ASME Journal of Engineering for Sustainable Buildings and Cities
Online journal at:
https://asmedigitalcollection.asme.org/sustainablebuildings

Energy Impact of Radiative Cooling Paints in Warehouses Under Various United States Climates

Emily Barber
School of Mechanical Engineering,
Purdue University,
West Lafayette, IN 47906
e-mail: barber57@purdue.edu

Ravi Anant Kishore
National Laboratory of the Rockies,
Golden, CO 80401
e-mail: ravi.kishore@nrel.gov

Marcus V. A. Bianchi
National Laboratory of the Rockies,
Golden, CO 80401
e-mail: marcus.bianchi@nrel.gov

Travis Horton[1]
School of Mechanical Engineering;
School of Civil Engineering,
Purdue University,
West Lafayette, IN 47906
e-mail: wthorton@purdue.edu

Xiulin Ruan[1]
School of Mechanical Engineering;
Birck Nanotechnology Center,
Purdue University,
West Lafayette, IN 47906
e-mail: ruan@purdue.edu

Although radiative cooling research is widely found in the literature, no comprehensive study has yet been conducted on the impact of novel radiant cooling (>0.91 reflectance) on the energy efficiency of warehouses. In this work, we develop three building models based on a Department of Energy prototype warehouse model using TRNSYS, representing a typical warehouse with a black roof, a typical warehouse with a white roof, and a warehouse with novel radiative cooling (RC) paint on its roof. These models are run for 15 different cities, each representative of a different ASHRAE climate zone, to better understand the impact of RC in many different climates. It was found that an RC-coated roof in a warehouse could reduce the building's annual heating, ventilation, and air conditioning (HVAC) loads by up to 14.11 kWh/m^2 of the roof area compared to a black roof, resulting in a maximum reduction in energy costs of 0.55 \$/m^2 or \$2646/year for a large 4835 m^2 warehouse. Similarly, replacing the typical white roof coating with an RC coating could reduce the warehouse's energy consumption by up to 8.17 kWh/ m^2 of roof area, thus reducing energy costs by as much as 0.29 \$/m^2 or \$1386/year for a 4835 m^2 warehouse. In addition, applying RC paint to an unconditioned warehouse could reduce the building's ASHRAE Standard 55 indoor temperature exceedance by up to 1330 h/year compared to a black roof and up to 532 h/year compared to a white roof. [DOI: 10.1115/1.4070748]

Keywords: warehouse, energy efficiency, black roof, white roof, radiative cooling, energy savings, cost savings, TRNSYS, temperature exceedance, occupant comfort, air conditioning, building, clean energy, demand side management, environment, heat transfer, materials, net-zero energy, radiation, resilient buildings, resilient systems, simulation, smart materials, sustainability, testing, thermal comfort, thermodynamics

Introduction

Warehouse and storage buildings in the United States consumed 528 trillion BTUs of site energy in 2018, or about 8% of the electricity consumed by commercial buildings that year [1]. In addition, the 2018 U.S. Energy Information Administration (EIA) Commercial Buildings Energy Consumption Survey reports that warehouses are the most common commercial building in the US, that over 40% of warehouses in the country are found in warm or hot climates, and that only 36% of warehouses surveyed have cool roof technologies [1]. Therefore, energy reduction in warehouses could significantly contribute to overall building energy efficiency. Numerous approaches to reducing energy use in warehouses can be found in the literature. Techniques include automating energy/workflow systems in warehouses [2,3], integrating renewable energy [4,5], and focusing on efficient warehouse layout [6,7]. However, these are not options for all warehouses, as cost is a major factor for many owners [4] and would hinder all these options to some degree.

One of the more recent developments in improving the energy efficiency of buildings is the use of radiative cooling (RC) coatings, which can significantly reduce the surface temperature of the building envelope, even below the ambient temperature, without any external energy input. RC technologies generate cooling in two ways: first, they have an ultra-high reflectance, often over 90% in the solar spectrum (0.3–2.5 μm), and second, they have a high emittance in the mid-infrared range, especially in the atmospheric window (8–13 μm). With these two components, RC technologies reflect a significant portion of solar heat gains and emit a large amount of heat into deep space, lowering the external surface temperature of the building and thus reducing the heating, ventilation, and air conditioning (HVAC) energy consumption, more specifically the cooling loads of the buildings [8,9].

Radiative cooling technologies have made significant advances in recent years that have enabled their consideration in the global climate discussion. Some technologies involve multi-layered and/or complex structures [10–14]; others focus on large-scale applications with easy-to-apply coatings [15–19]. With the development

[1]Corresponding authors.

Manuscript received August 11, 2025; final manuscript received December 18, 2025; published online January 28, 2026. Assoc. Editor: Zheng O'Neill.

of these technologies, up to 46% of cooling electricity savings in warm, marine climates (ASHRAE climate zone 3C) are possible in residential homes [20], and up to 301 kg/665 lbs of CO_2eq can be avoided per square meter of paint applied [9]. Beyond these studies, extensive work has already been done to understand the potential energy savings from using RC technology in buildings. Tzempelikos and Lee [21] investigated the energy saving potential of RC paints in big box retail stores, offices, and school buildings in the US and found up to \$0.48/m^2, \$0.70/m^2, and \$0.66/m^2 annual savings potential, respectively. A study of residential buildings found a 15.8–31.2% reduction in cooling energy consumption for five climate zones in China for a paint with an emittance of 0.87 and a reflectance of 0.92 [22]. Another study of residential buildings showed 30% cooling energy savings for El Paso, TX, with overall energy savings of 7.8%, assuming a solar reflectance of 0.9 [23]. A similar report based on a case study showed a simulated annual energy reduction of 45% for a building in Catania, Italy [24]. Other studies have completed life-cycle analyses, with one study showcasing a potential ~22,000 kg CO_2eq reduction over a 20-year period for a house in Brazil [8]. Other studies have focused on case studies, demonstrating a 0.85 correlation value between predicted and observed energy savings, confirming the relevance of modeling efforts for RC technologies [25].

Most previous studies on radiative coatings in the literature focus on residential or commercial buildings, and there is very little research that focuses specifically on RC applications for warehouses. Due to their large roof area, specific temperature requirements, and widespread use in industry, warehouses are a promising application site for RC technologies, so it is important to investigate their impact on an industrial scale. The impact of radiative cooling on warehouses in climates like the Guangxi province of China was investigated by Wang et al. [26], who showed energy savings of 21.2–65.2% using a 0.92 reflectance and 0.91 mid-infrared (MIR) emittance radiative cooling paint. Another study by Xu et al. [27] investigated the potential of RC for passive cooling of grain storage warehouses across seven climates across China's ecological zones and found a reduction in surface temperature of up to 9.9 °C for a 0.91 reflectance and 0.93 MIR emittance coating. A similar study by Seifhashem et al. [28] reported on the potential impact of RC technology on warehouses in Australia with a reflectance of 0.875 and emittance of 0.9 and found a maximum savings of 8.4 kWh/m^2/year. These prior studies demonstrated the significant benefits of RC paints or coatings for the energy efficiency of warehouses. However, as radiative cooling technology is rapidly advancing and becoming more effective, versatile, and cost-effective, large-scale simulations for warehouses in different regions and climates with novel RC technologies (>0.91 reflectance) are crucial.

