the roof are modified to 0.05 and 0.9, respectively, effectively simulating a black roof.
(2) The coefficients of performance (COPs) of all the air conditioners (ACs) were modified to 2. This is the average value of the COP for an AC as given by the ORNL Cool Roof Calculator.
(3) The heating is provided by natural gas furnaces, with their efficiencies modified to 0.7—consistent with the average efficiency of a gas furnace as per the ORNL Cool Roof Calculator.

The COP of the air conditioner and the efficiency of the gas furnace do not significantly impact energy savings, as the comparison between coated and black roofs is made under identical conditions. While they can influence the magnitude of cooling and heating energy consumption, they do not notably affect the percentage change. However, variations in the insulation value of the roof can substantially impact energy savings due to differing conduction heat transfer from the coated and black roofs. Therefore, the effect of various roof insulation values on energy savings is studied in this article.

The performance of the roof coatings is evaluated by adding an additional layer of coating on the top of the black roof. The baseline black roof has a solar reflectance of 0.05 and a thermal emittance of 0.9. These properties of the black roof are chosen as a standard by Oak Ridge Cool Roof Laboratory to evaluate the performance of a coating [18]. Table 1 provides an overview of the properties of commonly used commercial silicone, acrylic, and aluminum coatings available in the market. The properties were provided by the manufacturer in the form of technical data sheets. In the table, C-1 is a 100% silicone, moisture-cure coating. C-2, C-3, and C-4 are 100% acrylic white extreme elastomeric roof coatings, C-5 is fibered aluminum roof coating and C-6 is an acrylic polyurethane white waterproof roof coating.

3 Results and Discussion

3.1 Net Savings in Various Locations. Figures 3(*a*)–3(*d*) provide a comparative analysis of the net savings in HVAC

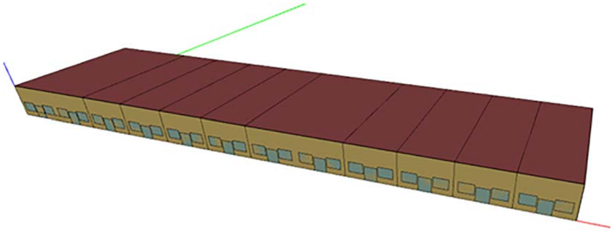
Fig. 2 Strip-mall building

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[2] https://energyplus.net/

Table 1 Material properties of coatings

Properties	C-1	C-2	C-3	C-4	C-5	C-6
Solar reflectance	0.87	0.86	0.84	0.86	0.53	0.83
Thermal emittance	0.9	0.9	0.91	0.88	0.5	0.91
Number of coats[a]	1	2	2	2	2	2
Thickness of single coat (mm)	0.407	0.407	0.407	0.407	0.407	0.407
Thermal conductivity (W m^{-1} K^{-1})	0.63	0.19	0.19	0.19	237	0.67
Density (kg m^{-3})	1210	1426	1408	1408	935	1307
Specific heat (J kg^{-1} K^{-1})	1147	1248	1248	1248	900	1253

