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The Potential of Using Passive Cooling Roof Techniques to Improve Thermal Performance and Energy Efficiency of Residential Buildings in Hot Arid Regions

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Abstract: In hot dry regions, the building envelope receives abundant solar radiation, which contributes to heat stress and indoor thermal discomfort. To mitigate overheating inside spaces, cooling is the main basic requirement during most of the year. However, due to the harsh climatic conditions, buildings fail to provide passively the required comfort conditions. Consequently, they are fully dependent on-air conditioning systems, which are huge energy consumers. As roofs are exposed to the sun throughout the daytime, they are estimated to be the main source of heat stress. In return, they can contribute significantly to achieve optimum comfort and energy savings when efficient design strategies are used in an early design stage. To examine the potential for cooling load reduction and thermal comfort enhancement by using cooling roof techniques in residential buildings, a study was performed in the city of Biskra (southern Algeria). Accordingly, an in-field measurement campaign was carried out on test-cells during five days in summer. Three different cooling roof techniques were addressed: (a) cool reflective white paint (CR), (b) white ceramic tiles (CT) and (c) a cool-ventilated roof (C-VR). These roofing alternatives were investigated by monitoring both roof surface temperatures and indoor temperatures. Comparative analysis showed that a cool-ventilated roof is the most efficient solution, reducing the average indoor temperature by 4.95 °C. A dynamic simulation study was also performed based on TRNSYS software to determine the best roofing system alternatives in terms of thermal comfort and energy consumption, considering the hottest month of the year. Simulation tests were run on a base-case model representing the common individual residential buildings in Biskra. Results showed that a double-skin roof combined with cool-reflective paint is the most efficient roofing solution. By comparison to a conventional flat roof, meaningful improvements have been achieved, including reducing thermal discomfort hours by 45.29% and lowering cooling loads from 1121.91 kWh to 741.09 kWh.

Keywords: cooling roof techniques; thermal comfort; energy efficiency; test cells; dynamic simulation; residential buildings; hot arid climate

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1. Introduction

Nowadays, the dependency on energy consumption is increasing exponentially as well as global warming. Studies focused on this issue indicate that the building sector is one of the main contributors to both environment global warming and the energy crisis. This sector is responsible for more than 40% of the total energy consumption, and consequently it is the major producer of global greenhouse gas emissions [1]. In general, a significant portion of the energy consumed in buildings is dedicated to maintaining indoor thermal comfort. This denotes an increased reliance of buildings on mechanical systems that are dependent on electricity generated from fossil fuels [2]. A recent study by Ayçam et al. [3] stated that half of the energy in the buildings is used in heating-cooling and air-conditioning ventilation (HVAC) systems to provide comfort. This energy is essentially electric, so the contribution of building sector electricity use to total electricity consumption is even higher. Otherwise, due to major transformations in living standards and the raising of the building users' comfort requirements, such as electric lighting, air conditioning, and other appliances, residential demand for electricity is expected to be boosted. As a consequence, the energy supply deficit consumed by air conditioning (HVAC) systems is estimated to double by 2030 [4].

In hot dry regions that take up 1/3 of the world's land and are home to 15% of the world's population, cooling is the main basic requirement during most of the year, and about 34% of the energy used addresses cooling needs to mitigate heat gain from solar radiation. In such regions, where buildings are greatly dependent on air-conditioning to provide occupants with comfortable thermal conditions, cooling requirements account for up to 64% during summer heat waves [5]. This fact emphasizes the imperative need to improve climate building design to achieve both optimum comfort and energy savings.

Algeria is a North African country with a coastline on the Mediterranean Sea and a desert interior, the Sahara. As a large country with an area of approximately 2,382,000 km^2, Algeria possesses a diversity of climatic conditions, ranging from extremely hot conditions in the southern regions to a mild Mediterranean climate along the northern coasts. However, with a desert that covers more than 4/5ths of Algeria's territory, the hot arid climate is of primary concern in terms of buildings' thermal performance.

As in most countries, energy use in the building sector in Algeria is undergoing an alarming increase. According to [6], Algeria is the third-largest carbon dioxide (CO_2) emitter among African countries; in 2014, the total emissions reached 147 MT CO_2. Biskra, a middle-sized Algerian city, illustrates the extent of this critical situation. The harsh climate (hot and dry) prevailing in this Saharan region, in addition to the inefficient constructions, resulted in an unprecedented increase in the use of air conditioning systems for cooling the buildings. In this regard, an alarming report noted that, in 2017, electricity energy consumption in the residential sector reached 102.70 Gwh. As stated by the general management of SONELGAZ (National Society for Electricity and Gas) this represents the tenth-highest electricity consumption in the country [7].

The main reason for both overheating and high energy consumption is related to inefficient design of the building's envelope, including: wrong orientation, large glazing area with no shading devices, low-quality materials, etc. According to Yu et al. [8], the building's energy demand is directly associated with the efficiency of its envelope [8]. The building envelope consists of structural materials and finishes that enclose space, separating inside from outside. This includes walls, roofs, openings (windows, doors), and all the surrounding exterior surfaces of a building that provide protection to the occupants. Design features and material properties of the envelope can significantly lower the building's energy consumption. Furthermore, as reported by the literature review, the climate is one of the most important factors affecting the envelope's design in terms of thermal comfort and energy efficiency. Different climates (hot/dry, hot/moist, temperate, or cold) will suggest different design strategies. Specific designs and materials can take advantage of or provide solutions for the given climate [9], while the building's envelope design can affect 20–60% of the building energy input, making it crucial for achieving energy efficiency [10].

In this regard, a well-designed envelope that considers hot and arid regions is expected to ensure a lower heat load penetrates inside the building, followed by a reduction of the energy requirement for cooling. To do this, the envelope should be designed according to specific cooling strategies that will work as a total system to achieve optimum comfort and energy savings [11]. In general, the main design principles of passive cooling are intended to reduce or eliminate external heat gains during the day and maximize air movement to cool the building and its occupants when exterior temperatures are lower by night [12]. Natural cooling sources including air movements, evaporative cooling, and earth coupled thermal mass can also provide thermal comfort [13].

Among envelope components, the roofing system is considered the main source of heat penetrating inside the building [14]. Moreover, it can contribute approximately to 70% of the total heat gain inside a building. The reason is that roofs are, in general, horizontal or near horizontal surfaces [9]. As such, they are exposed to sunlight throughout the daytime, and consequently receive the maximum direct solar radiation. Being an essential interface between the indoor and outdoor, the exterior roof surface constantly interacts with the external environment in different forms, which include the reflection of incident solar radiation, the emission of infrared thermal radiation, the absorption of incoming atmospheric radiation, and so forth [13]. The process significantly influences the roof heat gain, thus affecting building energy consumption. In this regard, by analyzing the hourly average values of beam and diffuse radiation for a typical summer day, Amer [15] found that a horizontal roof receives around 1.5 times more solar radiation than a west-facing wall and about four times more than a south-facing wall. On annually based records, the horizontal surface also receives radiation at higher levels than are received by vertical walls. Furthermore, considering the heat transfer in a roof, it appears that the portion of the absorbed solar radiation that reaches the inner surface is enhanced by the physical properties of the material surfaces [14]. Hence, these properties have a great influence on determining the amount of heat conducted through the surface and can significantly lower the cooling loads [16]. Consequently, an optimal design of the roof may provide significant reductions in cooling loads.

In hot and arid climates which are characterized by high solar radiation intensity, roofs are estimated to be the main sources of overheating risk inside spaces. Works available in the scientific literature documented that the roof covers 36.7% of the total solar radiation falling on a single-story building [13,17] and contributes about 50% of the inside heat gain [18]. Therefore, the International Energy Agency reported that more than 40% of cooling energy expected savings is directly attributable to the thermal behavior of roofs [19].

In this view, to reduce the amount of heat transfer induced by the thermal behavior of a roof, especially for climates dominated by cooling loads, reflective roofing represents an interesting passive cooling technique able to mitigate substantially building energy requirements for cooling [20].

2. The Potential of Using Cooling Roofs as a Design Passive Strategy in Hot and Arid Regions

A reflective roof or a cool roof is basically a roof that reflects and emits the sun's heat back to the sky instead of transferring it into the building below [21]. Furthermore, as cool roofs present high solar reflectance and also high infrared emittance [22], they have the ability to keep the roof surface temperatures down. This leads to substantially reduced heat conduction to the building. In this regard, the amount of solar radiation that is reflected by a cool roof surface is extensive due to the higher reflectivity of the roof. Two surface properties that affect the thermal performance of these roof surfaces are solar reflectance (SR) (reflectivity or albedo) and infrared emittance (or emissivity). Accordingly, conventional roofing materials have a SR of 0.05–0.25, whilst reflective roof coatings can increase the SR to more than 0.60. All these aspects point to the potential of this type of roofing systems in terms of environmental, eco-friendly and cost-efficient resources to enhance the thermal comfort and energy efficiency in buildings. Moreover, the potential of cool roofs to reflect the sun's heat makes them most convenient when the solar radiation intensity is very high and maximum diurnal variation occurs.

In this regard, research conducted in the desert region of Haifa demonstrated that the difference in the maximum external surface temperature between a black-and-white roof in the desert during summer can be between 30 °C to 40 °C [23]. Furthermore, the benefits from a cool roof include the reduction in cooling energy consumption, carbon emissions, air pollutants, and urban heat island problems [24,25]. A reduction of from 10% to 40% in air conditioning energy was unregistered when applying a cool roof on a building [26–28]; instead, Ramamurthy et al. [29] have shown that a white membrane roof surface fluctuated in a range between 10 °C and 45 °C during summer months, while the black membranes ranged between 10 °C and 80 °C. Cool roofs are also appreciated for being low-cost and energy-efficient retrofits that are easy to install on the building envelope.