In this work, a one-story warehouse model was developed in TRNSYS to build on the previous research and successfully create and analyze the effects of $BaSO_4$-based RC paints on energy consumption in warehouses. The key objectives of this research include: (1) formulating building energy models for warehouses using TRNSYS and incorporating methods to evaluate the radiative properties of RC paints and their impact on energy consumption; (2) conducting building energy simulations under 15 different U.S. climates to understand the impact of RC paints on energy consumption; (3) conducting a preliminary cost savings analysis using total annual energy savings and a representative electricity rate to determine both the technical as well as the financial viability of RC technology for warehouse applications; (4) understanding the potential benefits of maintaining indoor comfort temperature in a non-conditioned warehouse through the use of RC technology to the roof; and (5) comparing the impact of RC on energy usage in a warehouse versus a residential building. For this purpose, the weather of a representative city from each of the 15 climates was input into the TRNSYS building modeling software as well as three representative warehouse models (typical black, typical white, and $BaSO_4$ RC roofs). The total thermal energy demand corresponding to the warehouse HVAC operation was output, along with a measure of heat stress reduction and the potential energy savings for building owners.

Methods

Building Model. To simulate the thermal performance of different buildings, the developed building models were entered and executed in TRNSYS, a building simulation program developed by the Thermal Energy System Specialists and the University of Wisconsin Solar Energy Laboratory [29]. While models such as ENERGYPLUS are more widely used in the recent literature, TRNSYS allows for easy implementation of the variable emissivity that allows RC paints to function, therefore it was used for this work.

The TRNSYS model was built utilizing Department of Energy (DOE) Post-1980 v1.4 prototypes for Warehouses [30], originally built for ENERGYPLUS but placed into TRNSYS using SketchUp and details from the ENERGYPLUS model. The warehouse models considered in this study consist of single-story buildings with a large open zone with two windows and a flat roof, as shown in Fig. 1. The buildings have a floor area of 4835 m^2 and a ceiling height of 9.1 m. The envelope-related parameters of this building are listed in Table 1. According to the EIA, 33.6% of warehouses are space conditioned, and 66.4% are not [1]. We therefore consider both cases in this work. The space-conditioned building has a fixed setpoint of 7.2 °C for heating and 25 °C for cooling, considering past literature cooling setpoints in the range of 20–25 °C, with no heating setpoints considered in Refs. [26–28]. In this case, we add a very small heating setpoint to account for a realistic minimum temperature, which is often enforced by staff using individual space heaters or packaged heating units [1]. We added significant thermal mass to the simulation as well to account for storage within the warehouse. To understand how much thermal mass to add, we took the original thermal mass, calculated as capacitance by TRNSYS to be 52,815 kJ/K, and added that to the capacitance of grain filling 60% of the warehouse with a density of 750 kg/m^3 and a specific heat of 1.3 kJ/kg/K. Therefore, the total capacitance of all the modeled buildings was set to 2.57×10^7 kJ/K.

It was assumed that there were no buildings in the surrounding area, so no urban effects on wind patterns or air temperatures were considered. Additionally, a high view factor of 1 was assumed for the roofs of the warehouses due to their large footprint,

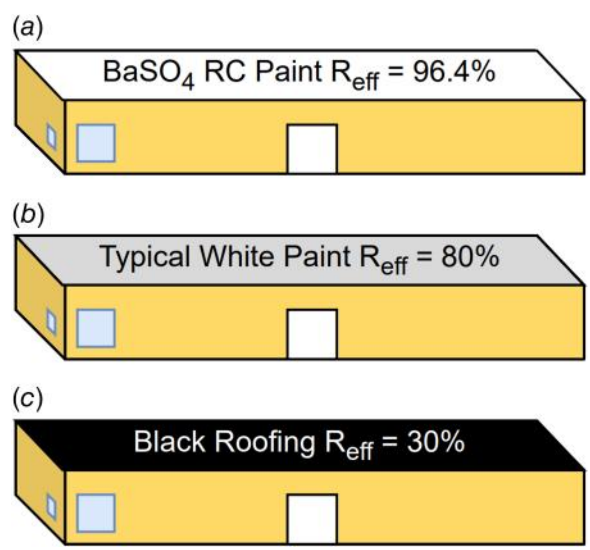

Fig. 1 The models for the three warehouse buildings used in the study: (*a*) the roof with radiative coating, (*b*) the roof with white paint, and (*c*) the roof with black paint

Table 1 Envelope components, key geometrical parameters, and surface properties of the warehouse buildings

Parameter	Value	Unit
Conditioned floor area	4835	m^2
Building volume	44,001	m^3
Wall area	2735.46	m^2
Total window area	30.4	m^2
Roof area	4835	m^2
Roof thermal resistance	See Table 2	m^2-K/W
Wall thermal resistance	See Table 2	m^2-K/W
Floor thermal resistance	3.39	m^2-K/W
Roof thermal emissivity (RC/white/black)	Variable/0.9/0.9	—
Wall emissivity	0.9	—
Roof solar absorptance (RC/white/black)	0.036/0.2/0.7	—
Wall absorptance	0.5	—

height, and lack of self-shading, while a 0.5 view factor was assumed for the walls. A large overhead door was also added, as these doors are often found in warehouses to optimize the fast loading and unloading of a large amount of material. The door was added to the TRNBuild type as a variable air infiltration rate, which is considered "on" (0.565 air changes per hour) when the door is open during working hours (08:00 a.m.–06:00 p.m.) and "off" when the door is closed during the night with negligible infiltration.

Effective Properties of Radiative Coatings. Three different building models were created with roofs coated with black, white, and RC paint, respectively, with the reflectance and emittance of the roof varying depending on the type of paint. The black roof case is included to demonstrate the highest possible effect compared to the RC paint, while the white roof case is included as a more common solution for energy-conscious warehouse roofs.

The black roof has a solar reflectance of 30% and a thermal emittance of 0.9, while the white roof has a solar reflectance of 80% and a thermal emittance of 0.9. The RC roof has a reflectance of 96.4% (assuming $BaSO_4$-based RC paint, as demonstrated by Li et al. [16]) and a spectrally variable emittance, which was determined experimentally in the study [16].

To calculate the heat balance on the roof surfaces, we use the method adapted from Ref. [20]. We start with a basic heat balance equation

$$q''_{conv} + q''_{cond} + q''_{rad} = 0. \quad (1)$$

The conduction and convection heat flux terms (q''_{cond} and q''_{conv}) are calculated in TRNSYS Type 56 (multizone building model) using the outdoor temperature and wind speed data from the TMY3 data and the thermal conductivity values in Table 1. However, the radiation heat flux term (q''_{rad}) must be treated separately, as TRNSYS does not account for spectral variations in emittance. For the control cases (black and white paints), this is not a major issue, due to the low spectral variance in the radiative properties of these materials. For RC, however, the variable reflectance and emittance values require that we modify the standard TRNSYS equations to accurately capture the effects of the RC paint. Following the steps in Ref. [20], the amount of thermal radiation leaving a surface (P_{LWR}) is given by

$$P_{LWR}(T_s) = \int_0^{\pi/2}\int_0^{\infty} 2\pi \sin(\theta)\cos(\theta) I_{bb}(Ts, \lambda)\varepsilon_S(\lambda, \theta)d\lambda d\theta \quad (2)$$

where Ts is the surface temperature, ε_S is the emittance of the surface, and I_{bb} is the black body spectral emittance, calculated as follows:

$$I_{bb} = \frac{2\hbar c_0^2}{\lambda^5\left[\exp\left(\frac{\hbar c_0}{\lambda T k_B}\right) - 1\right]} \quad (3)$$

where ħ is Plank's constant, c_0 is the speed of light in a vacuum, and k_B is Boltzmann's constant.