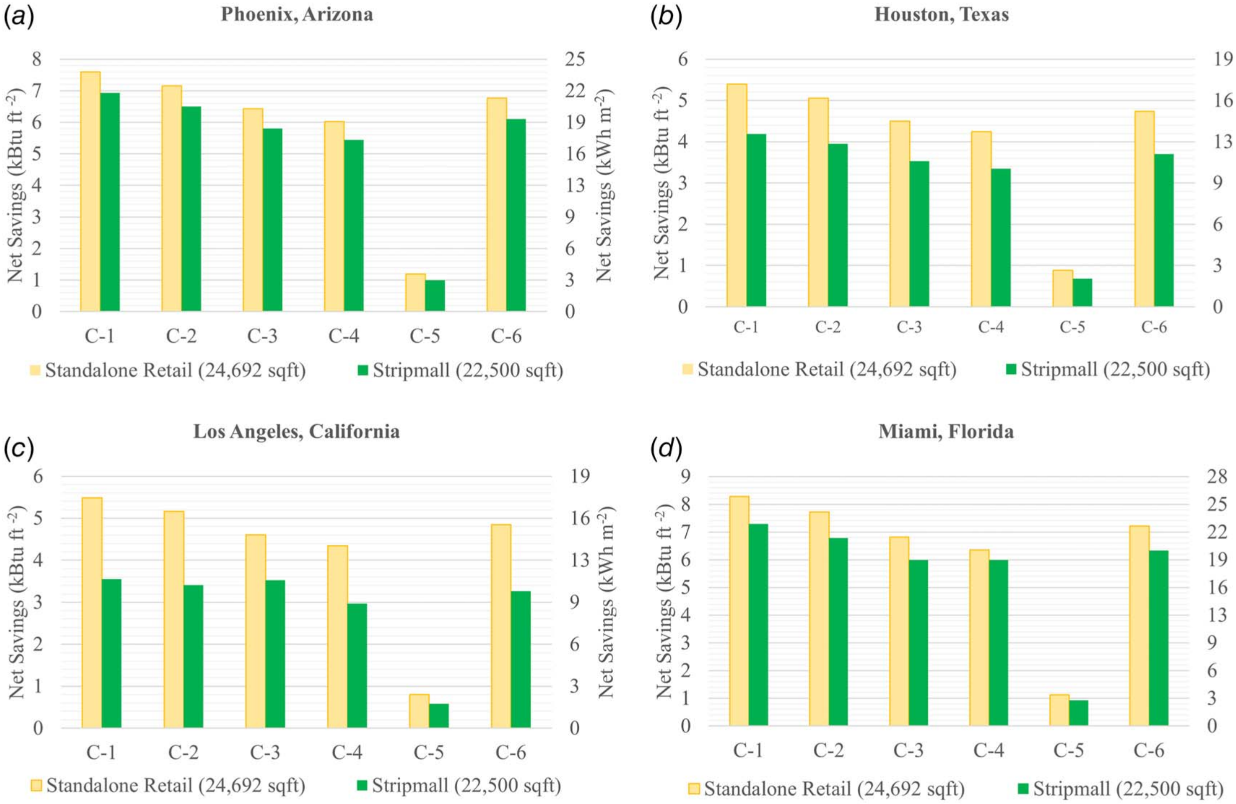
[a] Suggested by the manufacturer.

energy consumption resulting from the application of different reflective roof coatings in the four chosen geographic locations, for both the standalone and strip-mall buildings. Net savings are determined by subtracting the energy penalty incurred during heating from the energy savings achieved during cooling. The results are normalized by floor area, making it possible to apply them to other buildings with different areas, provided they have similar characteristics in terms of construction, HVAC type, and building loads. Notably, Miami exhibits the highest level of savings for both standalone retail and strip-mall buildings followed by Phoenix. It can also be seen that buildings in Houston and Los Angeles show very similar levels of HVAC energy savings, making them comparable in this regard.

Solar reflectance and thermal emittance values of a coating play an important role in determining its performance. As can be seen in Fig. 3, the performance of coating C-5 is worse as compared to others because of its lower solar reflectance and thermal emittance values. Given that the HVAC load per square foot varies depending on the size and type of a building, slight variations in the net savings per square foot for the standalone and strip-mall buildings across all locations for all the coatings, can also be observed.

3.2 Effect of Solar Reflectance and Thermal Emittance on Roof Temperatures. To study the effect of solar reflectance and thermal emittance on roof surface temperatures, we analyzed hourly temperatures on August 8th in Phoenix—a day characterized by the highest average temperature, as indicated by EnergyPlus TMY3 data. As depicted in Fig. 4, an uncoated black roof can reach temperatures of 93.3 °C (200 °F) in the afternoon, nearly twice the ambient air temperature at that time. With the application of a coating, an increase in the solar reflectance value of the coating results in lower roof temperatures during daylight hours. Remarkably, super cool roofs having a solar reflectance value close to 1 can achieve temperatures below ambient during all the times of the day. However, such higher values of solar reflectance are challenging to attain and maintain due to the accumulation of dust and dirt over a period of time. While most of the commercially available cool roof materials typically exhibit a maximum solar reflectance of 0.86 and an emissivity of 0.9, recent studies unveiled materials that can possess an exceptionally high albedo exceeding 0.95, along with high thermal emissivity exceeding 0.95 as well [19–21].