Beside these solutions relating to reflective roofs, many studies reported in the scientific literature have addressed a broad spectrum of passive roofing methods and treatments for residential buildings in hot areas that are effective in improving energy and thermal performance in buildings and environments with different levels of efficiency [30,31]. In this regard, roofing systems such pond roofs, ventilated roofs and shaded roofs are potentially suitable for residential buildings in Biskra, given that the most common types of construction are flat roofs. Furthermore, it was noticed that when combined with cool materials, the above cooling roof techniques improve their cost efficiency on both building and urban levels (low energy and natural climatic control) [32–34].

Despite its importance, the cool-roof technology has not been sufficiently investigated and applied in Algeria. From this point of view, it will be interesting to assess the effectiveness of certain passive cooling roof systems in improving the thermal performance of residential buildings under desert climate conditions and within the Algerian context. A research study was carried out to address the issue. The study was undertaken in southern Algeria, and precisely in Biskra where a very hot and arid climate prevails. It aims to compare different passive cooling roof techniques in terms of their potential to overcome overheating, which leads eventually to reducing the energy spent for cooling and air conditioning. Moreover, the research intends to explore how to effectively adapt these techniques to improve the thermal conditions in non-air conditioned buildings and mitigate the energy consumption in air-conditioned buildings. More in detail, this study focuses on the possibility of applying accurate passive roof design concepts and technologies to existing residential buildings.

The research process has been performed at two levels: (a) experimental monitoring in small-scale models treated with cooling roof techniques, and (b) numerical analysis of a base case model where variants of cooling roof systems have been implemented. From the available literature, three passive cooling roof techniques were investigated to determine which was the most suitable, low cost and easy to install on existing roofs in Biskra. These passive cooling techniques were comparatively tested in a real hot dry environment using four test cells. Then, simulations were carried out with TRNSYS software in order to quantify thermal comfort improvements, energy savings achieved and CO_2 emissions impact. The outcomes from this research have a great potential to reach the expected targets relating to the sustainability of the low-cost residential building stock of southern Algeria showing novel cooling roof systems that are affordable, easy to implement and do not require much maintenance intervention for extensive use in Algeria.

3. Materials and Methods

The research methodology implemented is based on a comparative approach that quantifies the energy consumption and the thermal conditions generated in residential buildings where different selected passive cooling roof systems were used under hot and dry climatic conditions. To examine the effectiveness of the passive roof design techniques, in terms of reducing cooling loads and improving thermal performance with special references to hot arid areas, the study has been developed through two main stages.

The first one involved the thermal characterization of three (03) cooling roof techniques through an experimental campaign using test cells. These small-scale models were tested and monitored in free-floating real climate conditions of Biskra (Algeria) over five days in summer. The cool roof alternatives analyzed are: (a) cool reflective white paint (CR), (b) white ceramic tiles (CT), and (c) a cool-ventilated roof (C-VR). In the second stage, calculations of the energy-saving and thermal comfort improvements achieved through the whole hottest month (July) by using cool roofing techniques in residential buildings were carried out through a series of dynamic simulations. A representative family house located in the city of Biskra was used as a case study to assess the efficiency of the roofing techniques which are best suited to hot and arid climatic conditions. The selected residential building has been modelled under TRNSYS V17 software, and the model has been calibrated and validated using in-situ measurements. Furthermore, CO_2 emissions were also calculated.

As a whole, the study aims to assess a broad number of passive roof enhancements to extract the most efficient passive roof design methods for cooling purposes with the fewest possible restrictions, considering the Algerian context. Figure 1 illustrates the research methodology, shows the workflow of the study and provides details on the methods used in each stage. The experimental investigation, the modelling procedure and simulation, as well as the results are discussed in the following sections.

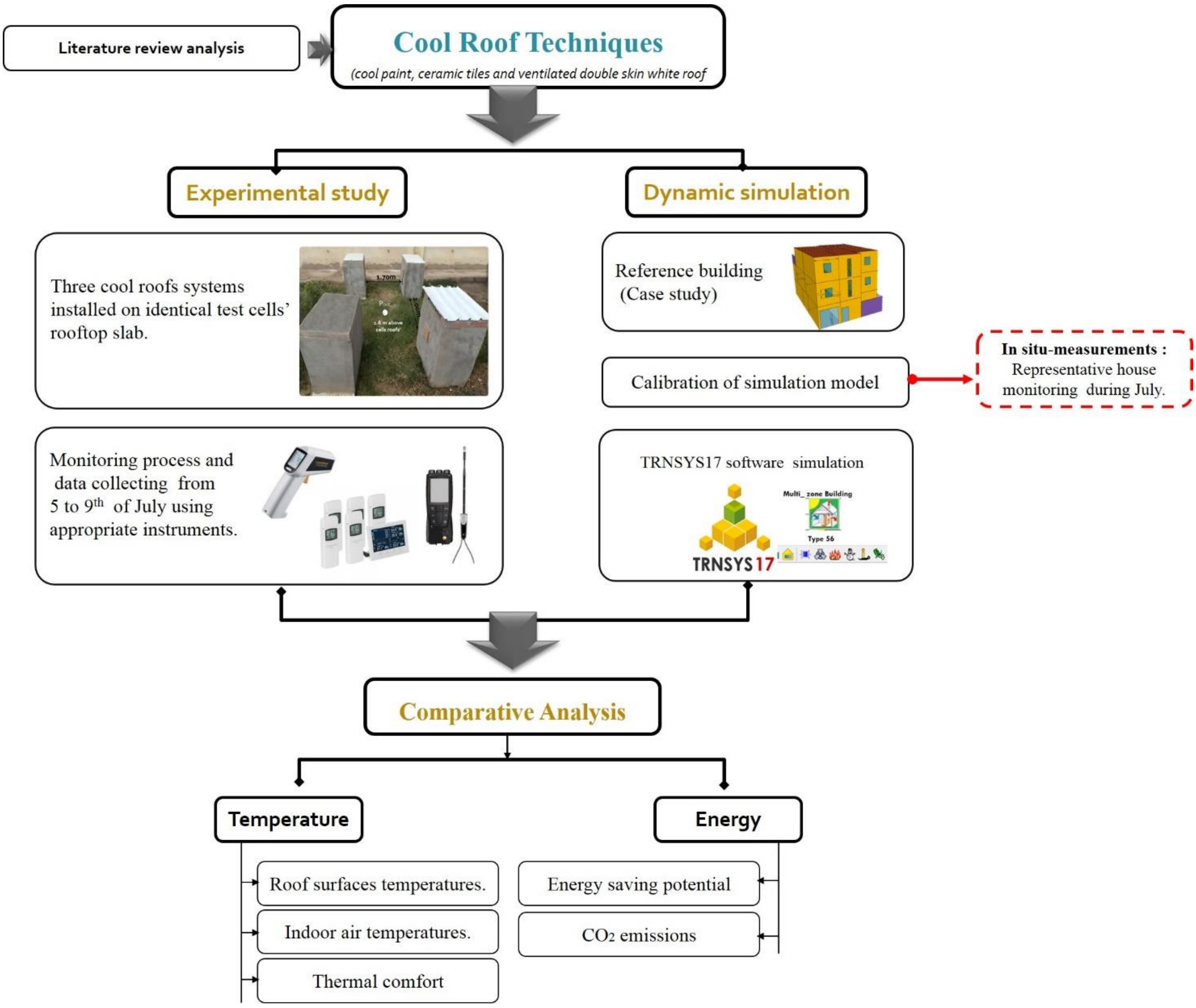


Figure 1. Research methodology workflow.

3.1. Experimental Setup

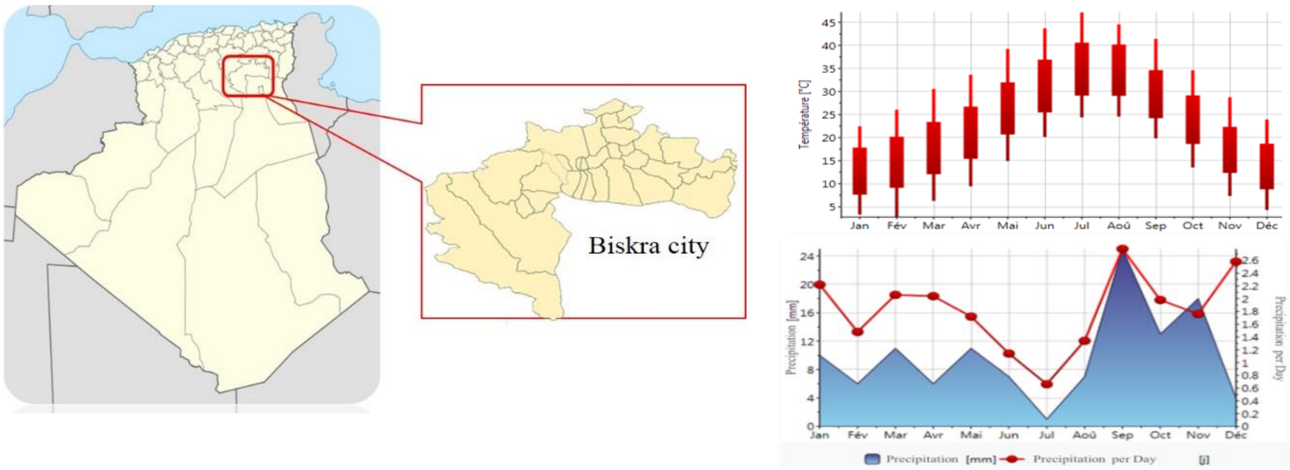
To assess the effect of the selected passive cooling roof techniques on the thermal performance of a typical residential building under hot arid climate conditions, in situ measurements were carried out in Biskra. Four (04) different roofing techniques were examined; the first one is the common type of roofing structure used locally, which consists of a flat roof made of hollow-core blocks and reinforced concrete compression slabs. The other three roofing systems were generated from the basic flat roof structure by adding specific covering materials and components. The three passive cooling techniques, namely cool reflective white paint (CR), white ceramic tiles (CT) and a cool-ventilated roof (C-VR), were compared to the common type of roofing structure that serves as a base case (REF).