The amount of thermal irradiation absorbed by the surface from the atmosphere (P_{atm}) is

$$P_{atm}(T_{amb}, PW) = \int_0^{\pi/2}\int_0^{\infty} 2\pi \sin(\theta)\cos(\theta) I_{bb}(T_{amb}, \lambda)\varepsilon_S(\lambda, \theta)\varepsilon_{atm}(\lambda, \theta, PW)d\lambda d\theta \quad (4)$$

and the amount of absorbed power due to solar irradiation (P_{solar}) is

$$P_{solar}(PW) = \int_0^{\infty} I_{solar}(\lambda, PW)\varepsilon_S(\lambda)d\lambda \quad (5)$$

where T_{amb} is the ambient temperature, ε_{atm} is the atmospheric emittance, PW is the precipitable water, and I_{solar} is the solar intensity. These are used to find the net radiation leaving the surface (P_{rad})

$$P_{rad} = \beta[P_{LWR}(T_S) - P_{atm}(T_{amb}, PW)] - P_{solar}(PW) \quad (6)$$

where β is the sky clearness factor provided by the TMY3 data. Reference [20] contains more detailed information on these equations, but the general framework shown above represents the methodology for calculating the net radiation balance on the RC cooling systems.

Simulation Details. To better understand the potential of RC paints, the impact within multiple climates must be investigated. Here, we conduct a year-long simulation for the three building cases (black-, white-, RC-coated roof) for 15 cities, each of which is representative of an ASHRAE climate zone (see Table 2). The weather data sets for these cities were obtained as TMY3 files from the U.S. Department of Energy's ENERGYPLUS Weather Data files [31]. For the simulations that include space conditioning, the thermal loads for all three cases are output from the

Table 2 Climate zone-specific values

Climate zone	Representative city	Wall *R*-value (m^2-K/W)	Roof *R*-value (m^2-K/W)	COP
1A	Miami, FL	0.25	2.38	4.06
2A	Houston, TX	1.01	2.64	4.37
2B	Phoenix, AZ	0.56	3.80	4.12
3A	Atlanta, GA	1.19	2.42	4.82
3B	Las Vegas, NV	0.93	3.64	4.49
3C	San Francisco, CA	1.19	1.99	5.14
4A	Baltimore, MD	1.80	3.00	5.19
4B	Albuquerque, NM	1.60	2.97	5.17
4C	Seattle, WA	1.74	2.72	5.51
5A	Chicago, IL	1.98	3.36	5.44
5B	Boulder, CO	1.98	3.47	5.57
6A	Minneapolis, MN	2.54	5.35	5.68
6B	Helena, MT	2.27	3.62	5.78
7A	Duluth, MN	2.87	4.37	6.03
8A	Fairbanks, AK	3.75	5.71	6.76

Note: The *R*-values of the buildings for each climate zone are obtained from the DOE Post-1980 v1.4 prototype warehouse models [30], and the individual layers from each model are input into TRNSYS, which then automatically calculates the *u*-value.

Table 3 The electricity and natural gas prices used for each of the 15 representative cities, obtained from the Feb. 2024 U.S. Energy Information Administration data [34,35]

Climate zone	Electricity price (cents/kWh)	Natural gas price ($/thousand cubic ft)
1A	15.28	20.79
2A	14.31	13.53
2B	14.46	19.76
3A	12.95	14.09
3B	16.69	19.61
3C	31.23	20.43
4A	17.60	15.20
4B	14.14	8.85
4C	11.40	15.45
5A	15.72	10.55
5B	14.47	9.75
6A	14.36	11.85
6B	11.96	7.74
7A	14.36	11.85
8A	22.88	11.00

TRNBuild file for these simulations, and the changes in load and costs are then calculated. To complete this, the coefficient of performance (COP) was calculated for each climate zone by first taking the average temperature of each of the 15 representative cities for Feb. 2024–Jan. 2025 from NOAA [32]. Then, assuming a COP of 3 at 37 °C, Fig. 18 in Ref. [33] is used to give an average COP based on the city's average temperature. The final COP values can be found in Table 2. To calculate the cost changes, the average prices for electricity and natural gas in Feb. 2024 were obtained for each U.S. state, and then applied to each modeled city, with the city assigned to the state in which it is located [34,35]. These average costs can be found in Table 3.

These cost reductions associated with HVAC do not apply to the warehouses without space conditioning. To understand the impact of RC, we therefore use two separate metrics. First, we calculate the average annual indoor temperatures and compare them in all three cases (black, white, and RC). Then, to understand how these differences may affect the operational efficiency of the warehouse, we consider the indoor temperatures compared to ASHRAE Standard 55 limits for heat exposure [36]. These limits require a temperature and humidity input—however, since indoor humidity is the same as the outdoor humidity for these non-conditioned simulations, we use the average humidities in each type of climate. For climate type A (humid), we assume 60% relative humidity (RH), for climate type B (dry), we assume 40% RH, and for climate type C (marine), we assume a 75% RH. Using Fig. 5.3.1.1A in ASHRAE 55, we can determine a maximum temperature of 24.8 °C for climate type A, 25.4 °C for climate type B, and 24.3 °C for climate type C [36]. These thresholds are then compared to the hourly indoor temperature for each warehouse, and the number of times these thresholds are exceeded is recorded.

Results and Discussion

This section discusses the results and observations of this study, which is divided into four distinct stages: (1) First, we use a numerical model to determine the cooling and heating energy use in warehouses with black, white, and RC roofs. We then compare different cases and calculate the energy savings potential of RC coatings in warehouses compared to black and white paints; (2) Using a representative energy price rate, we calculate the corresponding impact on HVAC energy costs and the associated energy cost savings under different climates; (3) We consider unconditioned warehouses that have no HVAC system to regulate indoor temperature and determine the impact of different roof coatings on occupant comfort; (4) Lastly, we compare our results with a similar past study from the literature, particularly focused on residential buildings [9].

To determine the energy savings due to RC coatings, we must first know the thermal load of the warehouse buildings. In our TRNSYS model, the building's thermal load was calculated by taking the "QCOOL" and "QHEAT" outputs from the TRNBuild simulation. These outputs are based on the spectral properties of the building, solar irradiation, building temperatures, and ambient temperatures, and consider the radiative, conductive, and convective heat fluxes for the building, infiltration rates, internal loads (which are assumed to be low), and solar gains through the windows.

The resulting thermal loads are shown in Fig. 2, in terms of kilowatt-hour of annual thermal energy (or the sum of heating and cooling needs in kilowatt-hour) per square meter of floor area so that extrapolation to other building sizes is straightforward. Figure 2(*a*) shows the cooling loads for the black, white, and RC cases, while Fig. 2(*b*) shows the heating loads for the same cases. It is worth noting that the cooling demand is only observed in 12 of the 15 climate zones, and heating demand is only observed in 10 of the 15 climate zones (with 4C having very low loads for both). Typically, the maximum outdoor temperature in the moderate climates, such as San Francisco, CA (3C) and Seattle, WA (4C), and the cold climates like Duluth, MN (7A) and Fairbanks, AK (8A), remains below the cooling setpoint (25 °C) considered in this study, resulting in a negligible cooling load. Similarly, the minimum outdoor temperature in the moderate or hot climates, such as San Francisco, CA (3C) and Seattle, WA (4C), Las Vegas, NV (3B), Atlanta, GA (3A), Phoenix, AZ (2B), Houston, TX (2A), and Miami, FL (1A), remains above the heating setpoint (7.2 °C) considered in this study, resulting in a negligible heating load.

The percentage reduction in the building's annual heating and cooling energy between the black roof case and the RC case can be seen in Fig. 2(*c*). As mentioned previously, adding RC to a black roof is practically the "best case" for the implementation of RC coatings. While the high percentage reduction in cooling load is seen in mild climates like Baltimore, MD (4A) with an annual cooling energy reduction of 100% and Albuquerque, NM (4B) with annual cooling energy reduction of 97%, the real maximum cooling energy reduction is noted in hot climates like Phoenix, AZ (2B) with annual energy reduction of 14.11 kWh/m^2 (25%) and Miami, FL (1A) with an annual cooling energy reduction of 11.93 kWh/m^2 (22%). These percentages were calculated using a simple ratio as shown in Eq. (7)

$$\frac{\sum \text{Black roof energy needs} - \sum \text{RC roof energy needs}}{\sum \text{Black roof energy needs}} \tag{7}$$

There are some heating energy penalties when black paint is replaced with RC paint, which is to be expected since RC coatings have higher solar reflectance than black paint, resulting in a reduction in solar heat absorbed by the roof. While all climates with heating show some increase in the annual heating energy, the maximum penalty of 2.85 kWh/m^2 (7%) was observed in Duluth, MN (7A), followed by a penalty of about 2.53 kWh/m^2 (7%) in Minneapolis, MN (6A).