It is interesting to note that during nighttime, roof temperatures are generally less than the ambient temperature. This is the result


(a) Phoenix, Arizona

(b) Houston, Texas

(c) Los Angeles, California

(d) Miami, Florida

Fig. 3 (*a–d*) Location-wise net savings in HVAC energy consumption for different coatings

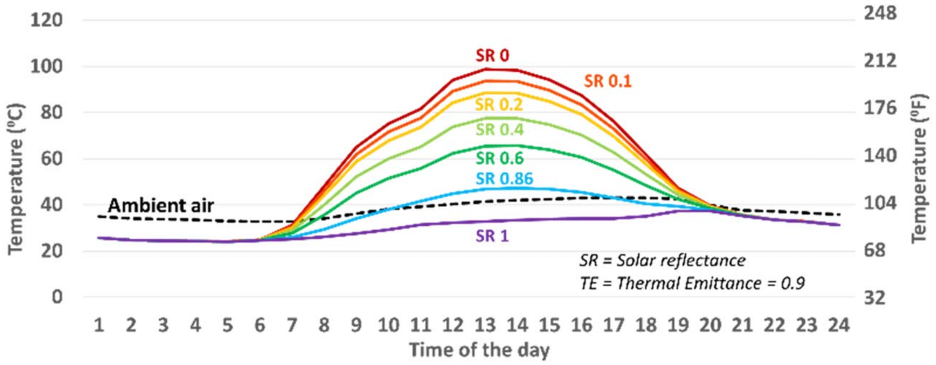


Fig. 4 Effect of solar reflectance on roof surface temperature at constant thermal emittance on August 8th in Phoenix, AZ

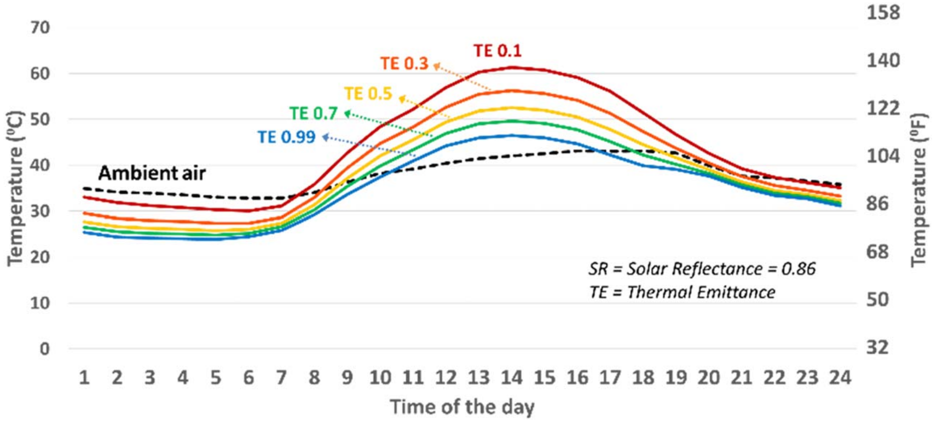


Fig. 5 Effect of thermal emittance on roof surface temperature at constant solar reflectance on August 8th in Phoenix, AZ

of a phenomenon known as nocturnal cooling, also called night sky cooling. It is the cooling of a building by long-wavelength radiation to the night sky. Building roofs emit heat continuously, releasing at a rate of up to 75 W m^{-2} day and night [22]. While this heat loss is counteracted by solar radiation gains during the day, it has the potential to reduce roof temperatures by 6–20 °C below ambient levels during the night [22]. A key factor affecting nocturnal cooling is the thermal emittance of the roof material. Higher thermal emittance corresponds to elevated rates of nocturnal cooling. Additionally, various other factors such as sky conditions, humidity, wind speeds, thermal mass of the roof, and geographical location also influence the rates of nocturnal cooling.

