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Towards the decarbonization of residential buildings through roof External Thermal Insulation (ETI) in arid zones: A case study

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Abstract

The objective of this article is to present a range of effective thermal insulation techniques for flat roofs, based on natural insulating materials, in order to reduce excessive energy consumption used for heating and air conditioning, improve the thermal comfort of occupants, reduce the high costs associated with energy bills, and minimize the emissions of harmful CO_2 gas from buildings. In this context, the methodology followed involves studying an existing residential apartment located in an arid region. To do this, three combinations of external thermal insulation systems (ETI) have been proposed: a hot roof system, an inverted roof system, and a combined roof system, supported by a numerical simulation carried out with natural-based thermal insulation systems (wood fiber and expanded cork). Subsequently, an economic study was conducted for all the tested systems. The numerical results obtained show that the combined roof thermal insulation system, with double insulation using wood fiber (3 cm) and expanded cork (4 cm), is the optimal solution, yielding savings of 7736.83 DZD per year. Additionally, the reduction in energy consumption (kWh/m². year) and CO_2 carbon emissions (kg/year) were approximately 52.34% and 40.65% respectively.

Keywords: Flat roof, Natural base, Thermal insulation, Energy consumption, CO_2 emissions, Economical

1. Introduction

The reduction of energy consumption for all sectors and especially for buildings has become a global priority and challenge in the face of the depletion of primary energy resources [1]. The building sector stands out as the most energy-intensive sector in the world, accounting for over 45% of total energy consumption, with 50% of total natural resources exploited [2]. Consequently, it also contributes significantly to air pollution (30% of total CO_2 emissions, greenhouse gases) [3]. At the residential level, the energy consumed is used for heating, air conditioning, lighting, hot water supply, and cooking, as well as the use of electrical appliances (refrigerator, television, oven, computer, etc.). The key issues are therefore to reduce energy consumption in this crucial sector, particularly energy used for heating and air conditioning, as well as to minimize the multiple impacts of construction on the environment.

In order to reduce energy consumption in buildings and the resulting greenhouse gas emissions, it is necessary to reduce the needs and consumption by adopting efficient energy techniques such as: thermal insulation [4, 5], natural ventilation [6], thermal inertia [7] (ability to store heat in the walls, floor, etc.), natural lighting, and energy-efficient equipment. Indeed, thermal insulation of building envelopes [8] is one of the most effective solutions for improving the energy efficiency of this sector. It also plays an essential role in preserving energy, reducing heating and cooling costs, and improving the thermal comfort [9-11] of occupants by creating a more stable and pleasant indoor environment. Furthermore, thermal insulation also contributes to reducing greenhouse gas emissions (CO_2) related to the production of electricity and heat [12]. Therefore, this helps extend the lifespan of buildings by reducing temperature fluctuations and structural constraints.

On the other hand, external thermal insulation (ETI) [13, 14] of the roof is a very effective technique, as it represents the major source of heat loss from the building (30% of the total volume), closely followed by the walls (25%), windows (13% of thermal losses), the floor (7%), and thermal bridges (5%) [15]. In addition, this ETI process aims to minimize energy consumption, maintain user comfort, eliminate a large majority of thermal bridges [16], and can be used for both new construction and renovation. Several studies focus on the application of external thermal insulation of the roof to improve energy efficiency in buildings. Take, for example, the study conducted by Chandra et al. [17] in 2019, which focuses on the experimental fabrication of a new roof slab insulation system using a natural material. The measurement results show that the proposed system minimizes the negative environmental impacts caused by the use of artificial insulation materials. The optimal insulation layer thickness is 25 mm, with a 53% reduction in heat gain, a decrement factor of 0.61, and a 3 hours' delay.

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Another study was carried out by Nascimento et al. [18], in 2021 on the study of crushed rubber from unusable tires as insulating material for walls and flat roofs. An experimental apparatus was built and instrumented to determine the thermal conductivity of crushed rubber from used tires and the overall thermal conductivity of composite walls and roofs with inserted crushed rubber. The experimentally obtained measurement results show that the thermal conductivity of crushed rubber is approximately 0.25 W/m, and the flat roof recorded a 23.3% reduction in solar heat gain by increasing the thickness of the rubber layer from 15 to 25 cm. Additionally, Meddage et al. [19], in 2022 studied the exploration of the applicability of expanded polystyrene (EPS) concrete panels for insulating roof slabs in tropical areas. The work included field experiments and numerical simulations performed in Designbuilder. Furthermore, a proposal on the holistic approach to the life cycle to study the economic and environmental feasibility of alternative forms. The results obtained show that the roof slab with 75 mm EPS insulation and a white exposed surface performed satisfactorily, as did the corresponding decrease in life cycle cost, carbon emissions (kgCO_2e), and operational energy consumption. On top of that, there exist more current studies related to the energy issue in buildings. For this purpose, the following works can also be mentioned [20-25].