Figure 2(*d*) shows the difference in the building's energy use for roofs coated with standard white paint and the selected RC paint, using Eq. (7) and exchanging the black roof values with white roof values. Again, the RC coating leads to a high reduction in annual cooling load reduction compared to white paint in hot climates, especially Phoenix, AZ (2B) with a reduction of 8.17 kWh/m^2 (16%) and Miami, FL (1A) with a reduction of 3.88 kWh/m^2 (8%). Also, under all climates, RC results in higher heating energy needs than white paint, sometimes leading to a penalty or negative energy reduction as shown in Fig. 2(*d*).

Table 4 shows the total annual thermal energy (in kilowatt-hour) for the three warehouse cases considered in this study. Overall, the impact of using RC in hot climates (1A–3B) is significant, with the

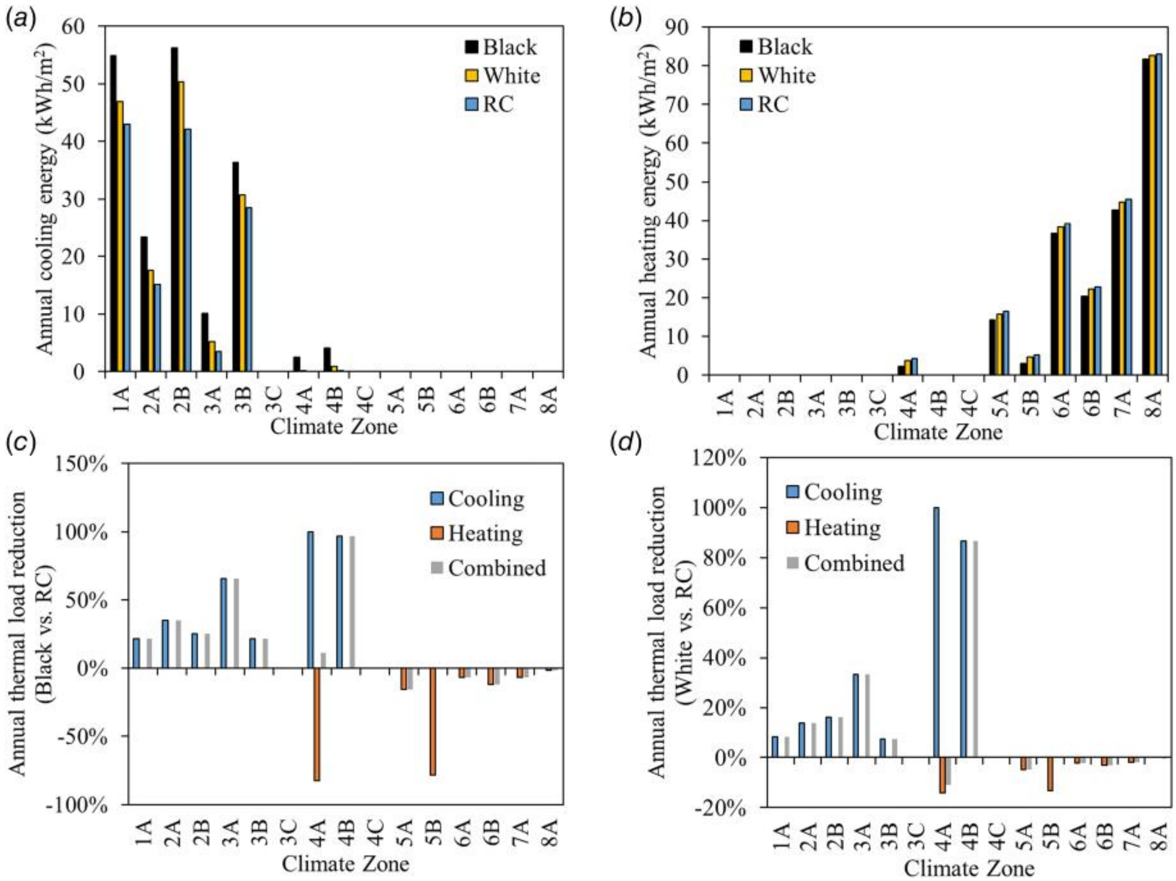

Fig. 2 The annual HVAC related thermal energy of the 15 representative cities for each climate zone: (*a*) the annual cooling thermal energy per unit area of the warehouse, (*b*) the annual heating thermal energy per unit floor area of the warehouse, (*c*) the percentage reduction in annual cooling and heating energy from black paint to RC paint, and (*d*) the percentage reduction in annual cooling and heating energy from white paint and RC paint

benefits of RC compared to black paint being greater than those of RC compared to white paint. Despite heating energy penalty in moderate to mild cold climates (3C–4C), there is an overall energy reduction or no change due to RC, compared to black and white paints. In extremely cold climates (5A–8A), however, there is an overall energy penalty due to lower solar heat absorbed by RC paint than black paint and white paint. In highly humid climates (zones 3C and 4C), we see minimal to no kilowatt-hour needs, due to the humidity damping the outdoor temperature fluctuation and keeping the outdoor temperature within the setpoint deadband for much of the year.

Table 4 Total annual thermal energy consumption, or the sum of heating and cooling needs in kWh, for the warehouses with roof coated with black, white, and RC paints

Climate zone and representative city		Total annual thermal energy (kWh)			Total annual reduction (kWh)	
		Black	White	RC	Black—RC	White—RC
1A	Miami, FL	265,636	226,716	207,941	57,696	18,776
2A	Houston, TX	112,959	85,047	73,226	39,733	11,821
2B	Phoenix, AZ	272,034	243,253	203,775	68,260	39,478
3A	Atlanta, GA	48,738	25,029	16,698	32,040	8331
3B	Las Vegas, NV	175,820	148,585	137,781	38,040	10,804
3C	San Francisco, CA	0	0	0	0	0
4A	Baltimore, MD	22,865	18,280	20,244	2621	−1964
4B	Albuquerque, NM	19,927	4630	626	19,301	4003
4C	Seattle, WA	0	0	0	0	0
5A	Chicago, IL	68,895	76,038	79,602	−10,708	−3564
5B	Boulder, CO	14,279	22,481	25,447	−11,168	−2967
6A	Minneapolis, MN	176,925	184,936	189,142	−12,217	−4206
6B	Helena, MT	98,241	106,985	110,126	−11,885	−3141
7A	Duluth, MN	206,153	216,025	219,935	−13,782	−3910
8A	Fairbanks, AK	394,615	399,864	401,690	−7076	−1827

Figure 3 shows the respective costs associated with the annual thermal energy shown in Fig. 2, converted from the thermal to electrical energy using a variable COP for cooling, as shown in Table 2. An efficiency of 0.92 for gas heating was used as a representation of a relatively efficient heating system [37], and an efficiency of 1 was used for electric heating, as electric resistance heating is widely known to be closest to 100% efficient. The cost rate is also shown for each climate zone in Table 3. Figure 3(*a*) shows the cooling energy costs for the black, white, and RC cases for each of the 15 climate zones, while Fig. 3(*b*) shows the heating energy costs for the same cases. Similar to the observations in Fig. 2, both cooling and heating demands are not observed in every climate zone, largely due to the large temperature difference for the dual setpoints combined with individual climate needs. For instance, in moderate climates with high humidity (i.e., San Francisco, CA (3C) and Seattle, WA (4C)), the outdoor temperature often remains within the setpoint deadband, resulting in minimal to no HVAC load throughout the year. Similarly, in very cold climates like Fairbanks, AK (8A) and Duluth, MN (7A), the temperature never rises above the predefined cooling setpoint, resulting in no cooling demand, much like how in very hot climates like Miami, FL (1A) and Houston, TX (2A), the heating demand is insignificant.