Similarly, as illustrated in Fig. 5, at a constant solar reflectance of 0.86, the thermal emittance of the coating is varied on the same day (August 8th) in Phoenix. It can be observed that lower thermal emittance values approaching zero can result in roof temperatures over 60 °C (140 °F) in the afternoon when the ambient temperature is around 43 °C (110 °F). A higher thermal emittance of the coating can bring roof temperatures close to ambient during the daytimes. During night hours, it can be seen that higher temperature drop in roof temperature occurs at higher values of thermal emittance. This phenomenon can be attributed to the same nocturnal cooling discussed earlier.

It can also be noted that the temperature at approximately zero thermal emittance is at least 40 °C (104 °F) less than the temperature in the case when solar reflectance is zero as depicted in Fig. 4. This highlights the significant influence of solar reflectance over thermal emittance in governing roof temperatures.

Reduced temperature of the roof with the application of coatings having high solar reflectance and thermal emittance is the primary reason behind the reduced cooling needs in the buildings.

3.3 Effect of Solar Reflectance and Thermal Emittance on Cooling Load Savings and Heating Load Penalty. To analyze the impact of the combination of solar reflectance and thermal emittance on roof coating performance, contour plots for annual savings in cooling energy and penalty in heating energy, as shown in Figs. 6 and 7 are generated for a standalone retail commercial building in Phoenix, Arizona. These plots offer insights into how specific values of solar reflectance and thermal emittance impact the building's cooling and heating requirements. Savings or penalty is with respect to the baseline black roof (indicated by a black dot in Figs. 6–8) with solar reflectance 0.05 and thermal emittance 0.9. As discussed previously, these properties of the baseline black roof are taken from the ORNL Cool Roof Calculator. It is evident that higher values of both solar reflectance and thermal emittance result in reduced cooling demands but increased heating demands. Yet, in regions like Phoenix, where the cooling demand significantly outweighs the heating demand, as indicated by the color bars in the contour plots, these coatings can lead to substantial savings in energy costs. The quantification of net savings with respect to black roof is done in Fig 8.

3.4 Reflective Roof Coatings Versus Roof Thermal Insulation. To explore the relationship between the insulation thermal resistance (*R*-value) of the roof and the resulting energy savings achieved by the application of reflective coatings, the following analysis has been done. This involves varying the insulation thermal resistance of the roof across a range from 1 m^2 K W^{-1} (5.6 ft^2 °F h Btu^{-1}) to 5 m^2 K W^{-1} (28.4 ft^2 °F h Btu^{-1}), while applying three distinct coatings (one at a time) with solar reflectance values of 0.42, 0.73, and 0.84. This analysis was carried out on a

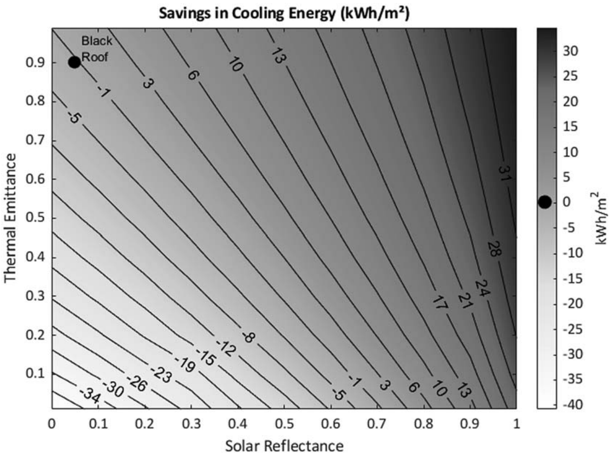


Fig. 6 Effect of solar reflectance and thermal emittance on annual savings in cooling energy with respect to baseline black roof (SR = 0.05, TE = 0.9) for Phoenix, AZ

