energies

MDPI

Article

Exploring Biomaterial-Based CoolRoofs: Empirical Insights into Energy Efficiency and CO_2 Emissions Reduction

Hasna Oukmi [1,2,*], Badr Chegari [3,4,*], Roland Soun [3], Ouadia Mouhat [5], Mohamed Rougui [5] and Mohammed El Ganaoui [2]

[1] Civil Engineering and Environment Laboratory (LGCE), Higher School of Technology, Mohammadia School of Engineers, Mohammed V University in Rabat, Rabat 8007, Morocco
[2] Laboratory for Studies and Research on Wood Materials (LERMAB) IUT H Poincaré de Longwy, University of Lorraine, 168 Rue de Lorraine, Cosnes et Romain, 54400 Longwy, France; mohammed.el-ganaoui@univ-lorraine.fr
[3] Cool Roof, Domblans Street, Z.A, Quiella, 29590 Le Faou, France; rsoun@coolroof-france.com
[4] Techniques of Informatics and Microelectronics for Integrated Systems Architecture (TIMA), CNRS, Grenoble INP, Institute of Engineering, Université Grenoble Alpes, 38031 Grenoble, France
[5] Civil Engineering and Environment Laboratory (LGCE), Higher School of Technology, Mohammed V University in Rabat, Rabat 8007, Morocco; ouadie.mouhat@gmail.com (O.M.); m.rougui@um5r.ac.ma (M.R.)
* Correspondence: hasna.oukmi@research.emi.ac.ma (H.O.); bchegari@coolroof-france.com (B.C.)

Abstract: The Cool Roof concept, known for its efficiency in summer due to high temperatures during this period, employs a light coating that covers the roof to prevent the absorption of heat and maintain lower indoor temperatures. This study integrates a chemical component with biomaterials to enhance performance and reduce CO_2 emissions. The composition investigated in this research is recognized for its durability and ability to lower outside temperatures, thereby mitigating the urban heat island effect. This experimental study evaluates the sustainability of CoolRoofs in a cold room located in Signes, France. Temperature measurements are conducted from 25 September 2023 to 27 July 2024, both with and without the coating, to assess energy performance and CO_2 emissions. The selection of the building type ensures optimal performance in both summer and winter. Results show that the maximum outside and inside surface temperatures for a Cool Roof are 48.7 °C and 25.6 °C, respectively, compared to 72.9 °C and 32.2 °C for an uncoated roof. Additionally, implementing a CoolRoof reduces thermal load through the cold room by 56%, while CO_2 emissions can be reduced by up to 27.31 kg CO_2/m^2 over a 20-year period. This study presents a solution for enhancing energy and environmental performance year-round using a resilient composite.

Keywords: CoolRoof; coating; energy performance; thermal performance; CO_2 emissions

check for updates

Citation: Oukmi, H.; Chegari, B.; Soun, R.; Mouhat, O.; Rougui, M.; Ganaoui, M.E. Exploring Biomaterial-Based CoolRoofs: Empirical Insights into Energy Efficiency and CO_2 Emissions Reduction. *Energies* **2024**, *17*, 5499. https://doi.org/10.3390/en17215499

Academic Editor: Anastassios M. Stamatelos

Received: 12 September 2024
Revised: 14 October 2024
Accepted: 25 October 2024
Published: 3 November 2024

1. Introduction

Rising global temperatures due to greenhouse gas emissions pose a significant challenge. The Intergovernmental Panel on Climate Change (IPCC) [1] predicts that even if greenhouse gas emissions are reduced by 50% by 2030, global temperatures could still exceed 1.5 °C between 2021 and 2040. This warming trend has a direct impact on buildings. Nearly half of a building's energy consumption is dedicated to maintaining a comfortable indoor temperature, underscoring the critical importance of enhancing building performance [2].

Among building components, the roof accounts for 5–10% of total building energy consumption and over 40% of electricity usage in upper-level constructions [3]. Due to its direct exposure to sun radiation, the roof's external surface temperature rises by 50–70 °C, raising the indoor temperature [4]. This is why prioritizing the reduction in cooling loads is crucial, across passive solutions that serve to decrease energy usage and enhance the indoor comfort levels. Within these passive solutions for summer, shading, natural ventilation, and Cool Roofs can be found [5]. Cool Roofs are known for their ability to reflect sunlight and rapidly release absorbed heat as infrared radiation. This is due to their high solar reflectance and high infrared emittance, respectively. These properties work together to decrease heat transfer to the building [6].

Bozonnet et al. [7] suggest that research in France prioritizes improving building envelope insulation for winter energy performance. Cool Roof techniques, which could offer a solution for summer conditions, are not yet widely adopted. Macintyre et al. [8] found that 20 to 70% of energy savings could be attributed to increasing the roof's albedo. While Synnefa et al. [9] established that increasing the solar reflectance of the roof lead to a decreasing in cooling load 18–93%. Piselli et al. [2] explored that the optimal typology of the roof is increasing the solar reflectance and decreasing the insulation thickness except for extreme climate. The main findings extracted from reviewed papers on Cool Roof studies are presented in Table 1. Several studies have investigated integration of material to improve the Cool Roof system such as the PCM [10–12], Thermochromic Cool Roof [13,14], and recycled material such as waste glass [15]. Challenges in evaluating Cool Roofs include accounting for factors like coating material resilience, sunlight reflection, and outdoor thermal comfort, with existing frameworks falling short of fully capturing their performance. Challenges of Urban Scale Simulations also contribute to the difficulty of evaluating Cool Roof effectiveness at the city level [16].

Table 1. Overview of analyzed Cool Roof technologies.

Location	Type of Building	CoolRoof Type	Specification and Reflectivity	Conclusion	Reference
Seoul, Korea	-	PCM CoolRoof System	Phase Change Material with Wood–Plastic Composite	5.7 °C reduction in summer peak surface temperature	[10]
Athens	Residential	Thermochromic Dye-Based Roof Coating	Roof with $U_{roof} = 3\ \mathrm{w/m^2K}$	17.13% reduction in energy consumption compared to the Baseline Scenario	[13]
-	-	Recycled Waste Glass Coated Roof Tile	Lead silica waste glass derived mainly from cathode ray tube of television sets	Increased normal solar reflectance by 47.5% (flat tiles) and 27% (curved tiles)	[15]
India	-	CoolRoof Tile	Metakaolin (Chinese clay), Expanded polystyrene sheet, Sodium Silicate, Coating Material	Exterior: 8 °C reduction, Interior: 12 °C reduction during daytime	[17]
Central Italy	Residential (traditional)	Cool Clay Tile	Thermal Emissivity: 0.89Solar Reflectance: 0.77	Up to 4.7 °C reduction in summer peak indoor temperature	[18]
Barcelona Palermo, Cairo	Residential building	Thermochromic CoolRoof	Static CoolRoof: 0.75	Annual energy savings up to 8.5% compared to CoolRoof, and 19% compared to conventional roof	[19]
New York City	Apartment	Super CoolRoofing materials	Albedo > 0.95 Emissivity > 0.95	Reduction in outdoor air temperature of 0.85 K	[20]
Wuhan, China	Ventilation roof (SPCM)	The roof design incorporates ventilation features with shape-stabilized phase change material	30 mm thickness, phase change. Temperature: 36–38 °C. Night ventilation (v = 3 m/s)	The incorporation of the PCM reduced peak indoor air temperatures by 2.9 °C the cumulative cooling load decreased by 19.2% without night ventilation and by 22.9% with night ventilation	[21]

This research aims to assess the energy and environmental performance of a novel material, including a portion of biomaterial, as a CoolRoof coating through an experimental study. The objective is to implement this solution in cold rooms to ensure optimal performance throughout both summer and winter, given the imperative for low temperatures indoors. By enhancing the reflectivity and emittance of the CoolRoof, reductions in both indoor and outdoor temperatures are anticipated, thereby achieving energy consumption and CO_2 emission reductions, along with mitigating the urban heat island effect. Additionally, this study will explore coating materials with long-term durability.