Each passive cooling roof system was tested by monitoring its thermal behavior in the real conditions of the study site.

Four test cells were designed to support the roofing systems under study. The measurement campaign was conducted during the month of July. The parameters measured were: outdoor dry bulb temperature, ambient air temperature (indoor temperature), indoor and outdoor relative humidity (%), and roof and ceiling surfaces temperatures. The three techniques were assessed simultaneously through infield monitoring of the four test cells, including a reference cell which was fitted with the base-case roof. Data collected about the examined roofing systems in terms of their thermal performance were used to identify the most suitable passive techniques to be implemented in the dynamic simulation study.

3.1.1. Study Site and Climatic Conditions

The purpose of conducting a climate analysis related to the study site is to highlight the limits and even the opportunities for passive envelope improvements that include the selection of the most appropriate roofing system in terms of reducing cooling loads and improving thermal performance. The study was conducted in Biskra (34.8° N, 5.73° E and 87 m) located in southeast Algeria. Based on the Köppen climate classification, Biskra's climate falls in zone BWh; thus, it is characterized by hot and dry weather conditions. Summers are extremely hot; temperatures can range from 38 °C to 48 °C with 2 mm average rainfall during July (the hottest month of the year); winters are relatively cold. In these severe climatic conditions, the hot season is quite lengthy and occurs from June to October (Figure 2).



(a) (b)

Figure 2. (**a**) Location of Biskra in Algeria. (**b**) Monthly average temperature in °C, and monthly average precipitations in mm (period from 2010 to 2020).

According to the ASHRAE Standard, the thermal comfort zone for the hot and arid climate of Algeria ranges between 18 °C to 30 °C, while relative humidity ranges from 40% to 60% [35]. Consequently, it assumes that air-conditioning is required 24 h per day, given that the comfort conditions in July are reached only during 0.4% of the whole month.

3.1.2. Test Cells Description

Four identical test cells were built to simultaneously compare the considered passive cooling roof techniques in terms of their thermal behavior. Each test cell is 1.20 m × 0.80 m × 1.0 m long, wide, and high, respectively. The cells were oriented to the south and set up in a clear area of a house garden such that no cell shaded any other. None of the four cells, in turn, were in any shade of the neighborhood (Figure 3a). All four sides of each cell were made of hollow bricks of 10 cm thickness and had their external faces plastered with a 0.02 mm layer of cement (U = 1.91 W/m^2·K) to limit air infiltration and thermal bridges. The different roofs were hermetically sealed over the built structures.

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

Figure 3. (**a**) General view of the four test cells showing their arrangement. (**b**) The studied roofing techniques after their application on the test cells, namely from upper left to right and from top to bottom: reference test cell with base-case roof (REF), test cell with cool reflective white paint (CR) test cell with white ceramic tiles (CT) and test cell with a cool-ventilated roof (C-VR).

Each cell was provided with a small square window of 15 cm per side that was set in the north face. A wooden frame was used to open this window in order to take temperature measurements inside the cell. The floor was made of a 10-cm-thick concrete slab (U = 4.40 W/m^2·K) supported on a double wood panel with polyurethane foam in between and set 15 cm above the ground. The detailed composition of the cells is given in 3D figures. The roof covering is the only construction component that differs among the studied structures. The cell fitted with a bare gray roof was used as the referenceI) and represents the common configuration of the roofing system in Biskra; namely a roof of 20 cm thickness made of a reinforced concrete slab over hollow-core blocks (U = 2.49 W/m^2·K). The three passive cooling techniques, namely cool reflective white paint (CR), white ceramic tiles (CT) and a cool-ventilated roof (C-VR), were compared to the common type of roofing structure that serves as a base case (REF) (Figure 3b).

3.1.3. Description of the Studied Passive Cooling Techniques

Three passive cooling techniques were selected for improving the thermal behavior of the roofs: cool reflective white paint (CR), white ceramic tiles (CT) and a cool-ventilated roof (C-VR). Each flat roof of three test cells was equipped with one of these techniques. The fourth test cell, on which none of the cooling techniques were implemented, was used as base case. Figure 4 illustrates the studied passive techniques, details their design and construction, and explains their thermal behavior.

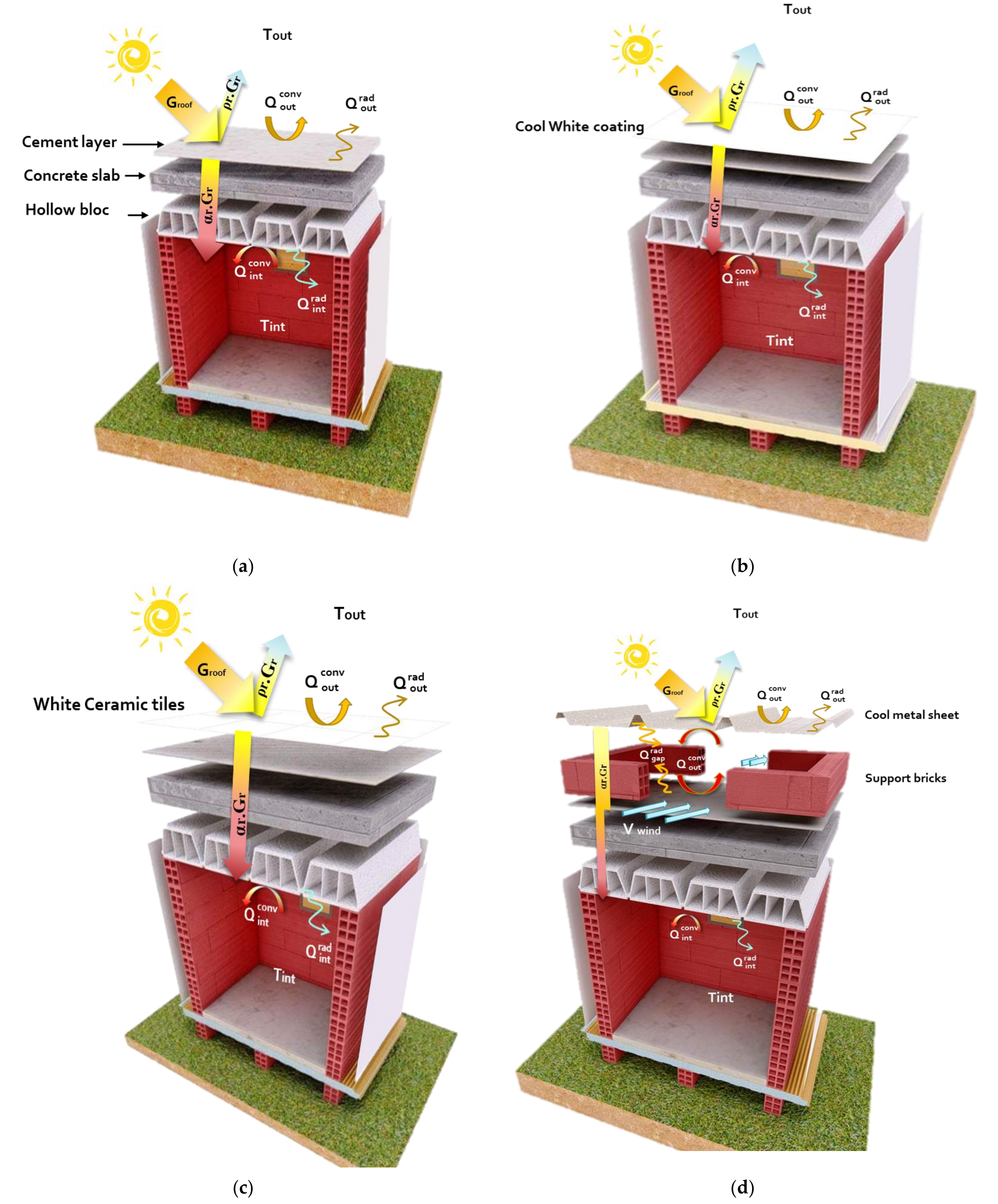


Figure 4. Schematic 3D sections of the test cells: (**a**) base case (REF), (**b**) cool reflective white paint (CR), (**c**) white ceramic tiles (CT), and (**d**) cool-ventilated roof (C-VR), showing the construction materials of the different roofing systems with heat flux implemented by the passive cooling techniques.