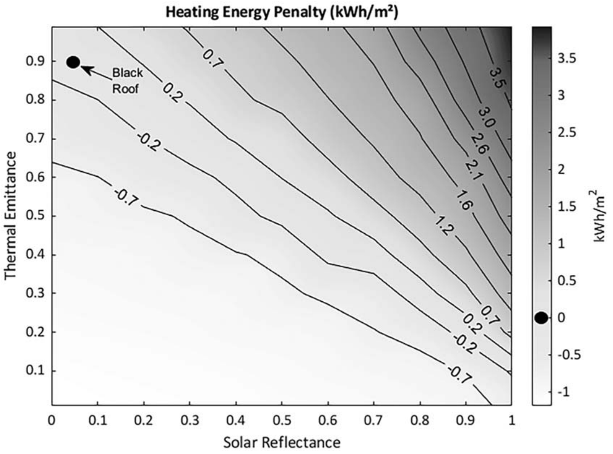


Fig. 7 Effect of solar reflectance and thermal emittance on annual heating energy penalty with respect to baseline black roof (SR = 0.05, TE = 0.9) for Phoenix, AZ

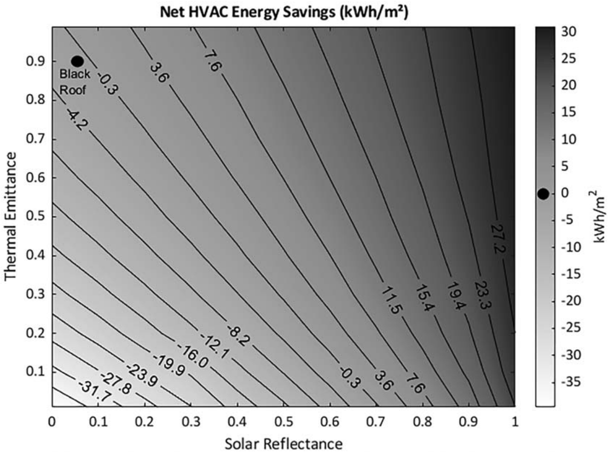


Fig. 8 Effect of solar reflectance and thermal emittance on net annual savings in HVAC energy with respect to baseline black roof (SR = 0.05, TE = 0.9) for Phoenix, AZ

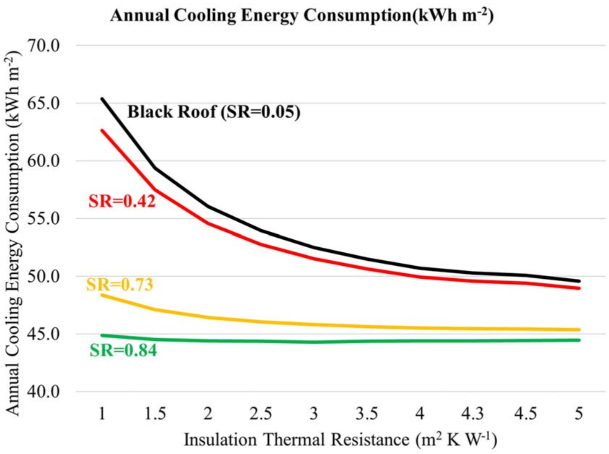


Fig. 9 Effect of insulation thermal resistance on annual cooling energy consumption for coatings of different solar reflectance (Phoenix, AZ)

strip-mall building situated in Phoenix, Arizona. The building has a packaged HVAC system with refrigerant-based cooling (COP-3.73) and natural gas furnace (efficiency 80%) based heating. ANSI/ASHRAE/IES Standard 90.1 and IECC C402.1.3 mandate a minimum roof *R*-value of 4.4 $\mathrm{m^2\ K\ W^{-1}}$ (25 $\mathrm{ft^2}$ °F h $\mathrm{Btu^{-1}}$) in buildings in climate zone 2 (Phoenix). This can have a significant impact on the energy savings that can be realized with the use of reflective coatings.