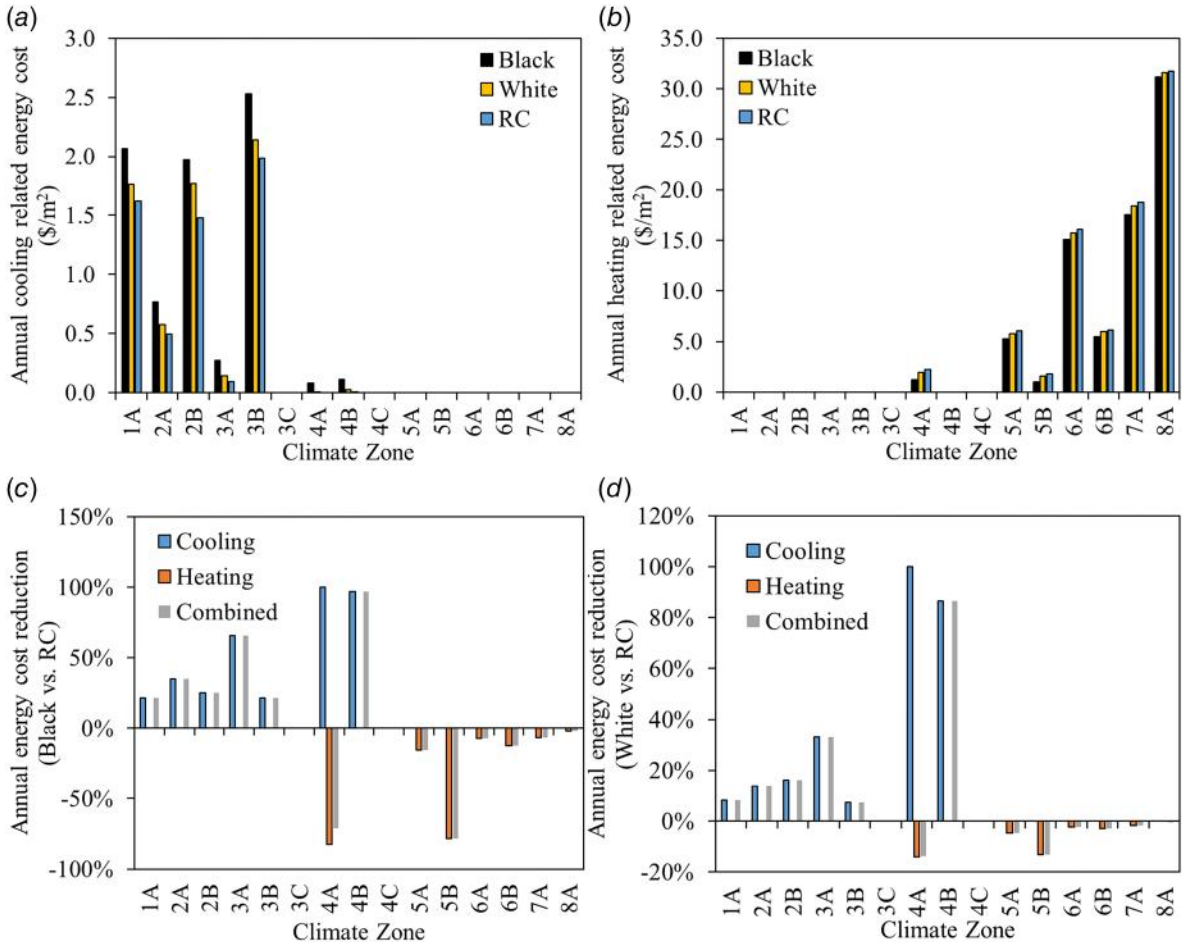

Fig. 3 The annual energy cost related to heating and cooling in the warehouses in the 15 representative cities for each climate zone: (*a*) the annual cooling related energy cost per unit floor area of the warehouse, (*b*) the annual heating related energy cost per unit area of the warehouse, (*c*) the percentage reduction in annual cooling and heating energy cost from black paint and RC paint, and (*d*) the percentage reduction in the annual cooling and heating energy cost from white paint and RC paint

The percentage reduction in the buildings' annual heating and cooling costs between the black roof case and the RC case can be seen in Fig. 3(*c*). While the high percentage reduction in the cooling energy costs can be observed to be in mild climates like Baltimore, MD (4A) with an annual cooling cost reduction of 100% and Albuquerque, NM (4B) with an annual cooling cost reduction of 97%, the true maximum cooling cost reduction is noted in hot, dry climates like Las Vegas, NV (3B) with an annual cost reduction of 0.55 $/m^2 (22%) and Phoenix, AZ (2B) with an annual cooling cost reduction of 0.49 $/m^2 (25%).

Regarding the heating energy costs, we again identify some penalties if black paint is replaced by RC paint. While all climates show higher annual heating energy cost due to RC over black paint, the maximum penalty of $1.17/m^2 (7%) was observed in Duluth, MN (7A), followed by a penalty of about $1.04/m^2 (7%).

Figure 3(*d*) shows the difference in the building's energy cost for roofs coated with standard white paint and RC paint. Again, RC coating results in a large reduction in annual cooling cost in hot climates, especially Phoenix, AZ (2B) with a reduction of $0.29/m^2 (25%) and Las Vegas, NV (3B) with a reduction of $0.16/m^2 (22%). Also, under all climates, RC results in a higher heating cost than white paint, leading to a cost penalty.

Overall, 6 out of 15 climate zones (1A–3B, 4B) save an average of 44% of total energy costs when switching from a black roof to an RC roof and an average of 28% of total energy costs when switching from a white to an RC roof. Additionally, two of the climate zones (3C and 4C) yield a negligible change when switching from black to RC, and seven climate zones (4A and 5A–8A) experience an average increase in overall HVAC costs (in Fig. 4(*b*), 8A has a small but non-zero impact). Consequently, RC paints on warehouses are beneficial in hot and warm climates and do not appear to be justifiable in cold climates.

In Table 5, the annual thermal energy consumptions from Table 4 are converted into the total annual energy costs for a warehouse in each of the 15 climate zones using a warehouse area of 4835 m^2 and the energy costs from Table 3. While the findings from this table are similar to those from Table 4, the cost of energy in each of these climates becomes clearer, making the results more intuitive and useful for building owners. The impact of using RC is significant in hot climates (1A–3B), with a maximum benefit of $2646/year in Las Vegas, NV (3B) when RC is compared to black paint and $1386/year in Phoenix, AZ (2B) when RC is compared to white paint. Notably, in some of the mild climates (4A–4B), while there was an overall reduction in total energy use, there was an increase in energy cost due to higher expenses for heating. In cold climates (5A–8A), there is an overall increase in total energy costs as expected due to higher energy use and energy price rate.