2. Materials and Methods

2.1. Theoretical Approach: Understanding the Impact of Heat Transfer Modes and Cool Roof Characteristics on Energy Performance and Thermal Stability

To comprehensively analyze the Cool Roof system, it is essential to grasp the intricacies of solar radiation and the influence of heat transfer modes, as well as the characteristics of CoolRoofs on energy performance and thermal Stability.

Before delving into the direct impact on the roof, understanding the significance of solar energy is paramount. Solar radiation, emitted by the sun encompasses a broad spectral range. This range is divided into three categories: ultraviolet ($\lambda < 400$ nm), accounting for 6%; visible ($400 < \lambda < 700$ nm), representing 48%; and infrared ($\lambda > 700$ nm), comprising 46% [22]. Notably, visible and infrared radiation contribute significantly to solar reflectance. While solar radiation serves as a substantial heat source, its interaction with the roof warrants careful examination to understand the thermal performance effectively. Irradiation stands as a fundamental mode of heat transfer, intricately tied to the roof's interaction with solar energy. Within this process, electromagnetic waves from the sun radiate onto the roof's surface. Subsequently, the roof reflects a portion of this solar radiation into the sky while some is absorbed by the roof, this portion stored is emitted as infrared radiation [23]. Convection, another critical mechanism, unfolds as heat transfer occurs through the movement of air. Around the roof's surface, this mode facilitates the exchange of heat between the roof surface and the external air, it is dependent on surrounding air temperature and wind speed, driven by the temperature gradient between the external air and the surface [24]. While conduction operates as heat transfer transpires through the roof's material itself. In this process, thermal energy propagates through the solid structure of the roof, moving from areas of higher temperature to regions of lower temperature. This mechanism governs the transmission of heat through the roof's layers, influencing its overall thermal behavior. Figure 1 presents an overview of these mechanisms.

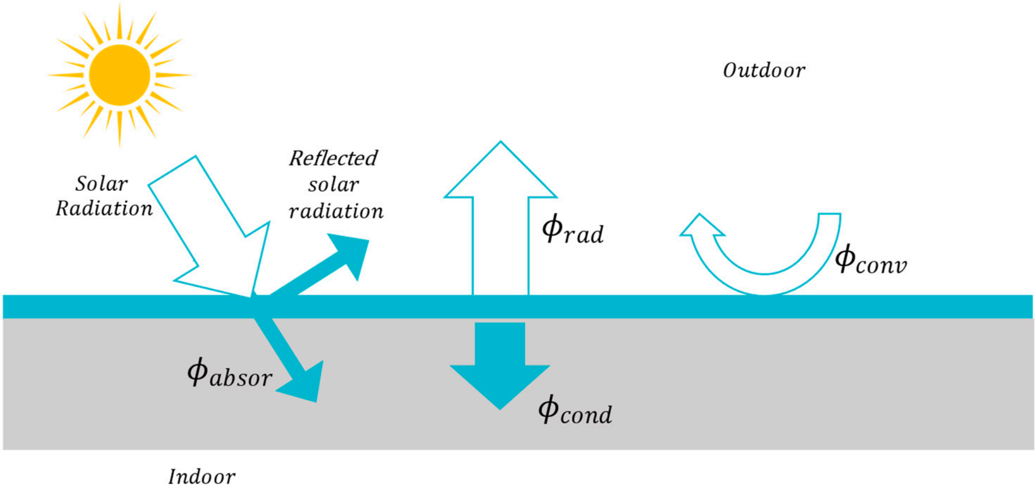

Figure 1. Representation of the different terms in the thermal balance of a roof.

The CoolRoof is recognized for its solar reflectance and infrared emissivity. Solar reflectance indicates the proportion of incident solar energy that a surface reflects, ranging from 0 for darker surfaces to 1 for cooler surfaces, while thermal emissivity, ranging from

0 to 1, measures the capacity of a warm or hot material to release heat through infrared radiation. These two parameters allow us to assess the surface's ability to avoid absorbing solar heat using the solar reflectance index (SRI) [25]. The SRI scale ranges from 0 to 100. Standard white has an SRI value of 100, with reflectance and emittance values of 0.80 and 0.90, respectively. In contrast, standard black has an SRI value of 0, with reflectance and emittance values also at 0.05 and 0.90, respectively [26]. The SRI is calculated according to ASTM standard E1980-01 [27] through (1):

$$SRI = 100 \cdot \frac{(T_{sb} - T_{se})}{(T_{sb} - T_{sw})} \tag{1}$$

The thermal balance equation of the roof is utilized to examine how both solar reflectance and infrared emissivity influence heat transfer modes.

$$\frac{T_{se} - T_i}{R_{i\_se}} = (1-r).I - \left[\sigma\varepsilon\left(T_{se}^4 - T_{sky}^4\right) + h_c.(T_{Se} - T_o)\right] \tag{2}$$

Equation (2) represents the energy balance for the roof. This equation illustrates the relationship between indoor and outdoor conditions, roof characteristics, and most importantly, the role of the external layer of the roof. This layer contains both values, such as the solar reflectance (r) and the thermal emittance (ε) [28].

While external properties like temperature and radiation cannot be modified, the quality of the materials employed in the roof and its external layer can be controlled. For a CoolRoof, this layer typically boasts higher solar reflectance and thermal emittance compared to a traditional roof. Consequently, this contributes to a cooler surface temperature [23].

According to Akbari et al. [29], decreasing the emissivity of the external roof layer during summer days leads to higher surface temperatures and increased cooling energy consumption. When comparing CoolRoofs to dark roofs, it becomes evident that CoolRoofs, due to their light color and reflective nature, effectively reduce energy costs by minimizing heat absorption. In contrast, dark roofs absorb more heat, leading to higher energy consumption for cooling. This difference results in CoolRoofs maintaining lower surface temperatures and contributing to reduced cooling energy usage. Additionally CoolRoofs offer environmental benefits such as lower CO_2 emissions, and help mitigate the urban heat island effect by lowering temperatures in urban areas. Thus, CoolRoofs not only enhance energy efficiency but also promote thermal stability, reduce urban heat island effects, and provide significant environmental advantages.

2.2. Case Study

This study, explores the utilization of environmentally friendly building materials for the CoolRoof coating, ensuring improvements in energy performance while reducing CO_2 emissions, as indicated by Figure 2. To achieve the study goal, several steps will be undertaken. First, the CoolRoof coating will be experimentally applied to a building. Next, the temperature of the building will be assessed both before and after the application of the CoolRoof coating. Following this, degree-hours of deviation will be calculated to evaluate thermal comfort. Moreover, heat loss will be quantified with and without altering the thermal resistance of the roof. Finally, CO_2 emissions associated with the building's operation will be computed.

The effectiveness of an innovative coating for CoolRoof installations was investigated in an experimental study to estimate the potential gains in thermal stability, energy efficiency, and environmental performance. This coating is examined for industrial buildings, especially cold rooms, to ensure significant reduction in energy consumption. Cold rooms require consistent low temperatures year-round; thus, the CoolRoof coating will help achieve this goal.