Figures 9 and 10, respectively, show the annual cooling energy consumption and corresponding percentage savings in cooling energy achieved by employing coatings of varying solar reflectance. The following observations can be made after examining Figs. 9 and 10:

(1) With an increase in the solar reflectance value of the coating, the dependence of cooling energy on the insulation thermal resistance of roof decreases. In an ideal situation with a perfect cool roof having a solar reflectance of 1, the graph would exhibit a horizontal trend i.e., cooling energy consumption would remain the same regardless of insulation.
(2) For a black roof, there is a significant decrease in cooling energy consumption with an increase in insulation thermal resistance, and this reduction occurs at the highest rate

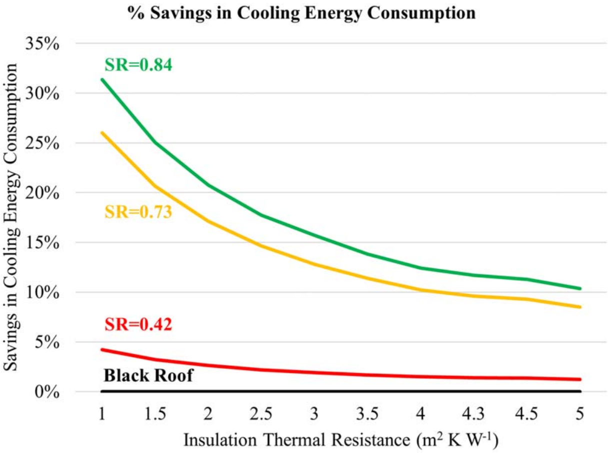


Fig. 10 Effect of insulation thermal resistance on % savings in annual cooling energy for coatings of different solar reflectance (Phoenix, AZ)

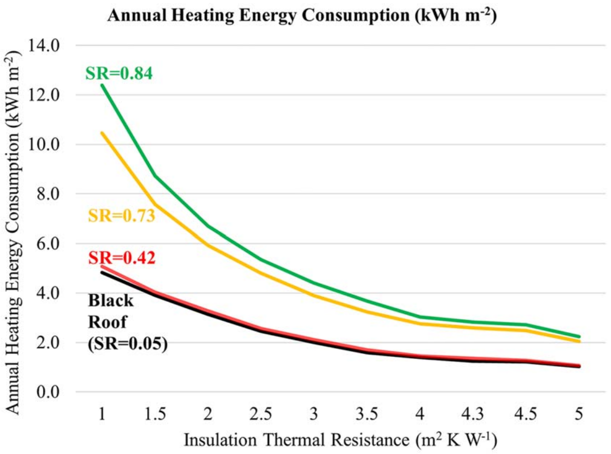


Fig. 11 Effect of insulation thermal resistance on annual heating energy consumption for coatings of different solar reflectance (Phoenix, AZ)

when compared to other coatings. However, as depicted in Fig. 9, with higher solar reflectance values of the coating, the rate of decrease in cooling energy diminishes, as indicated by the lesser slope of the line graph.

(3) All plotted line graphs for the reflective coatings converge with respect to the black roof. This convergence suggests that poorly insulated buildings can realize substantial energy savings through the application of coatings. For instance, a coating with a solar reflectance of 0.84 can result in approximately 30% reduction in cooling energy when the insulation thermal resistance of the roof is 1 m^2 K W^{-1}, compared to only 10% reduction in cooling energy when the insulation resistance is 5 m^2 K W^{-1}.

(4) There exists a threshold value of insulation thermal resistance beyond which further increases have minimal impact on cooling energy reduction. Consequently, the savings derived from reflective roof coatings remain relatively constant beyond this point.

Similarly, Fig.11 illustrates the annual heating energy variations across different coatings applied to a strip-mall building in Phoenix, Arizona. The pattern observed in the annual cooling energy consumption plot in Fig. 9 and the trends shown in Fig. 11 about the effect of insulation thermal resistance on building heating energy consumption are similar. Higher solar reflectance coatings have a significant negative impact on heating energy consumption at lower insulation values. Plots converge toward the black roof as insulation levels rise, suggesting a decline in the heating penalty. However, it is worth noting that the magnitude of the heating penalty is relatively small compared to the savings achieved in cooling energy. For instance, considering a coating with a solar reflectance of 0.84 and an insulation thermal resistance of 1 m^2 K W^{-1}, the heating penalty as compared to the black roof is approximately 7 kWh m^{-2}, while the savings due to reduction in cooling energy compared to the black roof are around 20 kWh m^{-2}. This results in overall savings of around 13 kWh m^{-2} under those conditions.