As mentioned in the Introduction, most warehouses in the United States are not space-conditioned. Therefore, a study based only on space-conditioned warehouses would provide an incomplete picture of the potential impact of RC technology. For non-

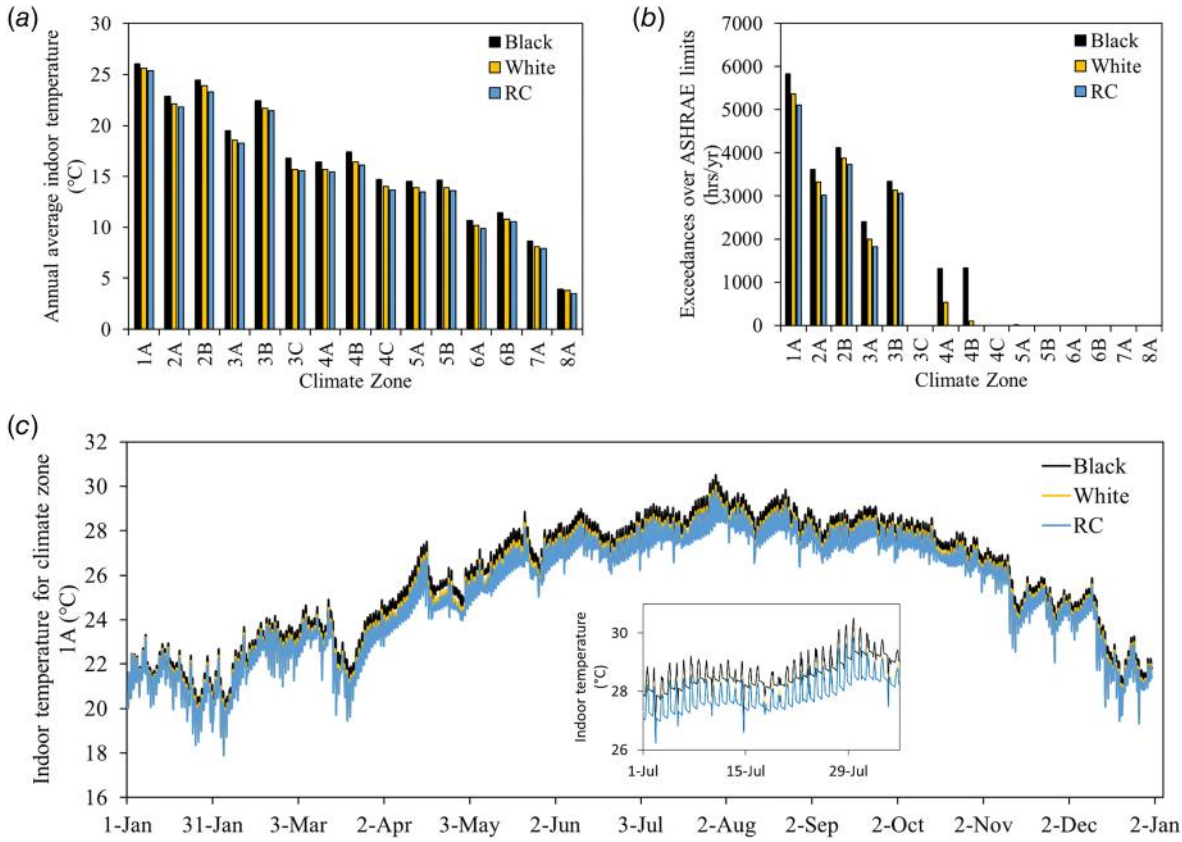

Fig. 4 The impact of RC roofs in the non-conditioned warehouses compared to black and white roofs, for the 15 climate zones: (*a*) annual average indoor temperature for all three cases for each climate, (*b*) amount of time in hours spent above the heat limits set by ASHRAE standard 55 throughout the year, and (*c*) the annual temperature for climate zone 1A, to show the consistent impact by RC paints

conditioned warehouses, we use average indoor temperature and time spent above ASHRAE Standard 55's thresholds as performance metrics. Since ASHRAE thresholds depend on both temperature and humidity, we use a temperature limit of 24.8 °C for humid climate zones A, 25.4 °C for dry climate zones B, and 24.3 °C for marine climate zones C. This variation in threshold temperatures is attributable to the higher heat capacity of humid air, which can lead to a higher perceived temperature for individuals.

In Fig. 4(*a*), we compare the annual average indoor temperatures of warehouses in the 15 climate zones for typical black, typical white, and RC cases. Figure 4(*b*) compares the number of hours that each of the three cases is above the threshold set by ASHRAE Standard 55 for the 15 climates during the simulated year.

The average indoor temperature steadily decreases as the climate zones become colder and more humid—this makes intuitive sense, as colder outdoor temperatures and no HVAC lead to colder indoor

Table 5 The annual HVAC energy costs for the entire warehouse buildings, and the differences in the energy costs between black and RC, and white and RC roof cases

Climate zone and representative city		Total annual thermal energy cost ($)			Total annual energy cost reduction ($)	
		Black	White	RC	Black—RC	White—RC
1A	Miami, FL	$9997	$8533	$7826	$2171	$707
2A	Houston, TX	$3699	$2785	$2398	$1301	$387
2B	Phoenix, AZ	$9548	$8537	$7152	$2396	$1386
3A	Atlanta, GA	$1309	$672	$449	$861	$224
3B	Las Vegas, NV	$12,229	$10,335	$9583	$2646	$751
3C	San Francisco, CA	—	—	—	—	—
4A	Baltimore, MD	$6254	$9398	$10,693	$−4439	$−1294
4B	Albuquerque, NM	$545	$127	$17	$528	$109
4C	Seattle, WA	—	—	—	—	—
5A	Chicago, IL	$25,257	$27,876	$29,182	$−3925	$−1307
5B	Boulder, CO	$4838	$7617	$8622	$−3784	$−1005
6A	Minneapolis, MN	$72,853	$76,152	$77,884	$−5031	$−1732
6B	Helena, MT	$26,423	$28,774	$29,619	$−3197	$−845
7A	Duluth, MN	$84,889	$88,954	$90,564	$−5675	$−1610
8A	Fairbanks, AK	$150,837	$152,844	$153,542	$−2705	$−698

temperatures, and more humidity leads to increased heat capacity in the atmosphere (from water vapor), which reduces the response to higher levels of radiation/heat. For example, while Atlanta, GA (3A), Las Vegas, NV (3B), and San Francisco, CA (3C) are all within climate zone 3, Atlanta is moderately humid (type A), Las Vegas is dry (type B), and San Francisco is very humid (type C). This is reflected in the indoor temperatures in Fig. 4(*a*), as the more humid the climate, the lower the indoor temperature is. Similarly, the climate becomes colder as the climate zone number increases, which is also reflected in the indoor temperature curve in Fig. 4(*a*).

Similar patterns can be seen in Fig. 4(*b*), where hotter and drier climates are longer above the threshold set by ASHRAE 55. For example, Phoenix, AZ (2B) and Houston, TX (2A) are both in climate zone 2, but because of Phoenix's dry climate, there are 208 more hours where the ASHRAE's indoor temperature thresholds are exceeded for the black case. In the 15 climate zones, switching from a black to an RC roof reduces a maximum of 1330 h in zone 4B and an overall average of 746 h below the ASHRAE limit, while in the white to RC case, it reduces a maximum of 532 h in zone 4B and an average of 228 h. It is worth noting that while these mild climates seem to have the largest impact, it is in part because their mild temperatures mean that they are already close to the ASHRAE thresholds, and therefore the cooling power introduced by the RC paints can more easily reduce the temperature below the threshold. Therefore, while the results show the most impact in zone 4B, warehouse workers in hotter climates like 1A or 2B might enjoy the benefits of the cooling power more. These results could generally vary if the individual humidity for each hour was considered instead of a general humidity assumption, but overall, they still represent the general heat danger limit within each climate. Additionally, it is worth noting that all results include only one overhead door and could vary further with the introduction of more doors.