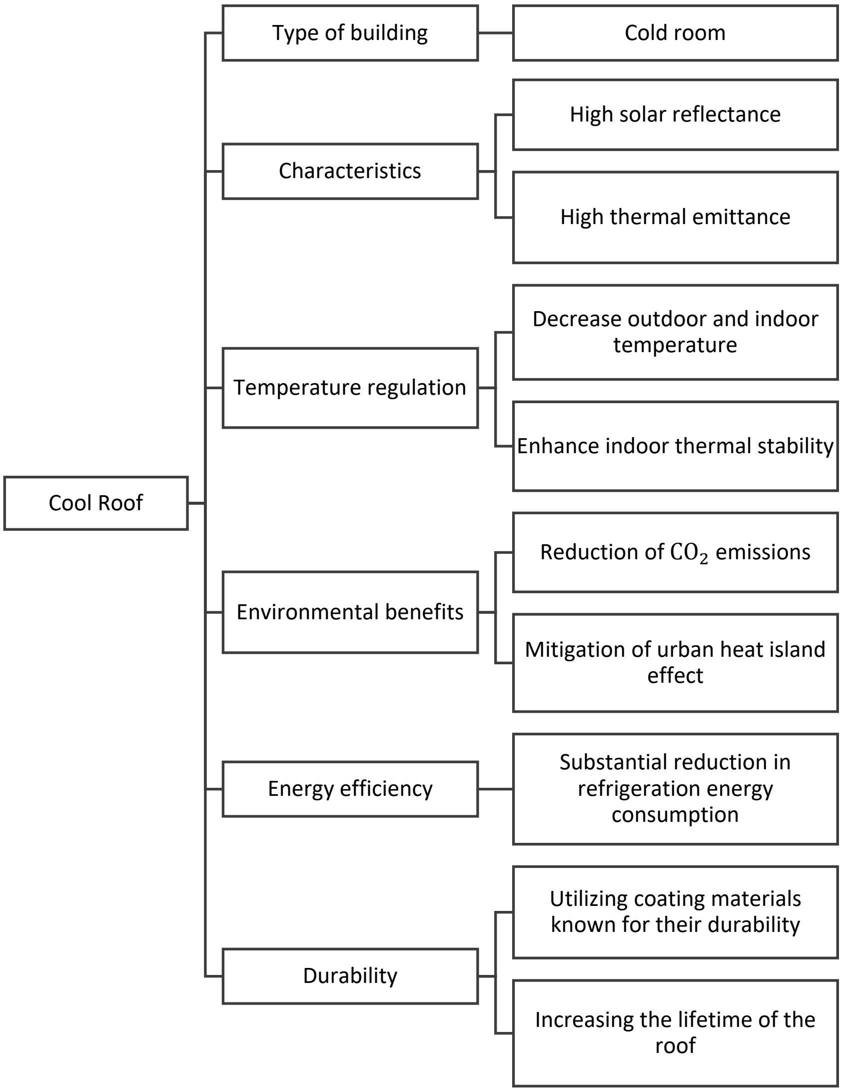

Figure 2. Overview of the Cool Roof investigation with their objectives.

The research was focus on the application of CoolRoof on 3770 m^2 of roofing in a cold room, which is 71.9 m long and 50.07 m wide as shown in Figure 3, with an indoor temperature to maintain of +4 °C for chilled rooms and −18 °C for freezer rooms. The components of each element of the cold room are represented in Table 2.

Table 2. Material composition and thermal properties of cold room roof.

Element	Material	Thickness [m]	Thermal Conductivity [W/mK]
Roof	CoolRoof coating	0.01	0.23
	Bituminous membrane	0.03	0.17
	Plenum	0.02	1.06
	Sandwich panel	0.06	0.04

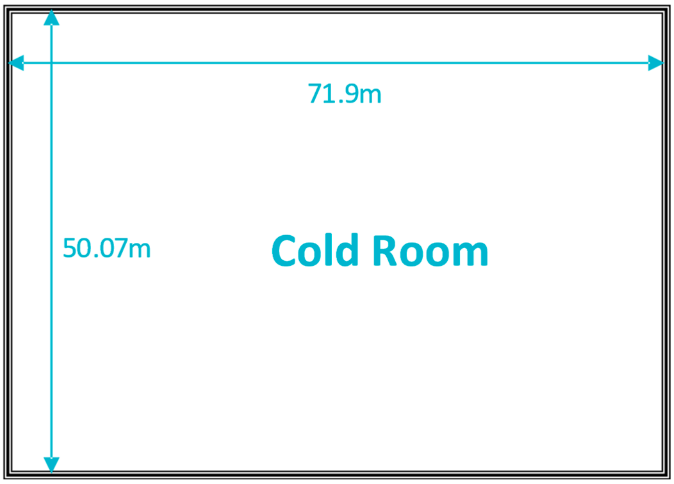

Figure 3. Schematic representation of cold room geometry.

This research explores a novel CoolRoof coating that incorporates materials from two distinct categories, the basecoat and the topcoat as illustrated in Figure 4. The basecoat ensures the coating's thermo-reflective properties and adhesion to the substrate using oyster shell powder material, and the topcoat ensures that the thermo-reflective properties are maintained over time through the anti-UV and anti-fouling protective layer using polyvinylidene fluoride polymer. This CoolRoof coating exhibits exceptional thermo-reflective properties, reflecting a remarkable 90% of solar radiation, which means that only 10% is absorbed and 90% of absorbed radiation is re-emitted in the far infrared range, resulting in an SRI of 113.

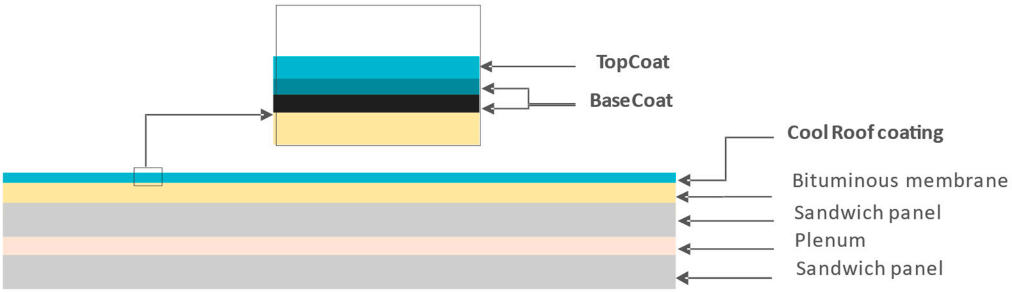

Figure 4. Material composition of cold room roof.

The application of CoolRoof depends on the surface texture: for highly rough or porous surfaces, it requires two basecoats and one topcoat with higher material quantities; for moderately rough surfaces, fewer materials are needed. For this study, a bituminous membrane and sandwich panel were used, necessitating the application of 2 coats of 300 g/m^2 basecoat followed by 1 coat of 150 g/m^2 topcoat.

Bretz and Akbari [30] discovered in their examination of various coatings with different albedo levels (high albedo) that the performance degradation of the coating's albedo occurred within the initial year of application. Furthermore, within the initial two-month period, one roof experienced a 70% decline in albedo, constituting the entirety of the albedo drop for the first year. On the other hand, this research emphasizes the durability of the material used, particularly in the topcoat, which is designed to be highly resilient. The lifetime of the CoolRoof coating is projected to maintain its performance over a span of 20 years. Notably, the degradation process takes approximately 14 years for the solar reflectance to decrease from 0.8 to 0.75. Additionally, it offers durable resistance to various factors including UV radiation, mold and fungi, chemical agents, and soiling.

The cold room is located in Signes, France, when studying the performance of CoolRoof in this location, it is crucial to consider the Outdoor air temperature variations, as illustrated in Figure 5 in July experiences the highest temperatures, reaching 35.1 °C. Conversely, January records the lowest temperatures, dipping to −1.3 °C. These high temperatures in summer necessitate high energy consumption for cooling to maintain low indoor temperatures for the cold room. During the summer months, not only does the temperature rise significantly, but there is also an increase in solar irradiance as shown in Figure 6, which serves as a significant source of heat, reaching a maximum of 1033 $W/m^2/h$.