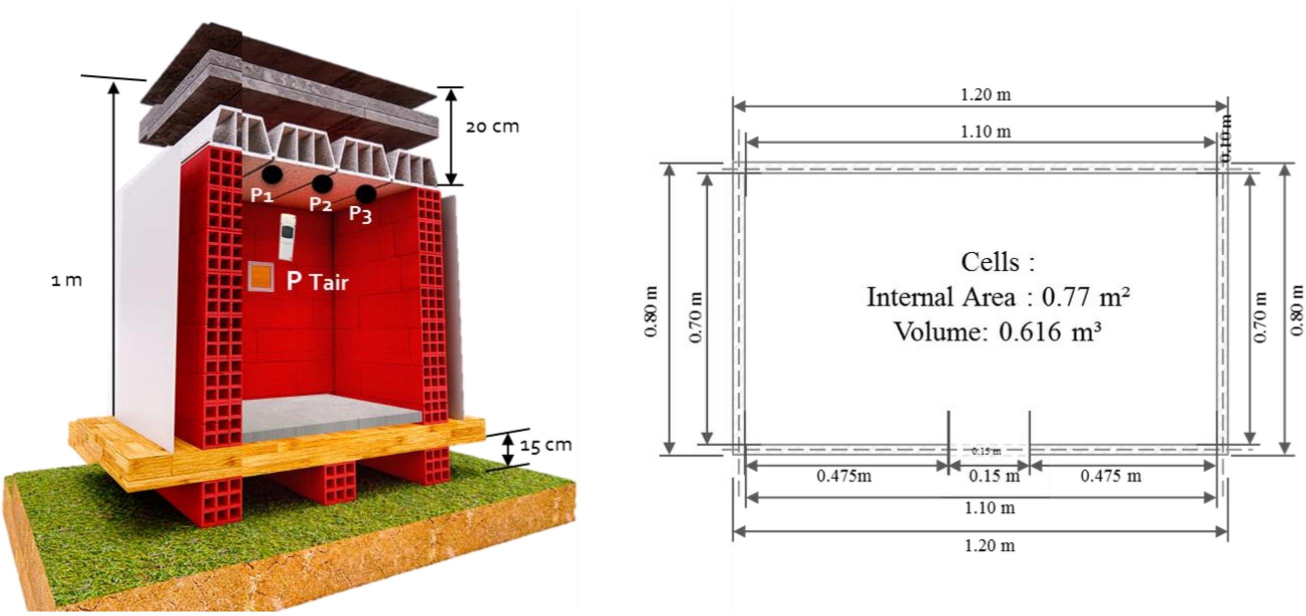
Regarding energy savings resulting from the application of cool roofs, the first applied passive cooling technique was a cool reflective roof (CR). This technique consists of a roofing system that reflects solar radiation and emits heat, keeping roof surfaces cool under the sun while slowing down the heat transfer into interiors. This particularity is due to the two main properties of the so-called cool materials that are used: increased solar reflectance and high infrared emittance [36]. As part of the experimental monitoring campaign, the application of a cool roof material was tested. The selected cool roof technology was a white waterproof coating based on nano hollow silica beads (20 μm micrometers), titanium oxide, water and silicone acrylic. These nanoparticles present a high reflectance of the visible spectrum of up to 90.4% and an infrared value of 94.6%, which minimizes the amount of heat absorbed by a surface and decreases heat transfer. This product is certified by Japan Industrial Standards JIS R 3106:1998 (Figure 4b).

The opportunity of using cool tiles (CT) as a passive device was also explored. This second technique offers the advantage of using a cheap and widely available material in the Algerian construction market. Accordingly, a cool roof based on white-painted tiles was tested as an alternative to cool paints. This covering system has many advantages; in particular, it is weather-resistant and highly reflective with low conductivity (Figure 4c). The infield measurements allowed assessing its resilience and thermal performance in terms of heat transfer and surface temperature fluctuations.

The last system tested was a cool-ventilated roof (C-VR). Basically, this is a double-skin roof fitted with a reflective material on its exterior surface. Researchers found that such a device when used on the roof can increase its thermal efficiency by up to 85% [37]. To assess this system, the initial roof surface (concrete slab) was covered by a metal sheet, and the two layers were separated by an air gap. The upper side of the double-skin roof is made of galvanized steel. A corrugated sheet metal plate of 1.20 m $\times$ 0.8 m and 20 mm thick was used. Its exterior surface was treated with a high thermo-reflective paint in order to increase its infrared emittance and reflectance propriety. Here, the sheet metal plate has the same behavior as a radiative shield, by which a significant fraction of the solar radiation is reflected to the sky. To provide a ventilated cavity, the sheet metal plate was lifted on bricks to a height of 10 cm. The bricks were placed on both sides of the roof, which allowed air to circulate through transverse openings of 25 cm $\times$ 10 cm (inlet and outlet). Moreover, the air cavity was perfectly shaded and the openings were in the wind direction (northwest and southeast) (Figure 4d).

3.1.4. Instrumentation and Monitoring Schedule

Monitoring was done using three instruments at 1-h intervals. Instrument probes were fixed inside the cells using a tripod sited in the middle (Figure 5). A MISOL thermo-hygrometer sensor was used through different sensors to record the indoor air temperature data in the center of each test cell and outdoor dry bulb temperature with an accuracy of ±1 °C (−40 °C to + 60 °C). The temperatures of interior and exterior surfaces were measured by the laser liner infrared Thermo Spot surface, which ensured an accuracy of ±2.5 °C + 0.05 °C (−10 °C to 365 °C). The measurements were taken at three spots uniformly distributed on the outer and inner roof surfaces; then, an average value was deducted for each side. A specific probe of Testo 480 was used to measure air velocity inside the air gap with an accuracy of ±0.1 m/s (0 to +20 m/s). The same instrument was used to monitor meteorological data while every 2 h, air temperature, relative humidity and wind speed were recorded under shadow.



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

Figure 5. (**a**) 3D section of the base case test cell showing interior measurement points. (**b**) Plan and dimensions of a test cell.

To ensure the accuracy of data collected during the experimental period, prior tests were conducted in 2019 to check that all the test cells had the same thermal behavior. Generally, a small difference of less than 1 °C (0.5 to 0.7 °C) was registered, which proves the reliability of the instruments as well as the accuracy of the probes and scale models. The final stage of the measurement campaign was done in summer 2021; the different roofing systems were monitored during the hottest month of the cooling season (July) and for five successive days (from 5 to 9 July 2021). During the experimental period, the weather was clear and sunny, with no wind.

4. Dynamic Simulation Study

A set of numerical tests were carried out using 'TRNSYS V17′ software to assess the effectiveness of cooling roof solutions on thermal comfort and energy consumption enhancement for a typical residential real-scale building during the hottest month of the cooling season. On the basis of the experimental investigation which compared the thermal behavior of several roofing alternatives, the two most efficient techniques, namely a cool-double skin ventilated roof (C-VR) and cool painted roof (CR), were chosen to perform the simulations. The potential benefit of this technology in a hot arid climate is studied on the basis of a calibrated simulation to extend the results. Furthermore, CO_2 emissions and energy cost savings were also calculated.

4.1. Base Case Model Description

A typical residential building that represents the common construction practices widely used in Biskra was chosen to perform different simulation scenarios. A building simulation model of the case study building was developed based on the existing building design and material characteristics. The two-story single-family house was modelled under the software as a rectangular row, aligned north, with a floor area of 185.25 m^2 and a total volume of 592.80 m^3 (Figure 6). The living room in the first floor was selected for conducting the simulation tests, given that it is the most frequented and, therefore, the most important space in the house. In addition, due to its location at the corner of the top floor and its double orientation, it is subject to solar radiation through three sides including the roof. Thermal comfort conditions inside this room are assumed to be unfavorable in terms of heat gain.

Figure 6. (**a**) View of the single-family house taken as reference case. (**b**) 2nd floor plan showing the living room. (**c**) 3D simulation model. (**d**) Roof construction details.

In the generated model, the studied zone (living room) is set in contact with the external environment through the roof with a net area of 25 m^2, while the west and south walls are adjacent to other rooms, stated as adiabatic. A window of 1.20 m^2 of glazed surface area is located in the north facade. The total volume for heating or cooling is 74.95 m^3. The core material is reinforced concrete with brick infill. The roof is on hollow concrete blocks and a reinforced concrete slab covered with a layer of plaster on the inside face; no protection or coating membranes are provided on the external face.

Table 1 shows the main characteristics of the materials used in the reference building. In the table, the thermo-physical properties are ordered from the interior to the exterior of the building; the values are defined according to the Technical Regulation Documents of the Ministry of Housing and Urbanism in Algeria (DTR) [38]. The materials used in the cool roofing systems are listed in Table 2 along with their thermal emittance and solar reflectance values.

Table 1. Thermo-physical properties of the materials used in the construction components of the base case building.

Building Elements			Thickness (m)	Thermal Conductivity (W/m·K)	Density (kg/m^3)	Specific Heat Capacity (kJ/kg·K)	U-Value (W/m^2·K)
Roof		Mortar	0.04	1.15	1900	1.08	2.49
		Concrete slab including hollow blocks	0.20	1.45	1450	1.08	
		Plaster	0.02	0.35	800	0.93	
Walls	**Exterior**	Mortar	0.04	1.15	1900	1.08	1.12
		Hollow brick	0.15	0.48	900	0.93	
		Air cavity	0.05	0.024	1.22	1.00	
		Hollow brick	0.02	0.35	800	0.93	
		Plaster	0.02	0.35	800	0.93	
	Partition	Plaster	0.02	0.35	800	0.93	1.86
		Hollow brick	0.02	0.35	800	0.93	
		plaster	0.02	0.35	800	0.93	
Floor	**Internal**	Tile	0.02	1.7	2200	0.93	1.98
		Mortar	0.04	1.15	1900	1.08	
		Concrete slab including hollow blocks	0.20	1.45	1450	1.08	
	Ground	Tile	0.02	1.7	2200	0.93	3.64
		Mortar	0.04	1.15	1900	1.08	
		Concrete	0.10	1.75	2500	1.08	
Window		Single glazing			5.74		

Table 2. Thermo-physical properties of the materials used in the passive cooling roofs.