In the overall design of the thermal insulation system, the effectiveness of the external thermal insulation technique (ETI) of the roof is significantly related to the nature and type of thermal insulating material used. Among these insulating materials, there are mineral insulators [26] (glass wool, rock wool, and perlite...), synthetic insulators [27] (expanded polystyrene, extruded polystyrene, and polyurethane), and bio-based insulating materials (natural origin) [28]. These different categories of thermal insulation materials are generally applied in building elements including walls, roofs, ceilings, and floors [29]. They can be found in different forms: rigid panels, rolls, and natural forms.

Currently, natural-based insulation materials are becoming attractive to researchers [30] as they replace traditional materials. Some of them have comparable thermal properties and can improve thermal and hydric buffering. This family of natural-based materials is favored for building thermal insulation [31, 32], due to their appeal, renewable, recyclable, environmentally friendly, more sustainable and healthier nature, and the lower energy required for their production compared to traditional materials. This type of materials is derived from natural resources (vegetable or animal), such as cellulose, hemp, recycled cotton, sheep's wool, wood fibers and expanded cork.

Over the past few years in Algeria, the construction sector has experienced significant expansion due to the increase in population growth, accompanied by a strong demand for housing. As a result, the government has mobilized enormous human and material resources to create new residential units in various forms, focusing solely on urban expansion. However, these housing units do not truly meet the thermal comfort needs of their occupants, especially during the winter and summer seasons, due to their poor design that does not consider the principle of energy conservation in buildings, particularly at the roof level as the main weak point in terms of heat loss in buildings. This leads to increased energy consumption, such as heating and air conditioning, and therefore high bills paid by the occupants, in addition to the depletion of the state's natural resources, especially natural gas. Faced with the worsening of this problem, what are the best thermal insulation techniques for the roof that can be proposed as effective solutions to minimize heat loss and thus significantly contribute to improving the energy efficiency of local buildings?

Before addressing this issue, the main objective of this article is to propose effective solutions for the thermal insulation of the roof, aiming to minimize excessive energy consumption in residential collective housing. To achieve this, three techniques of external thermal insulation of the roof have been studied: hot roof system, inverted roof system, and combined roof system, based on two natural thermal insulation materials (expanded cork and wood fiber) during the design of these thermal insulation systems, in order to achieve very important factors such as improving energy performance, durability, solving the problem of thermal discomfort, and reducing the emissions of toxic gases, particularly carbon dioxide, in the residential sector.

2. Methodology

In the context of this work, our case study is located in the city of Bechar in Algeria, which is situated 1150 km southwest of the capital, Algiers, at a maximum altitude of 773 m above sea level [33]. This region is characterized by a hot and dry climate (desert). It is worth mentioning that the case study concerns a residential apartment located precisely in a housing complex of 470 units (see Figure 1(a) below). The description of the reference apartment, which is the subject of this study, is shown in Figure 1(b). This accommodation is located on the third floor (top floor), with an area of 84.72 m² and a volume of 230.30 m³.