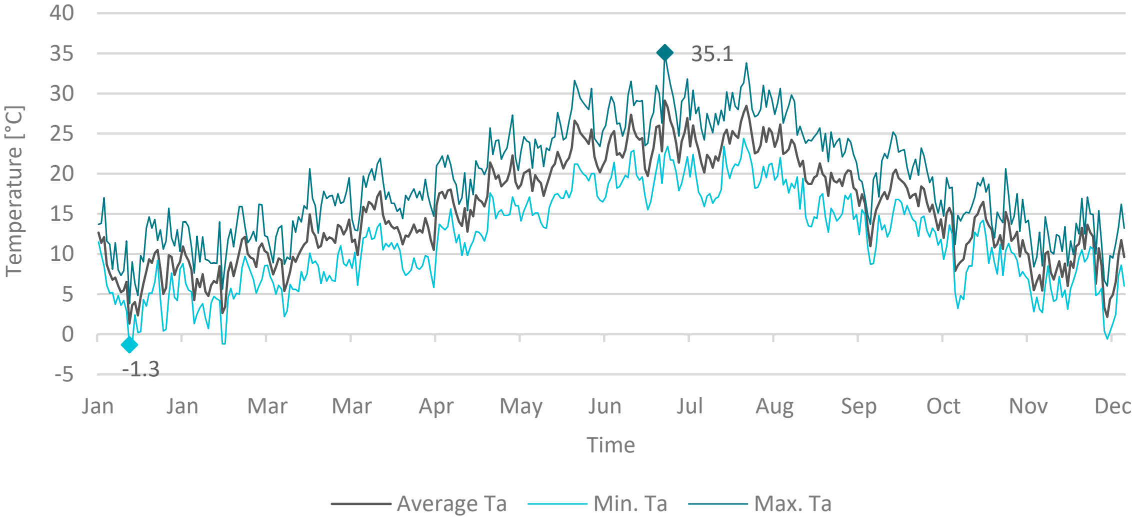

Figure 5. Outdoor air temperature variations (average, maximum and minimum temperature).

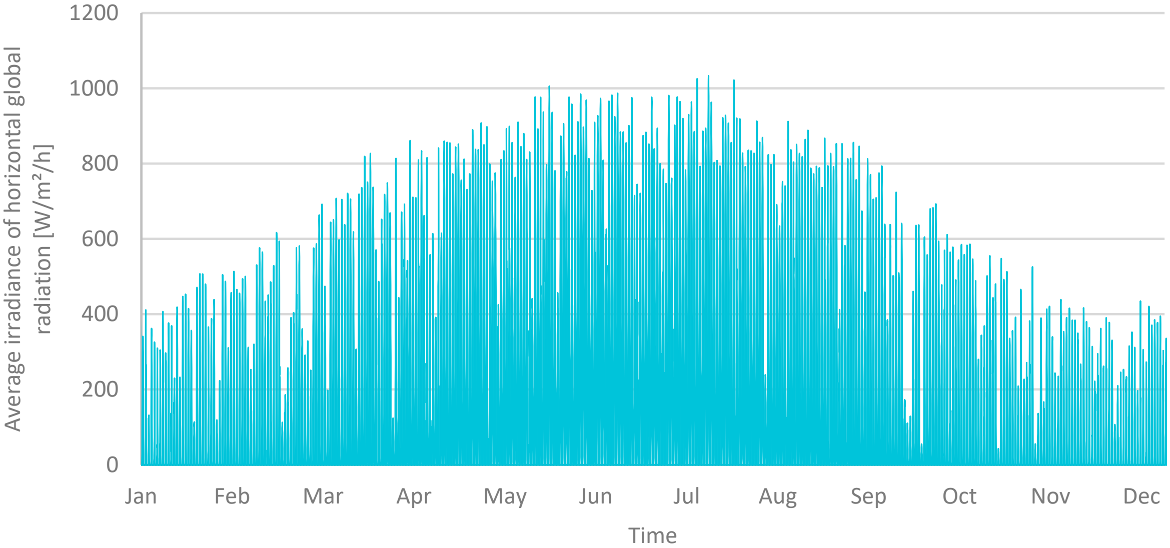

Figure 6. Variability of solar irradiance over time.

For the experimental part, the analysis includes real data from 25 September 2023 to 27 July 2024. Additionally, 8 temperature sensors are deployed on the site of the building to measure the ambient and surface temperatures on both side of the roof inside and outside temperatures. The measurement points are illustrated in Figure 7, and measurements are taken in both painted and unpainted areas each covering 50% of the surface.

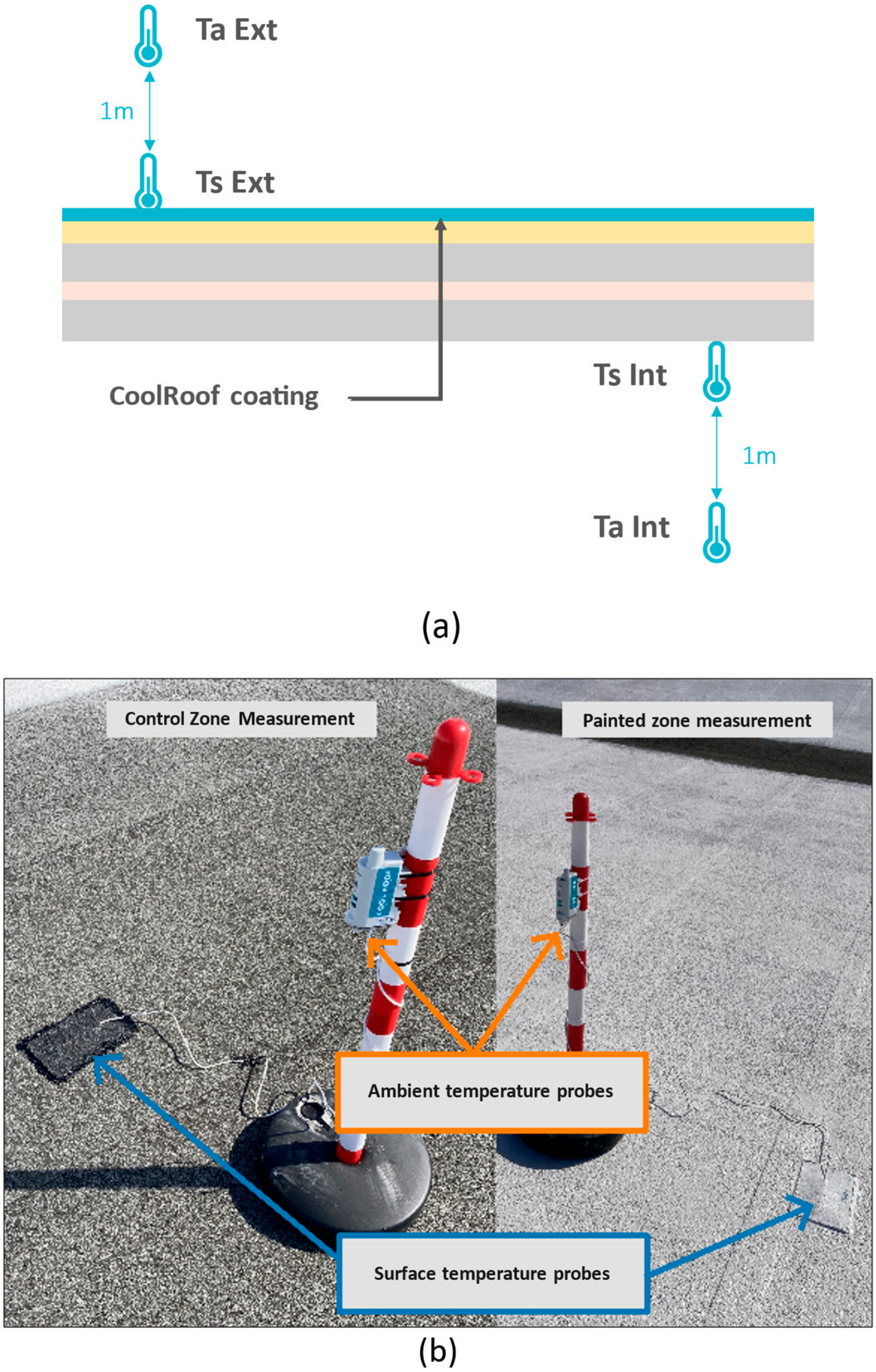

Figure 7. Temperature sensor placement within a roof layer: (**a**) illustration; (**b**) photos of the sensors on the roof for both configurations.