4 Conclusion

This study highlights the significant energy-saving benefits of high-reflective roof coatings in buildings located in cooling-dominated climates. Using EnergyPlus, net energy savings from roof coatings were compared in four different climates: Phoenix, Houston, Los Angeles, and Miami.

The roof coatings' potential to mitigate the urban heat island effect was also examined, emphasizing their ability to reduce roof temperatures, a key factor in energy savings. Higher values of solar reflectance and thermal emittance were found to be desirable, with high solar reflectance being particularly impactful in lowering roof temperatures. For example, in Phoenix, a reflective coating with 86% solar reflectance can reduce roof surface temperatures to near ambient levels during peak daytime, compared to around 100 °C (212 °F) with a black roof with 5% solar reflectance. Similarly, a high thermal emittance roof can lower roof temperatures significantly compared to over 60 °C (140 °F) with a roof with 0.1 thermal emittance. The temperature variation with different thermal emittance values is narrower compared to temperature variations with solar reflectance values, indicating that high solar reflectance is more influential in lowering roof temperatures.

Contour plots showed that higher solar reflectance and thermal emittance values reduce cooling requirements with negligible heating penalties in cooling-dominated climates like Phoenix. A coating with 86% solar reflectance and 90% thermal emittance could save approximately 25.5 kWh m^{-2} of HVAC energy in Phoenix, equivalent to about 23% savings. Maximum savings of over 31 kWh m^{-2} (28.7%) can be achieved with solar reflectance and thermal emittance values close to 1.

Finally, the impact of insulation thermal resistance on annual HVAC energy consumption at various solar reflectance values was discussed. In Phoenix, newly constructed buildings with at least 5 m^2 K W^{-1} insulation thermal resistance can achieve 10% savings with an 84% reflective coating, while up to 30% savings are possible with 1 m^2 K W^{-1} insulation. Reflective coatings are especially beneficial and cost-effective for older buildings with deteriorated insulation.

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

Data provided by a third party listed in Acknowledgment.

Nomenclature

Btu = British thermal unit
COP = coefficient of performance
DOE = Department of Energy
HVAC = heating, ventilation, and air conditioning
ORNL = Oak Ridge National Laboratory
SR = solar reflectance
TE = thermal emittance
TMY = typical meteorological year

References

[1] Yu, C., and Hien, W. N., 2006, "Thermal Benefits of City Parks," Energy Build., **38**(2), pp. 105–120.
[2] Wong, N. H., Jusuf, S. K., Syafii, N. I., Chen, Y., Hajadi, N., Sathyanarayanan, H., and Manickavasagam, Y. V., 2011, "Evaluation of the Impact of the Surrounding Urban Morphology on Building Energy Consumption," Sol. Energy, **85**(1), pp. 57–71.
[3] Konopacki, S., Gartland, L., Akbari, H., and Rainer, L., 1998, Demonstration of Energy Savings of Cool Roofs, https://www.osti.gov/biblio/296885.
[4] Synnefa, A., Santamouris, M., and Livada, I., 2006, "A Study of the Thermal Performance of Reflective Coatings for the Urban Environment," Sol. Energy, **80**(8), pp. 968–981.
[5] Nahar, N., Sharma, P., and Purohit, M., 2003, "Performance of Different Passive Techniques for Cooling of Buildings in Arid Regions," Build. Environ., **38**(1), pp. 109–116.