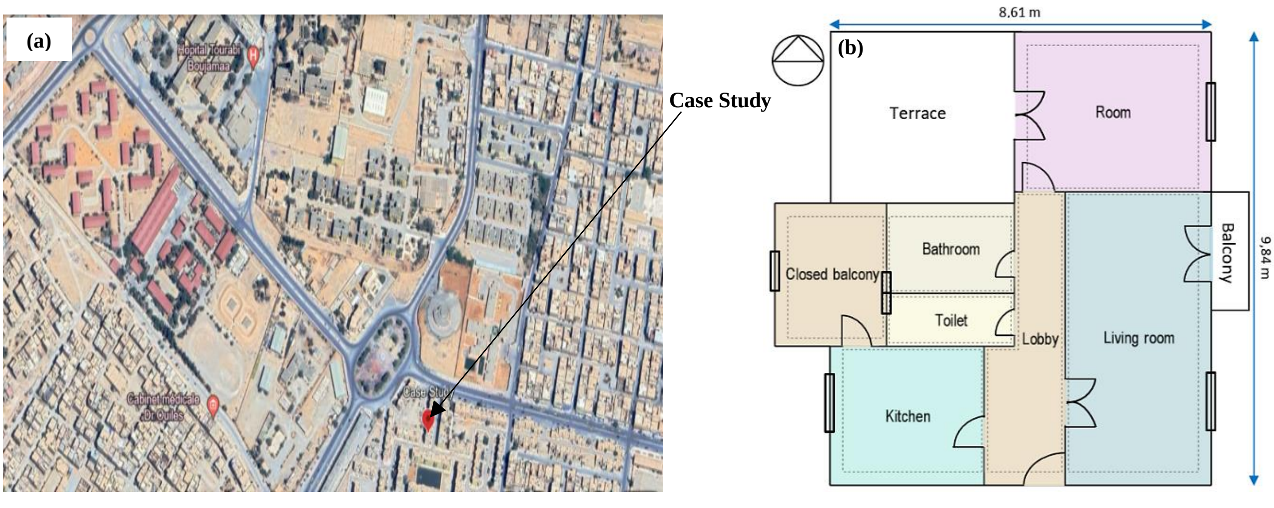


Figure 1 Presentation of the case study (residential apartment); (a) Situation plan of the apartment located in Bechar (Image source: Google Earth); (b) Plan of the studied apartment

In addition, this apartment has two facades (west and east) and the exterior windows are single glazed, with generous wooden frames (1.00 m × 1.20 m). They provide abundant light and offer a pleasant view of the outdoor environment. The main door, sturdy and secure, is made of steel, measuring (0.95 m × 2.15 m), ensuring a welcoming entrance.

As for the exterior walls, they are built with a focus on acoustic insulation. The exterior walls consist of double walls, with a total thickness of 0.29 m composed of: a 2 cm cement exterior coating, 10 cm of breeze block, followed by a 5 cm air layer, a second 10 cm breeze block wall, and finally, a 2 cm plaster interior coating. Also, this multilayer wall construction method helps minimize thermal losses in the exterior walls. Furthermore, the detailed construction elements of the apartment are specified in Table 1.

Table 1 Characteristics of elements of the construction from exterior to interior

Elements Construction	**Composition**	**Thickness (m)**	**Thermal transmittance U = 1/Rt (W/m².K)**
Exterior walls	External cement coating	0.02	0.413
	Breeze block	0.10	
	Air space	0.05	
	Breeze block	0.10	
	Interior plaster coating	0.02	
Flat roof	Solid concrete	0.05	2.976
	Hollow slab block	0.16	
	Interior plaster coating	0.02	
Internal partitions	Interior plaster coating	0.02	2.150
	Breeze block	0.10	
	Interior plaster coating	0.02	
Intermediate floor	Interior plaster coating	0.02	1.911
	Hollow slab block	0.16	
	Solid concrete	0.05	
	Sand layer	0.02	
	Cement mortar	0.02	
	Tiling	0.02	

The studied apartment houses a population density of five people, including three men and two women. The residents share the different areas of the apartment, creating a warm and harmonious environment, whether in the kitchen, the living room, or the common spaces. It is worth noting that this apartment contains household appliances that contribute to providing a functional and comfortable environment for the occupants. These appliances are distributed in different areas of the apartment. The kitchen is equipped with a spacious refrigerator, offering optimal storage space for fresh products, and a stove with modern cooking plates ensures efficient meal preparation. In addition, a natural gas heating stove, directly supplied from the urban gas network, is installed in the hallway. This stove represents an efficient and practical heating solution for individuals during the winter period. Also, a washing machine, integrated in a dedicated space (bathroom), offers a practical solution for laundry maintenance. To maintain a pleasant temperature during the summer period, two air conditioners have been strategically positioned in the living room, with one running on electricity and the other running on both electricity and water. Finally, there is a television set in the living room that serves as the focal point of domestic entertainment, offering captivating visual immersion for residents and guests. These selected amenities help simplify daily tasks and enhance the quality of life for residents. The illustration of actual apartment photos studied is shown in Figure 2.