An Internet of Things (IoT) network is deployed to take these measurements at different points in the building and transfer them. This network is illustrated in Figure 8. The sensors communicate their measurements via a LoraWAN network (radio communication protocol) to a Gateway located in the building. This Gateway retransmits the measurements to a server via 3G communication. The measurements are stored on this server.

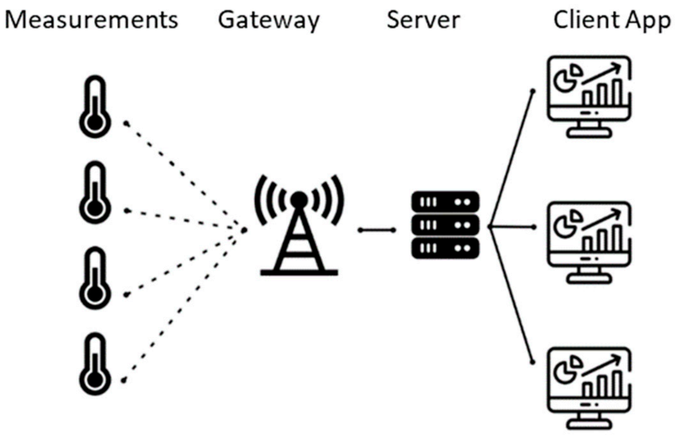

Figure 8. Typical IoT network for measurement.

3. Results and Discussion

This section presents the results of a study investigating the effectiveness of CoolRoofs in reducing thermal load, decreasing surface temperature, improving energy efficiency, and reducing CO_2 gas emissions, through measuring ambient, external and internal surface temperatures over 10 months. Additionally, the impact of CoolRoofs on thermal stability, energy consumption, and environmental factors was evaluated.

3.1. Thermal Performance and Thermal Stability

The temperature was evaluated through two configurations: a reference configuration without coating and the configuration with CoolRoof. The external surface temperature was measured from 25 September 2023 to 27 July 2024. As shown in Figure 9, it can be seen that temperature differences between a roof without CoolRoof coating and a roof with CoolRoof coating can reach a maximum of 50 °C, for an average of 10 °C during the day. As for the indoor temperature, as displayed in Figure 10, temperature differences can reach a maximum of 14.8 °C, with an average of 7.9 °C during the day.

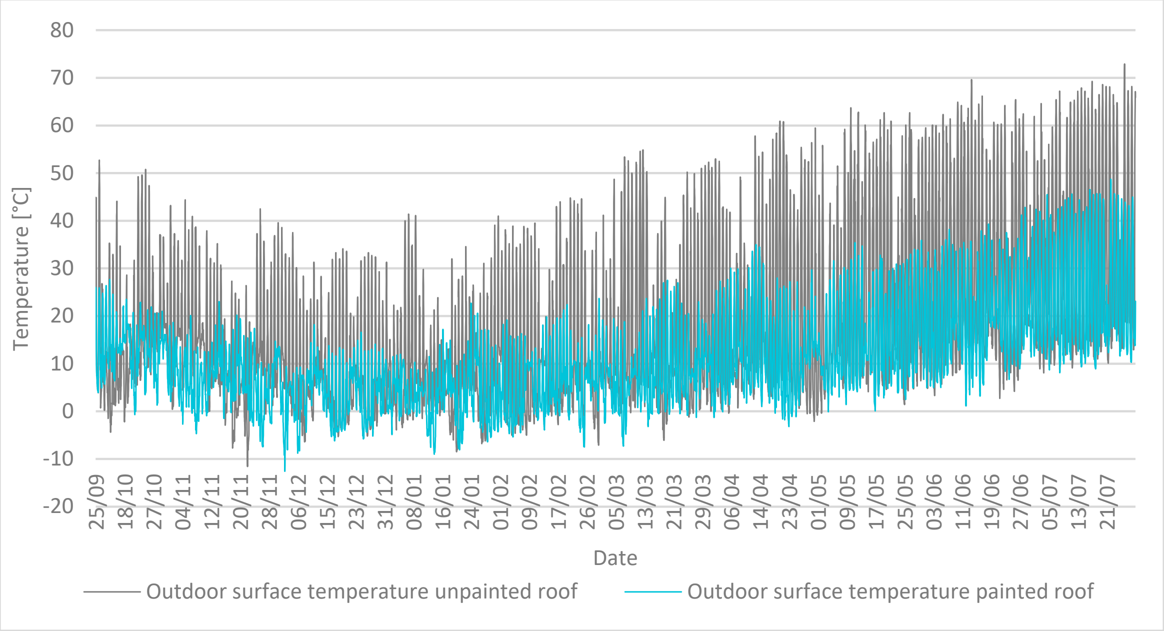

Figure 9. Measured external surface temperature variation in the roof.

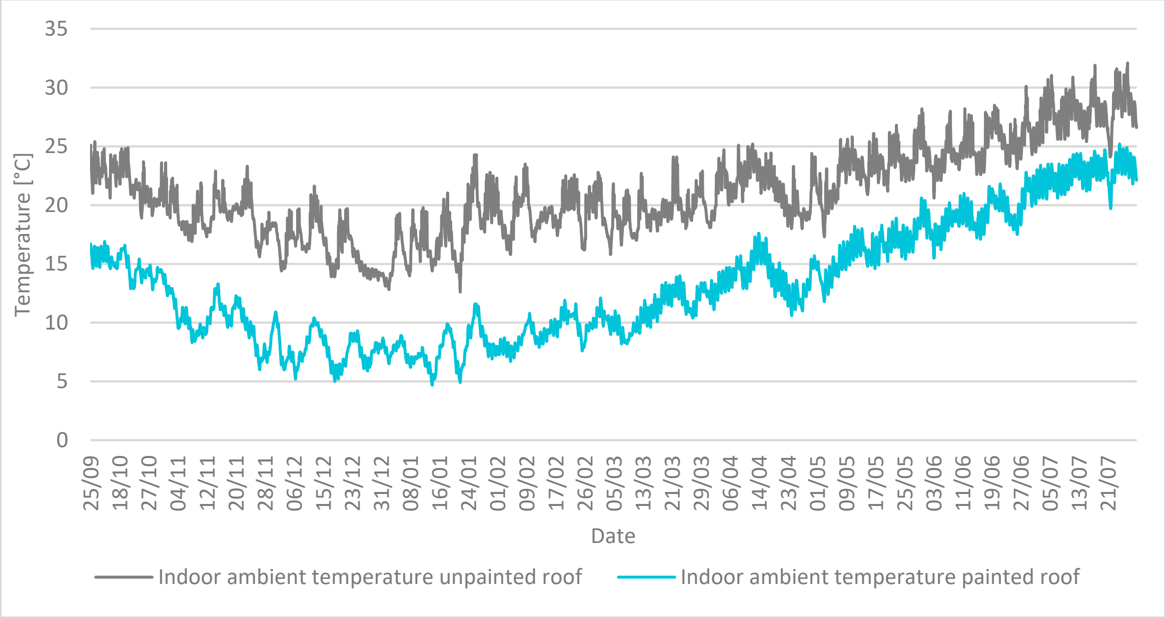

Figure 10. Measured indoor ambient temperature variations in the roof.