Materials	Thickness (m)	Thermal Conductivity (W/m·K)	Density (kg/m^3)	Specific Heat Capacity (kJ/kg·K)	Solar Reflectance (σ) and Thermal Emittance (ε)
Galvanized metal [39]	0.006	61	7520	500	σ = 0.92 ε = 0.90
Cool paint					σ = 0.94 ε = 0.90
Cool tiles					σ = 0.80 ε = 0.90

4.2. Simulation Framework and Settings

TRNSYS is a transient system simulation software that evaluates comfort levels and energy consumption of buildings [40,41]. Through TRNSYS 17, a three-dimensional model of the reference building was drawn with a SketchUp interface using a TRNsys 3D plug-in. The potential of the best selected techniques is evaluated over a time period of 31 days (744 h) of July with a time step of 1 h. The living room was modelled under TRNbuild using type 56 (multi-zone building). According to the modeling process, specific information related to the internal loads from occupancy (people), infiltration rate, lighting, electrical equipment, or any other source of energy is used as input data (Table 3).

Table 3. Internal heat gain for building model.

Internal Heat Gain		Value
Occupancy	Density (people/m^2)	0.0844
	Activity factor	0.9
	Summer CLO	0.5
	Schedule	9–10 h = 40% 10–12 h = 0% 13–18 h = 80% 18–19.30 h = 20% 19.30–8 h = 100%
Lighting	Incandescent lamps with average power	15 w/m^2 (scale = 4)
	Schedule	9–10 h = 100% 10–18 h = 0% 18–21 h = 100% 21–8 h = 0%
Infiltration rate		0.5 ACH/h
Set-point temperature	Summer cooling	23–26 °C
Home appliance		45 W/m^2

After modeling, the study proceeded to free-floating simulations to understand the thermal behavior of the model according to several roofing scenarios. Simulation outputs were compared by implementing the following indicators:

1. Thermal comfort of the occupants was analyzed in terms of discomfort hours during the cooling season (the thermal comfort zone for Biskra range between 18 °C to 30 °C [35].
2. Cooling demand was calculated using constant set-points established at 26 °C, respectively, according to Technical Regulation Documents of the Ministry of Housing and Urbanism in Algeria [42,43]. The power of the cooling system is considered unlimited.
3. The electricity emission factor used in Algeria is 0.65 kg of CO_2/kWh. CO_2 emissions are calculated using the following Equation (1):

$$\text{Monthly Electricity Consumption (KWh)} \times \text{Emission Coefficient (Kg CO}_2\text{/KWh)} \tag{1}$$

4.3. Model Calibration

Before conducting the simulation analysis, the base case model that refers to the analyzed room must first be calibrated-validated. This preliminary step is essential to see how closely the simulated results match the monitored data. The monitoring campaign for the living room was set up in order to measure the most relevant indoor and outdoor temperatures, as well as, top and bottom surface temperatures of the roofs. Using a Testo 480 and Lazer liner thermospots measurement kit, temperature recordings were taken at two-hour intervals from 8 am till 18 pm during the hottest three days in July. The room was not cooled during this period (the air conditioner was switched off) and the window was kept closed. The thermos-hygrometer sensor was placed in the center of the room at a height of 1.4 m.

Two indices of the ASHRAE Guideline 14 were used for the model calibration process: mean bias error (*MBE*) and cumulative variation of root mean squared error *CV*(*RMSE*). These two values were calculated using the following Equations (2) and (3):

$$MBE\ (\%) = \frac{\sum_{i=1}^{Np}(Mi - Si)}{\sum_{I=1}^{NP} Mi} \tag{2}$$

$$CV(RMES)(\%) = \frac{1}{M}\frac{\sqrt{\sum_{I+1}^{NP}(Mi - Si)^2}}{Np} \tag{3}$$

where Mi is the measured data and Si is the simulated data at time interval (i), M is $M = \frac{\sum_{i=1}^{Np} Mi}{Np}$, and Np is the total number of data values. ASHRAE Guideline 14-2014 [44] recommended an hourly MBE value within $\pm$ 10%, while hourly $CV(RMSE)$ values are $\leq$30%. The criteria and limit values set out in [44] indicate that the monitoring of the variables and the analysis of the aforementioned equations between the simulated and measured values defines the reliability of the thermal model.

After comparing the computed and the measured values of the indoor and outdoor air temperature (period of three days in July), it appears that daily variations of the calculated outdoor temperatures (see Figure 7, Tout simulated) follow the daily variation of measured outdoor temperature (Tout measured) with closer values. Likewise, the computed air temperatures in the room are identical (see Figure 7, Tair simulated) and close to the measured temperatures (Tair measured). The graph indicates that there is a maximum difference of 3.04 °C with respect to measured and computed data for outdoor air temperatures while the maximum range between measured and calculated indoor temperatures is equal to 3.33 °C.

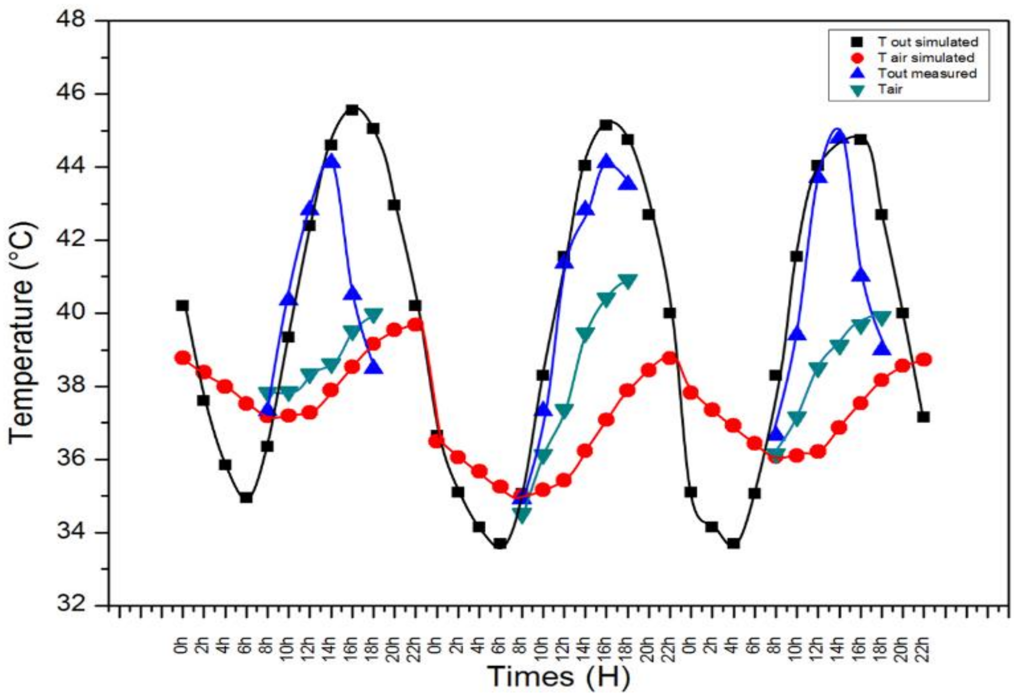


Figure 7. Measured and simulated indoor and outdoor air temperatures during the hottest three days in July.

These reports are verified by the calculation of the MBE and $CV(RMSE)$ values for indoor and outdoor air temperatures (Table 4). For the considered period, MBE and $CV(RMSE)$ of outdoor temperatures were found to be −1.638% and 4.95%, respectively, while MBE and $CV(RMSE)$ of indoor temperatures were found to be 3.833% and 4.39%, respectively. The validation criteria values of the simulation model fall within the acceptable range, given that hourly MBE values are within ±10% and hourly $CV(RMSE)$ values are below 30%. By referring to ASHRAE-14 [44], the developed model confirms its ability to well represent reality. Thus, it is considered calibrated and suitable for use in the following calculations.

Table 4. Validation criteria values of the simulation model.

Validation Criteria	Outdoor Air Temperature	Indoor Air Temperature
MBE (%)	−1.638	3.833
CV(*RMSE*) (%)	4.95	4.39

5. Results and Discussion

5.1. Comparative Analysis of the Studied Cooling Roof Systems Based on Infield Measurements

In climates with strong solar irradiation, such as Biskra, it is important to mention that the thermal behavior of any built structure is primarily influenced by exterior surfaces' material characteristics, solar radiation levels, and wind speeds. Figure 8 illustrates the indoor air temperature fluctuations of all the studied passive cooling techniques in free-floating conditions during five summer days in Biskra. The outside air temperature is also reported. The three cooling roof systems and the base case roof (without any treatment) were monitored mostly under a sunny clear sky with an outdoor air temperature ranging from 33.24 °C to 48.02 °C. In this regard, it is necessary to state that the test cell's indoor air temperature was recorded for comparison purposes only. This temperature does not represent the indoor conditions of a realistic building.