[6] Energy Information Administration, 2018, “2018 Commercial Buildings Energy Consumption Survey—Consumption and Expenditures Highlights,” https://www.eia.gov/consumption/commercial/

[7] International Energy Agency, 2018, “The Future of Cooling: Opportunities for Energy Efficient Air Conditioning,” https://iea.blob.core.windows.net/assets/0bb45525-277f-4c9c-8d0c-9c0cb5e7d525/The_Future_of_Cooling.pdf

[8] Testa, J., and Krarti, M., 2017, “A Review of Benefits and Limitations of Static and Switchable Cool Roof Systems,” Renewable Sustainable Energy Rev., **77**, pp. 451–460.

[9] Cheung, C. K., Fuller, R. J., and Luther, M. B., 2005, “Energy-Efficient Envelope Design for High-Rise Apartments,” Energy Build., **37**(1), pp. 37–48.

[10] Miller, W. B., Akbari, H., Levinson, R., Loye, K. T., Kriner, S., Scichili, R. G., Desjarlais, A. O., Weil, S., and Berdahl, P., 2004, “Special Infrared Reflective Pigments Make a Dark Roof Reflect Almost Like a White Roof,” Thermal Performance of the Exterior Envelopes of Buildings, IX, Proceedings of ASHRAE THERM VIII, Clearwater, FL, Dec.

[11] Santamouris, M., Haddad, S., Saliari, M., Vasilakopoulou, K., Synnefa, A., Paolini, R., Ulpiani, G., Garshasbi, S., and Fiorito, F., 2018, “On the Energy Impact of Urban Heat Island in Sydney: Climate and Energy Potential of Mitigation Technologies,” Energy Build., **166**, pp. 154–164.

[12] Kolokotsa, D., Maravelaki-Kalaitzaki, P., Papantoniou, S., Vangeloglou, E., Saliari, M., Karlessi, T., and Santamouris, M., 2012, “Development and Analysis of Mineral Based Coatings for Buildings and Urban Structures,” Sol. Energy, **86**(5), pp. 1648–1659.

[13] Zinzi, M., and Fasano, G., 2009, “Properties and Performance of Advanced Reflective Paints to Reduce the Cooling Loads in Buildings and Mitigate the Heat Island Effect in Urban Areas,” Int. J. Sustainable Energy, **28**(1–3), pp. 123–139.

[14] Berdahl, P., and Bretz, S. E., 1997, “Preliminary Survey of the Solar Reflectance of Cool Roofing Materials,” Energy Build., **25**(2), pp. 149–158.

[15] Hu, J., and Yu, X. B., 2019, “Adaptive Thermochromic Roof System: Assessment of Performance Under Different Climates,” Energy Build., **192**, pp. 1–14.

[16] Rawat, M., and Singh, R. N., 2021, “Performance Evaluation of a Cool Roof Model in Composite Climate,” Mater. Today: Proc., **44**, pp. 4956–4960.

[17] U.S. Department of Energy, “Commercial Reference Buildings,” https://www.energy.gov/eere/buildings/commercial-reference-buildings.

[18] Oak Ridge National Laboratory, “Cool Roof Calculator (Version 1.2),” https://web.ornl.gov/sci/buildings/tools/cool-roof/.

[19] Raman, A., Anoma, M., Zhu, L., Rephaeli, E., and Fan, S., 2014, “Passive Radiative Cooling Below Ambient air Temperature Under Direct Sunlight,” Nature, **515**(7528), pp. 540–544.

[20] Mandal, J., Fu, Y., Overvig, A. C., Jia, M., Sun, K., Shi, N. N., Zhou, H., Xiao, X., Yu, N., and Yang, Y., 2018, “Hierarchically Porous Polymer Coatings for Highly Efficient Passive Daytime Radiative Cooling,” Science, **362**(6412), pp. 315–319.

[21] Zhai, Y., Ma, Y., David, S. N., Zhao, D., Lou, R., Tan, G., Yang, R., and Yin, X., 2017, “Scalable-Manufactured Randomized Glass-Polymer Hybrid Metamaterial for Daytime Radiative Cooling,” Science, **355**(6329), pp. 1062–1066.

[22] Hollick, J., 2012, “Nocturnal Radiation Cooling Tests,” Energy Procedia, **30**, pp. 930–936.