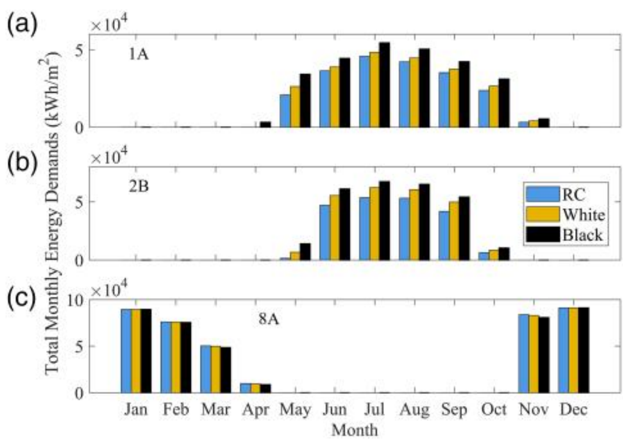

Fig. 5 Monthly energy demands for climate zones 1A (Miami, FL), 2B (Phoenix, AZ), and 8A (Fairbanks, AK), for the RC, white, and black cases

In Fig. 4(*c*), we see the hourly indoor temperatures for an entire year for climate zone 1A, to demonstrate the annual impact of RC on the indoor temperature in a hot climate. In the summer times, the RC impact is the greatest, as expected, whereas in the winter, the RC has minimal effect: this is ideal, as often the effect of RC paints can cause larger HVAC demands in the winter, which this graph shows as a minimized effect. Annually, adding RC paints to a black roof for 4B causes an average change of 1.31 °C, and adding RC paints to a white roof for 2B causes a change of 0.67 °C, all caused solely by the paint on the roof.

To better understand the impact of different roofing types over time, Fig. 5 explores some of the energy demands for all three roof types on a monthly basis. In Fig. 5(*a*), climate zone 1A (representative city Miami, FL) is shown, and in Fig. 5(*b*), climate zone 2B (representative city Phoenix, AZ) is shown. For both of these hotter climates, peak demands are in the summer months, as expected, with the dryer climate (2B) having larger energy demands. In Fig. 5(*c*), the results are plotted monthly for climate zone 8A (representative city Fairbanks, AK). For this cold climate, peak demand shifts to the colder months, with a negative, smaller impact due to the RC paints, similar to the heating demands shown in Figs. 2 and 3.

To further validate this data, Fig. 6 presents a comparison of the reduction of energy use due to RC and the average temperature for all climate zones studied. Generally, average yearly temperature drops as the number of the climate zone increases, and temperatures in "B" climates (dry) tend to be higher than their "A" counterparts (with the exception in climate zone 5), with any "C" climates (marine) having the lowest average temperature. Generally, the reduction of energy demand caused by RC follows the trend of outdoor temperatures, with larger outdoor temperatures leading to more savings due to RC, and lower outdoor temperatures leading to a gain in energy demand due to RC. However, we can also see that RC is always more effective in drier climates, reversing the trend we saw in climate zone 5A–B. Additionally, it has no impact on either of the "C" (marine) climates, likely due to the large latent heat in the humid air, which slows temperature fluctuations, and the prevalence of more overcast days, which stop the

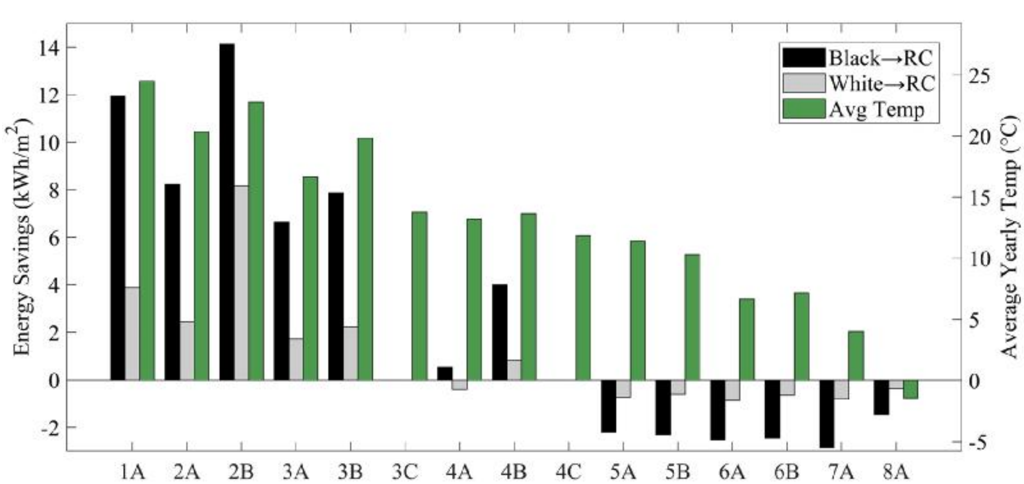

Fig. 6 A comparison of the reduction of energy use due to RC and the average temperature for all climate zones studied

RC paints from emitting into deep space, lowering their cooling ability.

Conclusion

In this study, we developed a building energy model for a warehouse for three cases: a black roof, a white roof, and a $BaSO_4$ RC roof. All three buildings were simulated in the building modeling software TRNSYS using an ENERGYPLUS warehouse prototype for 15 cities in different climate zones. These buildings were then compared with each other to understand how RC could save energy for both types of existing roofs in a wide range of climates. The main findings of the study can be summarized as follows:

- Replacing a black roof with an RC coating for a warehouse could reduce the energy consumption of the warehouse by up to 14.11 kWh/m^2, reducing costs by as much as $2,646/year for a 4835 m^2 warehouse.
- Similarly, replacing the standard white roof of a warehouse with an RC coating could reduce the energy consumption by up to 8.17 kWh/m^2, reducing costs by up to $1,386/year for a 4835 m^2 warehouse.
- Applying RC paints to a non-space-conditioned warehouse roof could reduce the building's exceedance of ASHRAE temperature Standard 55 by as much as 1330 h/year for a black roof and 532 h/year for a white roof.
- The use of RC paints in warehouses could be very influential, but considering the climate where the warehouse is located is key to understanding their benefits. Drier climates (zones B) allow RC paints to work more effectively, and hotter climates (zones 1–4) generally benefit more from the cooling power, meaning that some of the largest impacts are seen in hot, dry climates, whereas cold (5–8) and/or humid (A and C) climates generally show an increase in energy demand.

It is important to note that the TRNSYS warehouse model used in this study is relatively simple, only including one overhead door and not accounting for differences in envelope configurations that exist across the range of warehouses in the United States. The simple model is used here to best understand how warehouses will generally respond to the implementation of RC paints, but it would be worthwhile to perform future research using whole building modeling codes like ENERGYPLUS to better understand warehouses with more complex building envelopes or setpoint schedules.

Acknowledgment

E.B. acknowledges the support from the U.S. National Science Foundation through a Graduate Research Fellowship, and X.R. acknowledges the partial support from the Trask Fund at Purdue University.

This work was authored in part by the National Laboratory of the Rockies for the U.S. Department of Energy (DOE), operated under Contract No. DE-AC36-08GO28308. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

Conflict of Interest

The authors declare no competing interests in the work presented.

Data Availability Statement

All data and original codes mentioned in this study will be made available upon request from the research community.

Author Contribution Statement

X.R., E.B., T.H.: conceptualization; E.B., R.A.K., T.H., X.R.: methodology; E.B.: investigation, writing (original draft); E.B., R.A.K., X.R., T.H., M.V.A.B.: writing (review and editing); X.R., T.H., M.V.A.B.: resources; X.R., T.H., R.A.K., M.V.A.B.: supervision. The article was written through the contributions of all authors. All authors have given approval to the final version of the article.

References

[1] "2018 CBECS: Principal Building Activities Warehouse and Storage". EIA.

[2] Li, H., Wang, S., Zhen, L., and Wang, X., 2022, "Data-Driven Optimization for Automated Warehouse Operations Decarbonization," Ann. Oper. Res.,

[3] Minashkina, D., and Happonen, A., 2020, "Decarbonizing Warehousing Activities Through Digitalization and Automatization With WMS Integration for Sustainability Supporting Operations," E3S Web of Conferences, EDP Sciences, Melbourne, Australia, Dec. 18–20, pp. 1–7.