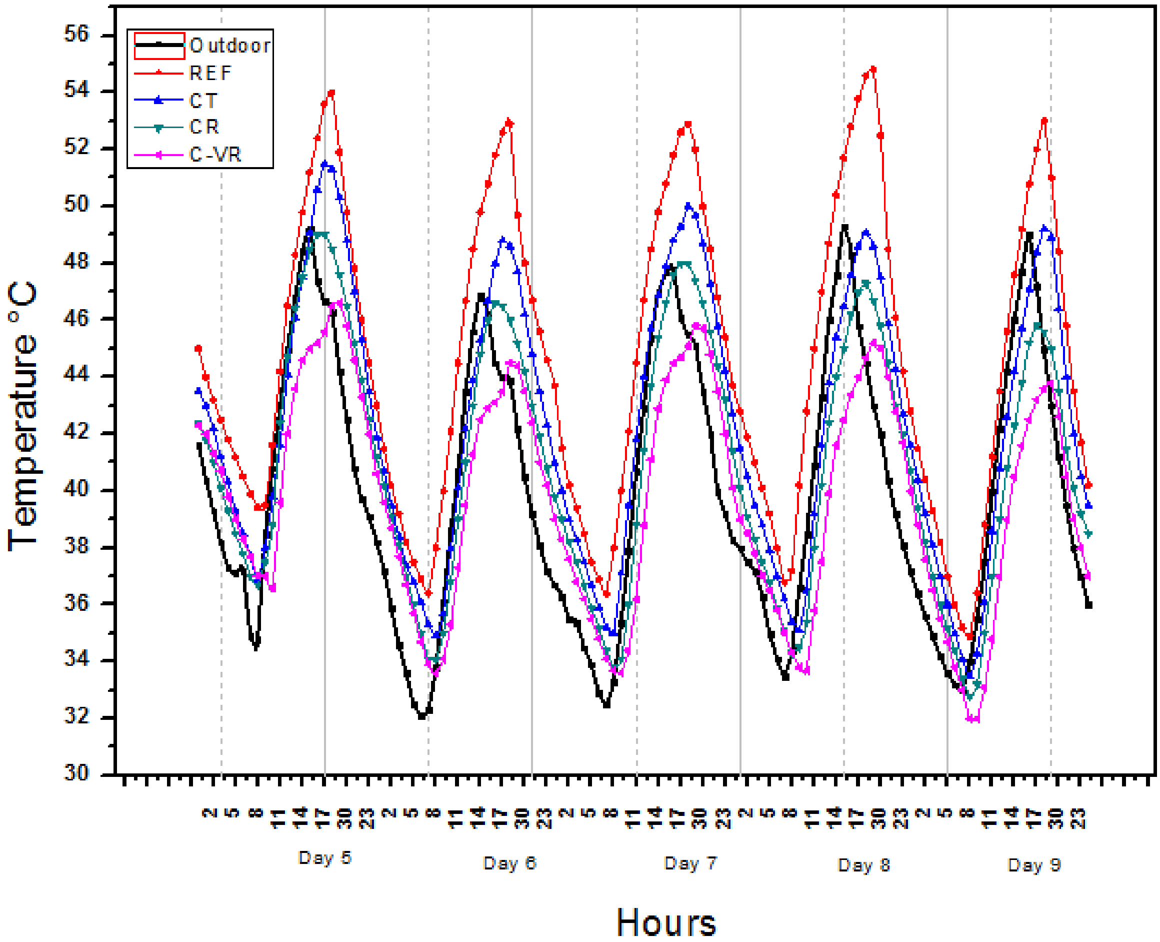
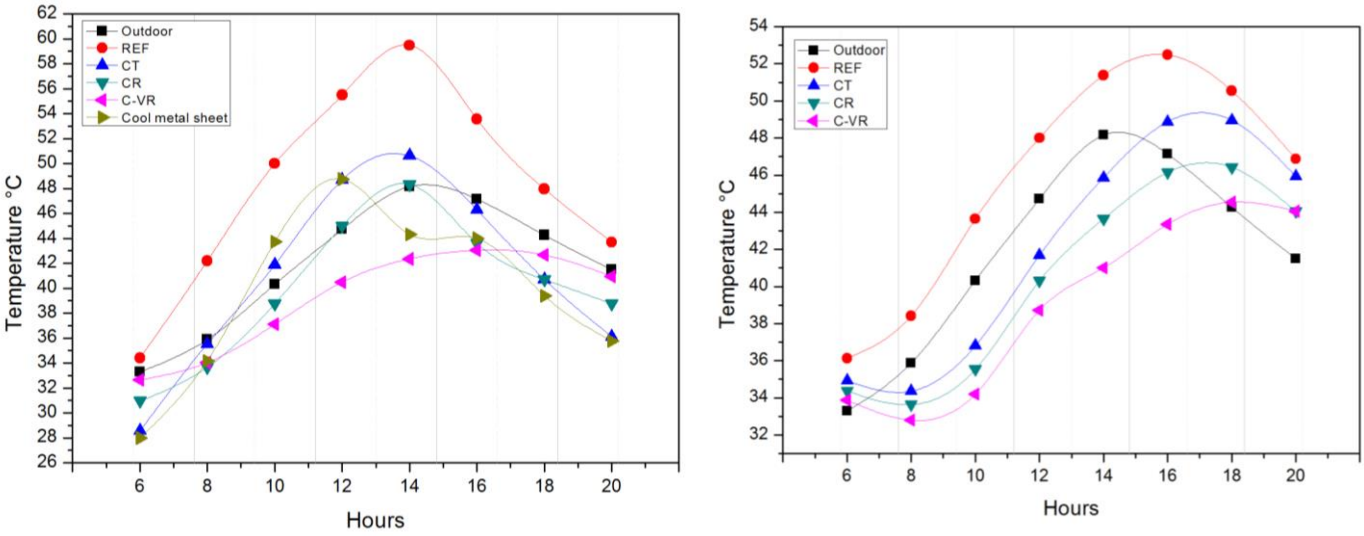


Figure 8. Indoor air temperature profiles of all the test cells from 5–9 July 2021.

Figure 8 shows that all the studied techniques provide a reduction in indoor air temperature compared to the reference test cell (REF). This reduction is maximal in the afternoons. The highest reduction in indoor air temperature is observed with the cool-double skin ventilated roof (C-VR). Graphs in Figures 8 and 9 indicate that C-VR has much lower temperature peaks compared to the reference case and the two other techniques. It achieves the best thermal performance and succeeds in decreasing heat gain from the roof surface by a maximum average of 17.12 °C. The galvanized metal sheet that acts as a second roof protects the main roof surface and receives all excessive solar radiation.



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

Figure 9. (**a**) Diurnal variations of the roof cells' external surface temperatures. (**b**) Diurnal variations of the ceiling temperatures.

Furthermore, the temperatures of the reflective metal sheet layer and the ceiling evolve with the same daily fluctuation. Accordingly, it was observed that when the surface temperature of the reflective layer peaks at 48.76 °C at midday, the ceiling temperature also peaks at 40.50 °C. Likewise, the amount of absorbed solar heat is substantially reduced. Consequently, C-VR managed to reduce the indoor temperature by a maximum average of 8.72 °C when average air speed inside the cavity reached 1.05 m/s compared to the reference case. These results revealed that the air gap between the two layers acts as an insulator by providing resistance to the heat transmission through conduction, convection and radiation. Besides, the white paint applied on the metal sheet top layer reflects 94.6% and absorbs 5.4% of the incident solar rays, which slows down heat flow to the cavity and boosts air circulation and heat loss to the outdoors.

During night-time and early mornings, the cool roof (CR) and the cool-double skin ventilated roof present quite similar indoor air thermal swings due to the effect of roof reflectance, which is insignificant, since there is no ambient radiation. However, the CR manages to record lower external temperatures by a maximum average of 2.20 °C. This is due to long-wave radiation exchanges with the sky during the night; in return, the metal sheet inhibits this advantage for cool ventilated roofs, creating a thermal buffer phenomenon.