Comparing the two configurations, integrating the CoolRoof coating significantly reduces both indoor and external surface temperatures, leading to lower temperature gains, as illustrated in Figure 11. A more in-depth analysis of the graph reveals that the gains are more significant in winter than in summer. This is due to the low thermal resistance of the wall and floor, which means that the roof becomes an effective cooling vector due to its reduced thermal diffusivity.

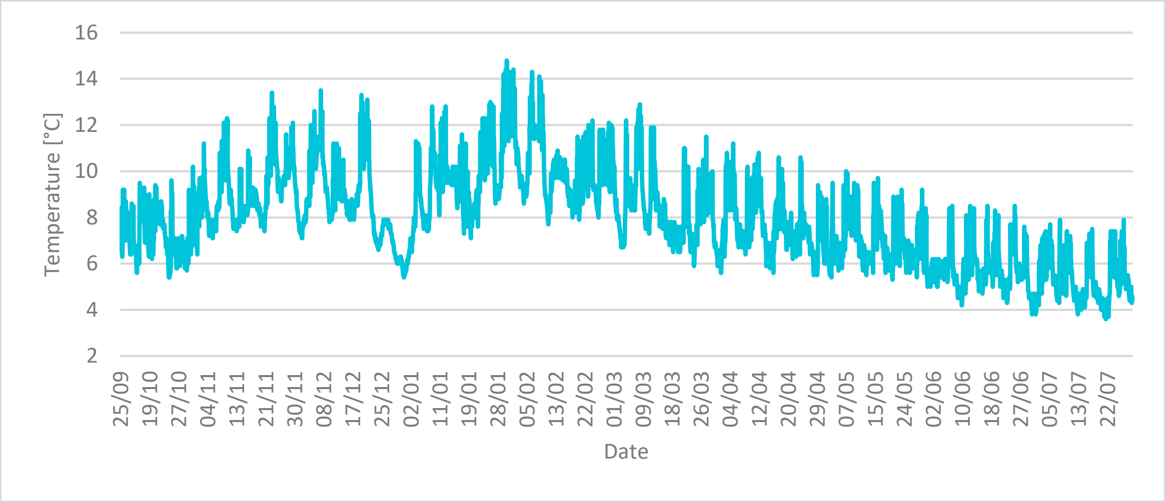

Figure 11. Indoor ambient temperature differences of the roof.

In a cold room, products are stored at specific temperature conditions. Therefore, it is necessary to calculate degree-hours of deviation through accumulating the temperature differences between the outdoor temperature and a predefined storage temperature over a given period. This calculation allows for an assessment of the severity of temperature deviations and their impact on refrigeration demand. In this case, the target temperature is +4 °C for chilled rooms and −18 °C for freezer rooms.

Figure 12 highlights the significant gains in degree-hours of deviation achieved through the implementation of the CoolRoof solution. This improvement translates into a 20% and 32% reduction in degree-hours of deviation for freezer rooms and chilled rooms, respectively.

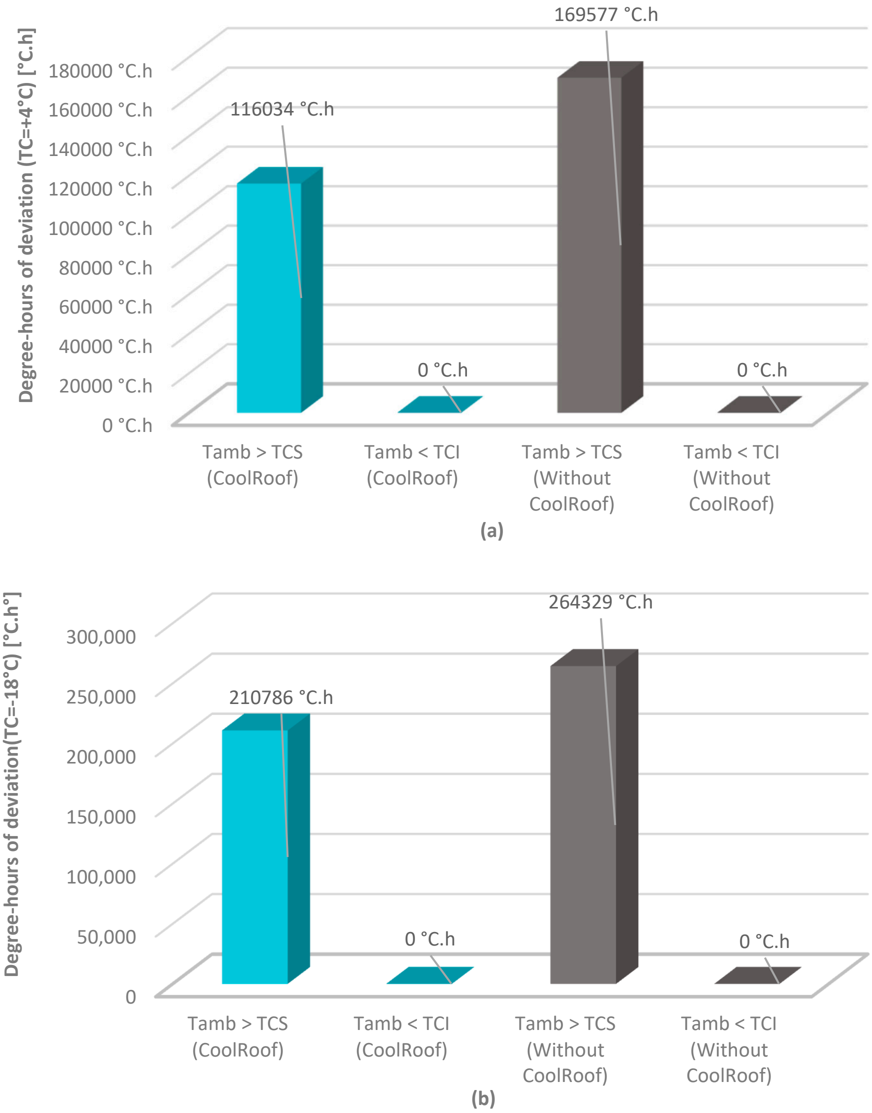

Figure 12. Annual degree-hours of deviation gains: (**a**) degree-hours of deviation (TC = +4 °C); (**b**) degree-hours of deviation (TC = −18 °C).

3.2. Energy and Environmental Performance

The application of the CoolRoof solution has a positive impact on energy and environment. From the perspective of energy efficiency, the use of this solution reduces the demand for refrigeration, thereby improving the energy efficiency of cold rooms. From an environmental standpoint, lower energy consumption leads to a reduction in greenhouse gas emissions, contributing to the reduction in the carbon footprint of facilities. This holistic approach reinforces the positive impact of the CoolRoof solution on all facets of building performance.

Applying the CoolRoof coating to the roof has a significant impact on thermal loads in the cold room. The CoolRoof solution achieves a notable reduction in thermal loads through the roof over the course of a year, as depicted in Figure 13. This reduction amounts to 56%, representing a decrease from 100.8 kWh/m^2/year to 43.9 kWh/m^2/year for configurations without and with CoolRoof, respectively.