[4] Bianchi, C., Rois Langner, M., Mishra, V., and Torcellini, P., 2023, "Accelerating the Adoption of Energy Efficiency and Renewables in Warehouses and Distribution Centers," https://www.nrel.gov/docs/fy23osti/83583.pdf.

[5] Boztepe, R., and Çetin, O., 2020, "Sustainable Warehousing: Selecting the Best Warehouse for Solar Transformation," Alphanumer. J., **8**(1), pp. 97–110.

[6] Lewczuk, K., Kłodawski, M., and Gepner, P., 2021, "Energy Consumption in a Distributional Warehouse: A Practical Case Study for Different Warehouse Technologies," Energies, **14**(9).

[7] Zhang, X., Mo, T., and Zhang, Y., 2023, "Optimization of Storage Location Assignment for Non-Traditional Layout Warehouses Based on the Firework Algorithm," Sustainability, **15**(13), pp. 1–21.

[8] Pirvaram, A., Talebzadeh, N., Leung, S. N., and O'Brien, P. G., 2022, *Radiative Cooling for Buildings: A Review of Techno-Enviro-Economics and Life-Cycle Assessment Methods*, Elsevier Ltd, Amsterdam, Netherlands.

[9] Barber, E., Vansal, N., Fang, Z., Hung, Y.-W., Peoples, J., Ciez, R., Horton, T., and Ruan, X., 2025, "Impacts of Radiative Cooling Paints for CO2 Reduction and Global Warming Mitigation," Energy Build., **332**, p. 115458.

[10] Li, M., Lin, C., Li, K., Ma, W., Dopphoopha, B., Li, Y., and Huang, B., 2023, "A UV-Reflective Organic–Inorganic Tandem Structure for Efficient and Durable Daytime Radiative Cooling in Harsh Climates," Small.

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

[12] Hu, Z., Qiu, Y., Zhou, J., and Li, Q., 2024, "Smart Flexible Porous Bilayer for All-Day Dynamic Passive Cooling," Small Sci., **4**(3), pp. 1–12.

[13] Lim, H., Chae, D., Son, S., Ha, J., and Lee, H., 2022, "CaCO3 Micro Particle-Based Radiative Cooling Device Without Metal Reflector for Entire Day," Mater. Today Commun., **32**, p. 103990.

[14] Kou, J., Jurado, Z., Chen, Z., Fan, S., and Minnich, A. J., 2017, "Daytime Radiative Cooling Using Near-Black Infrared Emitters," ACS Photonics, **4**(3), pp. 626–630.

[15] Li, X., Peoples, J., Huang, Z., Zhao, Z., Qiu, J., and Ruan, X., 2020, "Full Daytime Sub-Ambient Radiative Cooling in Commercial-Like Paints With High Figure of Merit," Cell Rep. Phys. Sci., **1**(10), p. 100221.

[16] Li, X., Peoples, J., Yao, P., and Ruan, X., 2021, "Ultrawhite BaSO4 Paints and Films for Remarkable Daytime Subambient Radiative Cooling," ACS Appl. Mater. Interfaces, **13**(18), pp. 21733–21739.

[17] Felicelli, A., Katsamba, I., Barrios, F., Zhang, Y., Guo, Z., Peoples, J., Chiu, G., and Ruan, X., 2022, "Thin Layer Lightweight and Ultrawhite Hexagonal Boron Nitride Nanoporous Paints for Daytime Radiative Cooling," Cell Rep. Phys. Sci., **3**(10), p. 101058.

[18] Bijarniya, J. P., Sarkar, J., Tiwari, S., and Maiti, P., 2022, "Experimentally Optimized Particle-Polymer Matrix Structure for Efficient Daytime Radiative Cooling," J. Renewable Sustainable Energy, **14**(5), pp. 1–11.

[19] Mandal, J., Yang, Y., Yu, N., and Raman, A. P., 2020, "Paints as a Scalable and Effective Radiative Cooling Technology for Buildings," Joule, **4**(7), pp. 1350–1356.

[20] Peoples, J., Hung, Y.-W., Fang, Z., Braun, J., Horton, W. T., and Ruan, X., 2022, "Energy Savings of Radiative Cooling Paints Applied to Residential Buildings," Int. J. Heat Mass Transf., **194**, p. 123001.

[21] Tzempelikos, A., and Lee, S., 2021, "Cool Roofs in the US: The Impact of Roof Reflectivity, Insulation and Attachment Method on Annual Energy Cost," Energies, **14**(22), p. 7656.

[22] Jiang, K., Zhang, K., Shi, Z., and Li, H., 2022, "Study on the Cooling Energy Saving Potential of a Novel Radiative Cooling Paints in Building Application," E3S Web of Conferences, EDP Sciences, Xi'an, China, Sept. 16–19, pp. 1–4.

[23] Wijesuriya, S., Kishore, R. A., Bianchi, M. V. A., and Booten, C., 2022, "Potential Energy Savings Benefits and Limitations of Radiative Cooling Coatings for U.S. Residential Buildings," J. Clean. Prod., **379**(2), p. 134763.

[24] Costanzo, V., Evola, G., Gagliano, A., Marletta, L., and Nocera, F., 2013, "Study on the Application of Cool Paintings for the Passive Cooling of Existing Buildings in Mediterranean Climates," Adv. Mech. Eng., **5**, pp. 1–10.

[25] Olawale-Johnson, O. P., Ajwang, P., and Ondimu, S. N., 2021, "Reducing Cooling Demands in Sub-Saharan Africa: A Study on the Thermal Performance of Passive Cooling Methods in Enclosed Spaces," J. Sustainable Dev. Energy, Water Environ. Syst., **9**(4), pp. 1–13.

[26] Wang, N., Lv, Y., Zhao, D., Zhao, W., Xu, J., and Yang, R., 2022, "Performance Evaluation of Radiative Cooling for Commercial-Scale Warehouse," Mater. Today Energy, **24**, pp. 1–9.

[27] Xu, W., Gong, S., Wang, N., Zhao, W., Yin, H., Yang, R., Yin, X., and Tan, G., 2023, "Temperature Reduction and Energy-Saving Analysis in Grain Storage: Field Application of Radiative Cooling Technology to Grain Storage Warehouse," Renew. Energy, **218**, pp. 1–12.

[28] Seifhashem, M., Capra, B. R., Milller, W., and Bell, J., 2018, "The Potential for Cool Roofs to Improve the Energy Efficiency of Single Storey Warehouse-Type Retail Buildings in Australia: A Simulation Case Study," Energy Build., **158**, pp. 1393–1403.

[29] Klein, S., et al., 2017, *TRNSYS 18: A Transient System Simulation Program*, Solar Energy Laboratory, University of Wisconsin, Madison, WI.

[30] Prototype Building Models. Department of Energy, https://www.energycodes.gov/prototype-building-models, Accessed June 15, 2025.

[31] Weather Data. US Department of Energy's Building Technologies Office. https://energyplus.net/weather. Accessed March 5, 2025.

[32] "Climate at a Glance: City Time Series." NOAA National Centers for Environmental Information, https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/city/time-series, Accessed August 25, 2025.

[33] Biswas, K., Lu, J., Soroushian, P., and Shrestha, S., 2014, "Combined Experimental and Numerical Evaluation of a Prototype Nano-PCM Enhanced Wallboard," Appl. Energy, **131**, pp. 517–529.

[34] "Electric Power Monthly". EIA, https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a, Accessed April 23, 2024.

[35] "Natural Gas Prices". EIA, https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PRS_DMcf_m.htm, Accessed April 23, 2024.

[36] "ANSI/ASHRAE Addendum d to ANSI/ASHRAE Standard 55-2017", 2020. www.ashrae.org

[37] U.S. Department of Energy. "Furnaces and Boilers" https://www.energy.gov/energysaver/furnaces-and-boilers, Accessed October 15, 2025.