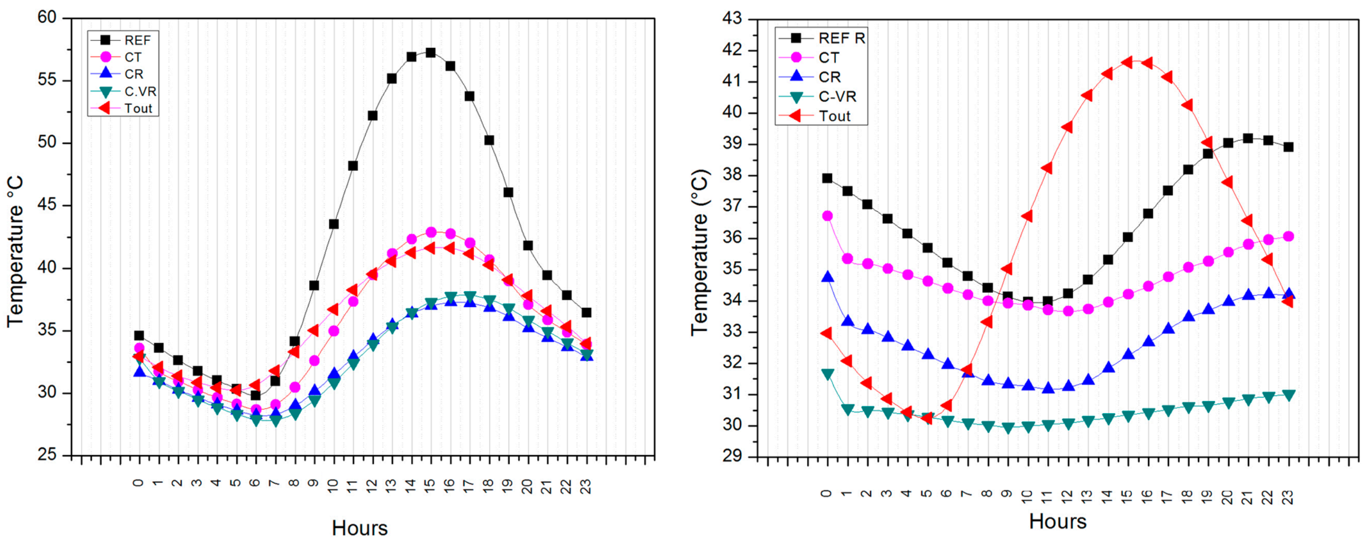
Figure 9 presents profiles of roof and ceiling average surface temperatures considering the three studied passive cooling alternatives. It can be seen that the day-night fluctuation of the temperatures at the external surfaces of the roofs is reduced by 11.4 °C and 8.86 °C, respectively, for CR and cool tiles (CT) compared to the base cell (Figure 9a). CT as a cheap and locally available material demonstrates a low thermal protection due to tile properties, in particular conductivity and heat storage. Likewise, the efficiency of CR is related to its ability to lower surface heat storage by fostering high solar reflectance (minimizing solar absorption) and high thermal emittance (maximizing thermal emittance). Moreover, results indicate that ceiling temperatures inside the REF systematically peaked over 50 °C, while C-VR, CR and CT maintained a much flatter thermal trajectory by 9.12 °C, 6.68 °C and 3.98 °C, respectively. Thus, peaks fall with a small-time lag of 3 to 4 h relative to the outside air temperature (Figure 9b).

5.2. Performance Evaluation of Passive Cooling Roof Techniques Based on Thermal and Energy Simulations

This section analyses the results of the simulation tests that have been implemented to assess the effectiveness of the cool roof technology based on various parameters, in particular: surface temperatures, indoor air temperature, thermal comfort and energy loads. The comparison is between the reference case (REF)—consisting of a common roof without any treatment—and two variants (C-VR) and (CR) of the basic roofing system that were provided with passive cooling techniques, namely a cool double-skin ventilated roof (C-VR) and a cool painted roof (CR).

5.2.1. Comparing Improvements in Thermal Behavior

Figure 10 shows profiles of average surface temperatures of the rooftops and ceilings during the hottest month of summer. As can be seen in Figure 10a, the daily variation of external surface temperature of C-VR and CR are quite similar during the whole time. Here, it may be noticed that increasing the roof solar reflectance can potentially lead to reduction of heat transfer from the roof, which results in lower indoor temperatures and improved thermal comfort conditions. In this regard, results of the simulations indicate an important decrease in the external surface temperature of the base-case roof that dropped from 57.22 °C to 37.27 °C due to the application of a cool paint on the rooftop. The decrease can reach a maximum of 20.52 °C.



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

Figure 10. (**a**) Diurnal variations of the roof surface temperature. (**b**) Diurnal variations of the ceiling surface temperature.

In more detail, the profiles of C-VR and CR show the strong impact of the cool coating on the surface temperature distribution. When solar radiation intensity reached 745.90 W/m^2, CR external surface temperature reached 37.27 °C at 16 pm. In return, the reference case peaked at 57.22 °C at 15 pm when solar radiation was equal to 877.80 W/m^2; thus, a substantial reduction by 19.94 °C was achieved. Furthermore, the maximum decrease was assessed at 14 pm by 20.52 °C, which can be explained by the high solar reflectance of the roof. Likewise, using shading, ventilation and high solar reflectance proprieties can generate an important temperature reduction of about 19.39 °C.

Considering the ceiling temperatures, it is worth mentioning that solar reflectance and thermal emittance are two key parameters influencing the solar absorption and heat dissipation of roof surfaces, which thereby can impose significant impacts on heat transfer between the exterior roof surface and the inside. As illustrated in Figure 10b, the maximum reduction in ceiling temperatures was observed in C-VR, at 5.33 °C during the daytime and 8.14 °C during the night. The clay layer performance is close to that of C-VR, and a reduction of 5.08 °C compared to the base case (REF) was reached. This highlights the thermal insulation performance resulting from the air gap enclosed in the roof. For CR the internal ceiling surface temperatures are reduced by 3.89 °C during the day time. This indicates the significant impacts of surface reflective properties on the building thermal performance contributing to varying temperature variations in the roof bottom surface. The resulting reduction in the ceiling temperature can mitigate both the convective and radiant heat transfer, leading to more comfortable spaces for occupants during hot days.

From the above observations, it appears that the optical properties of exterior surfaces play a main role in determining their temperatures and heat exchanges, which highlights again the strong effect of cool roof materials and their combined effect with other systems. Given these results, it is important to point out that cool roofs not only have a positive impact on the indoor performance but also extend the lifetime of the roof and cool the surrounding environment.

To analyze the effectiveness of applying a reflective roof and to highlight thermal stress variability inside the room, hourly air temperatures were calculated by implementing various roofing scenarios. In this respect, indoor temperatures were calculated through simulations for three different roofing systems, which included: (1) the base-case roof (REF) for comparison purposes; (2) a cool double-skin ventilated roof (C-VR), and (3) a cool painted roof (CR). Figure 11 presents the data generated for the studied room during July in terms of monthly mean indoor air temperature for the three alternatives; it also gives outdoor temperature variations.

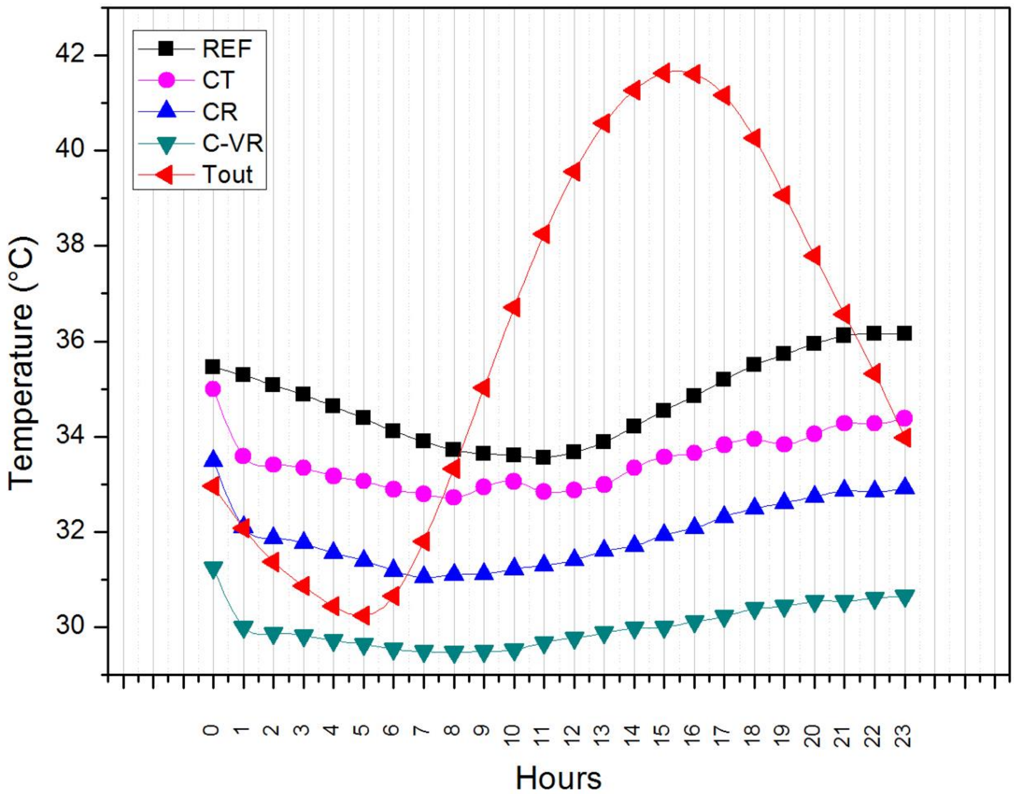


Figure 11. Average indoor air temperature calculated for all passive cooling techniques compared to the reference case during July.

A short analysis of the graphs in Figure 11 confirms the positive impact of the passive cooling roof techniques, particularly the C-VR system, which provides the best indoor conditions over the whole month. As a general trend, the outdoor temperature increased to a maximum value that was recorded at 15–16 pm. After this peak, the outdoor temperature starts to decrease. This behavior is due to the increasing of the solar radiation during the daytime. Furthermore, it may be noticed that the base-case roofing system (REF) indicated the most unfavorable thermal behavior. During 41% of the period considered, indoor temperatures relating to REF were higher than the outdoor temperature by 3.54 °C.

By applying a cool white coating (CR) on the roof, the maximum temperature amplitude was reduced to 0.25 °C for 29.66% of the time. Furthermore, the cumulative effect resulting from the combination of several techniques (cool roof, natural ventilation and clay layer) has led to more relevant results keeping the operative temperature cooler than the outdoor temperatures during the whole period. In this regard, the average indoor temperature amplitude was reduced to 4.95 °C by applying a cool-ventilated roof (C-VR) compared to the base case roof (REF) for the entire month of July.