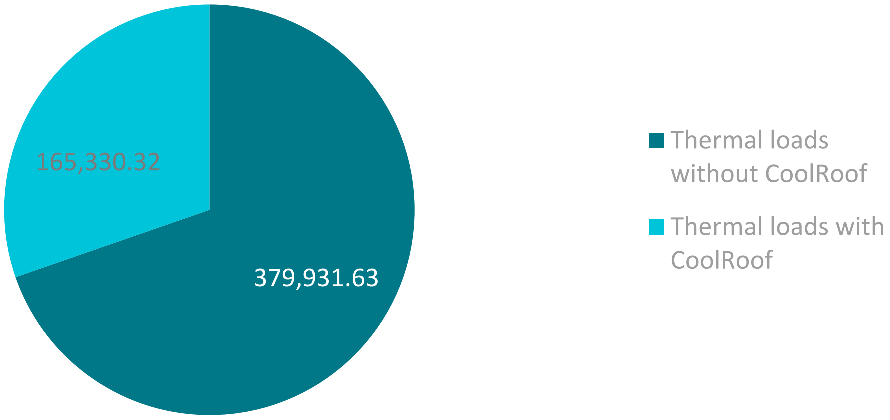

Figure 13. Predicted thermal loads without and with CoolRoof in kWh.

To generalize the results of energy savings, this study was analyzed across different roof thermal resistances. Figure 14 illustrate the variability of energy saved in accordance with roof thermal resistance. This representation highlights the considerable amplitude of the electricity consumption saved, ranging according to scenario number from 1 (uninsulated roof) to 5 (very well insulated roof). Increasing the thermal resistance leads to a decrease in energy saved. These gains in electrical energy consumption can reach 20.32 kWh/m^2/year.

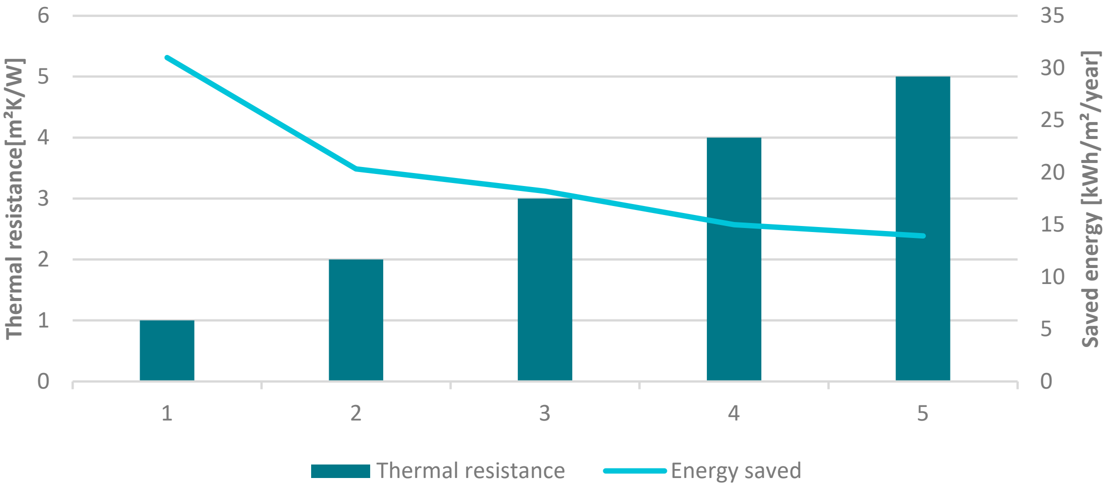

Figure 14. Electrical consumption reduced based on roof thermal resistance.

Figure 15 illustrates the variability of CO_2 emissions reduction over 20 years according to the thermal resistance of the roof. This representation highlights the considerable range of CO_2 emissions reduction, varying the thermal resistance between 1 (uninsulated roof) and 5 (very well-insulated roof). In view of the temperature differences recorded by the sensors, it would seem that the roof has a lower thermal resistance, thus reflecting a potential reduction in the carbon footprint, rather than a higher resistance. This reduction can reach 27.31 kg CO_2/m^2 over a period of 20 years.

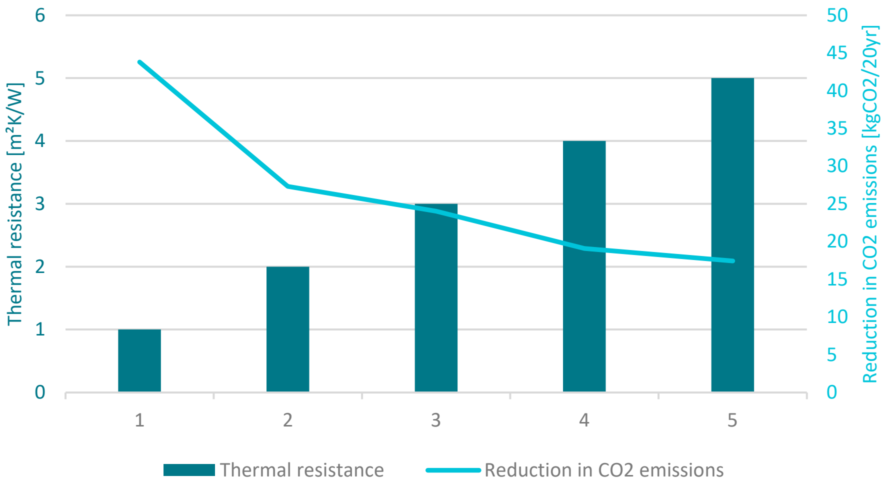

Figure 15. CO_2 emissions reduced over 20 years based on roof thermal resistance.

4. Conclusions

During summer, the top floor, which is more exposed to external conditions through both the walls and roof, experiences increased heat transfer. Therefore, the CoolRoof coating is a conventional approach to reduce cooling energy consumption by lowering the temperature inside the building, through reducing the absorption of heat. This study expands on previous research by addressing key aspects of CoolRoof systems, which have typically focused on integrating materials like PCMs, thermochromic coatings, and recycled materials. It highlights the challenges in evaluating CoolRoof performance, such as coating resilience and its impact on outdoor thermal comfort, particularly at the urban scale. This study emphasizes the CoolRoof's high solar reflectance and thermal emittance, its role in regulating temperatures, reducing CO_2 emissions, mitigating the urban heat island effect, and improving energy efficiency. It also focuses on the durability of the coating materials, which extend the roof's lifespan. This study utilized a combination of chemical and ecological materials, specifically oyster shell powder and polyvinylidene fluoride polymer, to achieve both the thermo-reflective properties and durability of the coating. Conducted in Signes, France, the research examined how the local climate influences the performance of these materials. To assess their effectiveness throughout the year, this study was carried out in a cold room, enabling a thorough evaluation of performance during both summer and winter months. The results demonstrated a significant difference in indoor temperatures between roofs with the coating and those without, with an average of 7.9 °C and a maximum of 14.8 °C, highlighting the positive impact of this solution on the thermal management of CoolRoofs. The results also show significant electricity savings, which can reach 20.32 $kWh/m^2/year$. In-depth analysis of the data highlights the environmental benefits, with a potential reduction in the carbon footprint of 27.31 kg CO_2/m^2 over 20 years. The application of CoolRoof coating emerged as an effective solution for improving the energy and environmental performance of cold rooms, paving the way for more sustainable and profitable management of these critical spaces. Further research could explore the examination of this solution in other climate zones as well to optimize performance and cost-effectiveness.

Author Contributions: B.C. and H.O., conceptualization, methodology, software, data curation, formal analysis, investigation, and writing—original draft; R.S., resources, writing —review and editing, validation, supervision, and project administration; O.M., M.R. and M.E.G., visualization, super-vision, and project administration. All authors have read and agreed to the published version of the manuscript.

Funding: The APC was funded by Cool Roof.

Data Availability Statement: This study did not generate any new data, and no additional data are available for sharing.

Conflicts of Interest: There is no conflict of interest.