5.2.2. Improvement of Thermal Comfort

Thermal comfort was assessed through the calculation of cumulative discomfort due to overheating conditions for 744 h (all of July). For the base-case model (REF), the overheating period is extensive and adds up to 721 h over the month (96%). Accordingly, thermal comfort conditions are potentially ensured only for 5.24% of the relevant period (Figure 12). In return, the impact of the C-VR was impressive; the cumulative distribution shows that the number of overheating hours with an operative temperature lower than 30 °C and higher than 18 °C is reduced to 407 h (54.70%), while discomfort hours account for only 337 h (45.30%). Likewise, a cool roof (CR) provides a significant increase in the potential period of comfort by ensuring an operative temperature in the range of thermal comfort during 342 h (45.96%). The simulation results showed again the noticeable impact of cool roof materials in decreasing the discomfort hours, especially when natural ventilation and high albedo are combined.

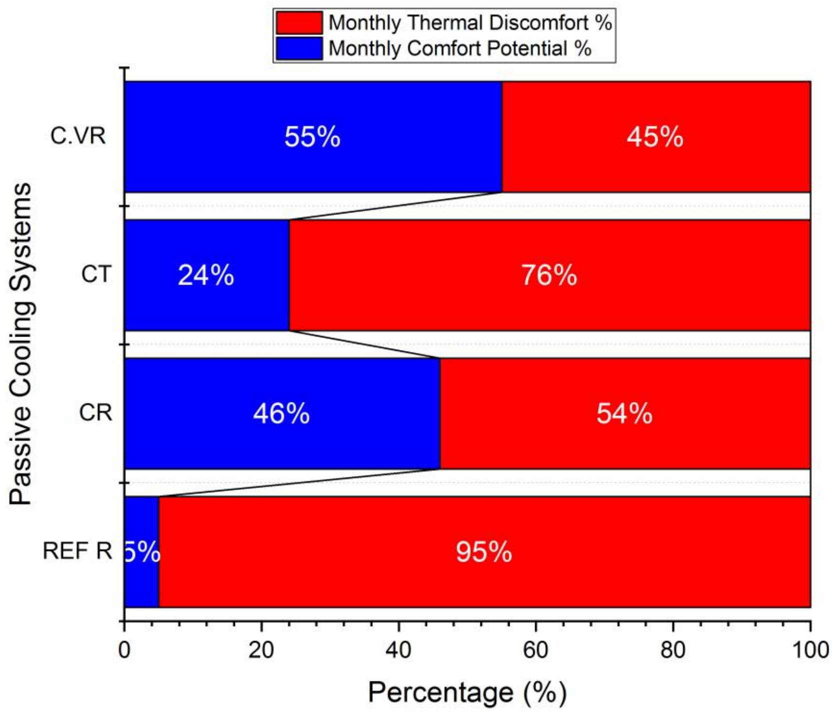


Figure 12. Percentage of potential comfort ensured during the hottest month and percentage of discomfort hours for the three roofing alternatives.

5.2.3. Energy Consumption and CO_2 Emissions

In order to estimate the impact of the cool roof on energy loads, simulations were run while assuming that the room is cooled during the entire month of July. Set point for cooling is kept at 26 °C. The carbon dioxide (CO_2) emissions for the month of July were also been estimated. Figure 13 shows the monthly energy consumption and possible savings in cooling loads for the base-case model and the two tested variants in which cool roof technology was implemented. Given the harsh climate prevailing in Biskra, cooling demand is the predominating energy requirement. Accordingly, a peak month cooling demand for the base-case model (REF) was 1121.91 kWh, while CO_2 emissions reached 729.24 $KgCO_2$. As expected, the application of the cool roof results in a decrease in the cooling load by 66.06% (741.09 kWh) for the cool-ventilated roof (C-VR) with an equivalent reduction in CO_2 emissions that dropped to 481.90 $KgCO_2$. Simulation results reveal that for CR (cool roof), the peak cooling consumption reached 612.01 kWh, which means that the solution cuts the electrical energy cooling demand by 45.45%, and thus substantially reduces the energy consumption by 508.60 kWh and CO_2 emissions by 330.59 $KgCO_2$. Better performance could obviously be achieved with the integration of the cool roof with other passive cooling solutions (Table 5).

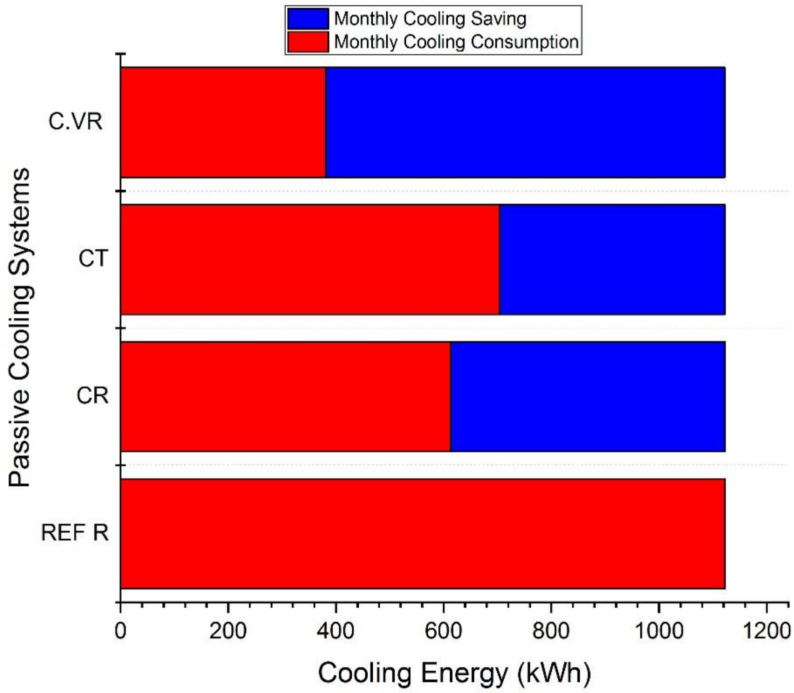


Figure 13. Average monthly cooling energy consumption of all roof solutions compared with the base case.

Table 5. Monthly cooling energy consumption, cooling energy saving and CO_2 emissions relating to the studied roofing systems.

Roof Solutions	Average Cooling Energy Consumption (kWh)	Average Cooling Energy Saving (kWh)	Cooling Reduction Percentage (%)	CO_2 Emissions $KgCO_2$
REF R	1121.91	0	0	729.24
CR	613.31	508.60	45.33	398.65
C.VR	380.82	741.09	66.06	247.53
CT	704.15	417.75	37.24	457.70

6. Conclusions

This paper describes research carried out to assess the effectiveness of cool roof techniques in improving the thermal performance of residential buildings under desert climate conditions and within the Algerian context. The study was undertaken in southern Algeria; precisely in Biskra where a very hot arid climate prevails. It aimed to compare different passive roofing techniques in terms of their potential to overcome overheating, which can thereby reduce the energy consumed to meet the cooling demand. The research was performed at two levels: (a) experimental monitoring in small-scale models treated with cooling roof techniques, and (b) numerical analysis of a base-case model where accurate cooling roof systems have been implemented. Three passive cooling roofs techniques were investigated to determine which was the most suitable, low cost and easy to install on existing roofs in Biskra. These cooling roof techniques, namely: (a) cool reflective white paint (CR), (b) white ceramic tiles (CT), and (c) a cool-ventilated roof (C-VR) were comparatively assessed in a real hot dry environment using four test cells. Then, simulations were carried out with TRNSYS software in order to quantify thermal comfort improvements, energy savings achieved, and CO_2 emissions impact mitigation.

Results of the experimental study indicate that among the three passive roofing systems investigated, the cool-ventilated roof is the most efficient solution. Furthermore, outcomes of the simulation tests reveal that compared with a common roofing system, reflective roofs represent an interesting passive cooling technique that is capable of improving thermal conditions in residential buildings while mitigating the energy consumption. The analysis showed that by applying cool roof techniques the external roof surface daily peak temperatures decrease by about 20.52 °C, while the maximum reduction in ceiling temperatures reached 5.33 °C during the daytime and 8.14 °C during the night. Average indoor temperature was also significantly reduced by 4.95 °C during the hottest month in summer. Furthermore, the cooling energy load reduction was 66.06% (741.09 kWh) for the cool-ventilated roof with an equivalent decrease in CO_2 emissions that dropped to 481.90 $KgCO_2$.

Thus, the usage of a cool roof system in a residential building, considering a location that has high values of global solar radiation and high exterior temperatures, can induce significant improvements in terms of average indoor temperature decreases, cooling energy savings and associated CO_2 emissions reductions. However, a comprehensive study is necessary to determine which roofing system offers the best long-term benefits in cost and energy load reduction over the whole year. Also, the simulation study was performed only for the hottest month (July). The calculated loads and expected savings in energy consumption did not cover the annual energy demand, which is important for evaluating the potential energy savings and the possible disadvantages for such specific roofing systems in the long run. Precisely, the long-term performance of the cool roof should be assessed by taking into account the cold season. Similarly, future studies should concentrate on testing the cool roof technique in real-scale residential roofs under ambient conditions.

Furthermore, the study was successful in establishing the effectiveness of the cool roof technique in achieving cooling load reduction and thermal comfort enhancement in residential buildings during the hottest days of the year in the city of Biskra (34°51 N); it is clear that the obtained results may apply to regions with similar climates.

Finally, given the outcomes of this research, it is clear that cool roofing techniques have a great potential to reach the expected targets relating to sustainability of residential building stock of southern Algeria, showing novel cooling roof systems that are affordable, easy to implement and do not require much maintenance interventions for extensive use in Algeria.

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