Nomenclature

ϕ_{cond}	Conducted heat flux
ϕ_{absor}	Absorbed solar heat flux
ϕ_{rad}	Radiative heat flux
ϕ_{conv}	Convective heat flux
T_{si}	Internal surface temperature
T_{se}	External surface temperature
T_i	Indoor temperature
T_{sky}	Sky temperature
T_C	Consign temperature
T_o	Ambient temperature
T_{sb}	the temperature of the reference black surface
T_{sw}	the temperature of the reference white surface
ε	Emissivity
σ	Stefan–Boltzmann constant
I	Solar irradiance
r	Reflectivity
h_c	Convective heat transfer coefficient
R_{i_se}	Thermal resistance between the interior and the surface

References

1. Nagasue, M.; Kitagawa, H.; Asawa, T.; Kubota, T. A Systematic Review of Passive Cooling Methods in Hot and Humid Climates Using a Text Mining-Based Bibliometric Approach. *Sustainability* **2024**, *16*, 1420. [CrossRef]
2. Piselli, C.; Pisello, A.L.; Saffari, M.; de Gracia, A.; Cotana, F.; Cabeza, L.F. Cabeza Cool Roof Impact on Building Energy Need: The Role of Thermal Insulation with Varying Climate Conditions. *Energies* **2019**, *12*, 3354. [CrossRef]
3. Chen, J.; Lu, L.; Gong, Q.; Wang, B.; Jin, S.; Wang, M. Development of a new spectral selectivity-based passive radiative roof cooling model and its application in hot and humid region. *J. Clean. Prod.* **2021**, *307*, 127170. [CrossRef]
4. Tian, D.; Zhang, J.; Gao, Z. The advancement of research in cool roof: Super cool roof, temperature-adaptive roof and crucial issues of application in cities. *Energy Build.* **2023**, *291*, 113131. [CrossRef]
5. Tarek, N.; Aly, A.M.; Ragab, A. Energy-Efficient Passive Cooling Design for Residential Buildings in Hot and Arid Climates: A Parametric Study. *Aswan Univ. J. Sci. Technol.* **2024**, *4*, 80–95. [CrossRef]
6. Rawat, M.; Singh, R.N. A study on the comparative review of cool roof thermal performance in various regions. *Energy Built Environ.* **2022**, *3*, 327–347. [CrossRef]
7. Bozonnet, E.; Doya, M.; Allard, F. Cool roofs impact on building thermal response: A French case study. *Energy Build.* **2011**, *43*, 3006–3012. [CrossRef]
8. Macintyre, H.L.; Heaviside, C. Potential benefits of cool roofs in reducing heat-related mortality during heatwaves in a European city. *Environ. Int.* **2019**, *127*, 430–441. [CrossRef]
9. Synnefa, A.; Santamouris, M.; Akbari, H. Estimating the effect of using cool coatings on energy loads and thermal comfort in residential buildings in various climatic conditions. *Energy Build.* **2007**, *39*, 1167–1174. [CrossRef]
10. Yang, Y.K.; Kim, M.Y.; Chung, M.H.; Park, J.C. PCM cool roof systems for mitigating urban heat island—An experimental and numerical analysis. *Energy Build.* **2019**, *205*, 109537. [CrossRef]
11. Roman, K.K.; O'Brien, T.; Alvey, J.B.; Woo, O. Simulating the effects of cool roof and PCM (phase change materials) based roof to mitigate UHI (urban heat island) in prominent US cities. *Energy* **2016**, *96*, 103–117. [CrossRef]
12. Saffari, M.; Piselli, C.; de Gracia, A.; Pisello, A.L.; Cotana, F.; Cabeza, L.F. Thermal stress reduction in cool roof membranes using phase change materials (PCM). *Energy Build.* **2018**, *158*, 1097–1105. [CrossRef]
13. Kitsopoulou, A.; Bellos, E.; Sammoutos, C.; Lykas, P.; Vrachopoulos, M.G.; Tzivanidis, C. A detailed investigation of thermochromic dye-based roof coatings for Greek climatic conditions. *J. Build. Eng.* **2024**, *84*, 108570. [CrossRef]
14. Hu, J.; Yu, X.B. Adaptive thermochromic roof system: Assessment of performance under different climates. *Energy Build.* **2019**, *192*, 1–14. [CrossRef]
15. Mourou, C.; Zamorano, M.; Ruiz, D.P.; Martín-Morales, M. Characterization of ceramic tiles coated with recycled waste glass particles to be used for cool roof applications. *Constr. Build. Mater.* **2023**, *398*, 132489. [CrossRef]
16. Elnabawi, M.H.; Alhumaidi, A.; Osman, B.; Alshehhi, R. Cool Roofs in Hot Climates: A Conceptual Review of Modelling Methods and Limitations. *Buildings* **2022**, *12*, 1968. [CrossRef]

17. Arunraj, E.; Hemalatha, G.; Noroozinejad Farsangi, E. A Novel Lightweight Phase-changing Cooling Roof Tile. *Int. J. Eng.* **2021**, *34*, 1398–1406. [CrossRef]
18. Pisello, A.L.; Cotana, F. The thermal effect of an innovative cool roof on residential buildings in Italy: Results from two years of continuous monitoring. *Energy Build.* **2014**, *69*, 154–164. [CrossRef]
19. Zinzi, M.; Agnoli, S.; Ulpiani, G.; Mattoni, B. On the potential of switching cool roofs to optimize the thermal response of residential buildings in the Mediterranean region. *Energy Build.* **2021**, *233*, 110698. [CrossRef]
20. Sinsel, T.; Simon, H.; Broadbent, A.M.; Bruse, M.; Heusinger, J. Modeling the outdoor cooling impact of highly radiative "super cool" materials applied on roofs. *Urban Clim.* **2021**, *38*, 100898. [CrossRef]
21. Yu, J.; Qian, C.; Yang, Q.; Xu, T.; Zhao, J.; Xu, X. The energy saving potential of a new ventilation roof with stabilized phase change material in hot summer region. *Renew. Energy* **2023**, *212*, 111–127. [CrossRef]
22. Islam, K.; Ahammad, T.; Pathan, E.H.; Khandokar, R.H. Analysis of Maximum Possible Utilization of Solar Radiation on a Solar Photovoltaic Cell with a Proposed Model. *Int. J. Model. Optim.* **2011**, *1*, 66. [CrossRef]
23. Singh, S.P. Sunayana Cool Roof Technology. *Int. J. Sci. Res. Dev.* **2017**, *4*, 97–101. [CrossRef]
24. Liu, Y.; Harris, D.J. Full-scale measurements of convective coefficient on external surface of a low-rise building in sheltered conditions. *Build. Environ.* **2007**, *42*, 2718–2736. [CrossRef]
25. Ghobadi, P. The Impacts of Cool Colored Roofs and Solar Reflectance Index of Material in Reducing Building Cooling Energy Use. *J. Urban Sustain. Dev. Autumn* **2015**.
26. Mastrapostoli, E.; Karlessi, T.; Pantazaras, A.; Kolokotsa, D.; Gobakis, K.; Santamouris, M. On the cooling potential of cool roofs in cold climates: Use of cool fluorocarbon coatings to enhance the optical properties and the energy performance of industrial buildings. *Energy Build.* **2014**, *69*, 417–425. [CrossRef]
27. Muscio, A. The Solar Reflectance Index as a Tool to Forecast the Heat Released to the Urban Environment: Potentiality and Assessment Issues. *Climate* **2018**, *6*, 12. [CrossRef]
28. Costanzo, V.; Evola, G.; Marletta, L.; Gagliano, A. Proper evaluation of the external convective heat transfer for the thermal analysis of cool roofs. *Energy Build.* **2014**, *77*, 467–477. [CrossRef]
29. Akbari, H.; Konopacki, S. THE IMPACT OF REFLECTIVITY AND EMISSIVITY OF ROOFS ON BUILDING COOLING AND HEATING ENERGY USE. *Therm. Perform. Exter. Envel. Build.* **1998**, 29–39.
30. Bretz, S.E.; Akbari, H. Long-term performance of high-albedo roof coatings. *Energy Build.* **1997**, *25*, 159–167. [CrossRef]