Figure 2 Actual photos of the studied apartment; (a) West facade; (b) South facade; (c) East facade showcasing the studied apartment framed; (d) Degraded flat roof (view from the North); (e) Inside the apartment

In order to better analyze the energy context of the apartment under study, we have summarized in Figure 3 the data on annual gas and electricity consumption in kWh for the last four years (2019, 2020, 2021, and 2022), collected from the national company (SONELGAZ) of the city of Bechar [34]. From these representations, we can see that:

- Over the past four years (2019, 2020, 2021, and 2022), the apartment has shown marked energy consumption trends. Regarding gas consumption, a significant decrease was observed from 2019 to 2020, dropping from 10943.13 to 9871.77 kWh, followed by a notable increase in 2021 to 12167.54 kWh, and a slight increase again in 2022 to 12364.32 kWh. These variations could be influenced by several factors, such as weather conditions and gas appliance usage habits;
- As for electricity consumption, a progressive decrease is observed from 2019 to 2022. In 2019, consumption was 4311 kWh, decreasing to 4230 kWh in 2020, then to 4110 kWh in 2021, reaching 3691 kWh in 2022. These successive decreases could be the result of more efficient monitoring and use of electrical appliances.

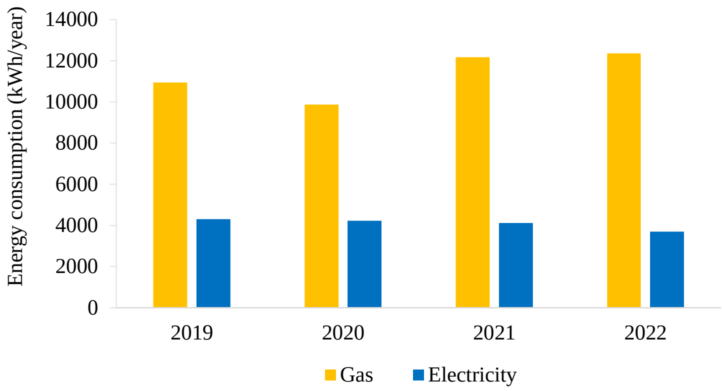


Figure 3 Evolution of the annual energy consumption of the studied apartment during the years 2019, 2020, 2021, and 2022

The data mentioned above highlight, on the one hand, the importance of monitoring energy consumption over time, and on the other hand, allowing residents to adjust their habits and implement improvements to optimize the energy efficiency of this apartment.

Then, the method followed consists of studying the previously selected apartment without the thermal insulation of the roof (reference roof), and then with the technique of thermal insulation of the roof. To do this: three combinations of external thermal insulation systems (ETI) have been proposed: hot roof system, inverted roof system, and combined roof system, based on two natural materials [35] which are wood fiber and expanded cork with thicknesses of 3 and 4 cm respectively. Finally, an economic investigation was carried out on the installation costs of these systems as well as the annual savings realized. Knowing that the numerical simulation was performed using the Design builder software (Figure 4), adopting the following hypotheses:

- The initial conditions of temperature and relative humidity are based on typical ambient conditions for the geographical location of the Bechar region, Algeria;
- Internal generation is not null (occupied apartment);
- The effect of thermal bridges is not taken into account;
- The heating and cooling needs of the apartment are deduced based on a set temperature of 20°C for heating and 26°C for cooling according to ISO 7730 [36] and the ASHRAE society [37].

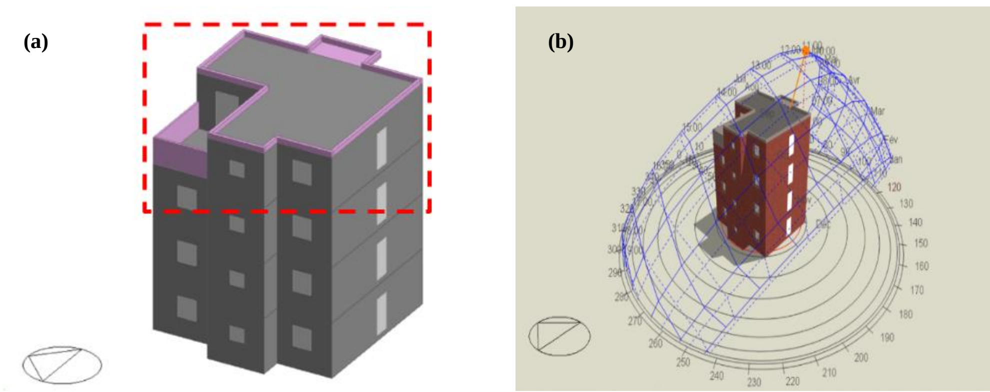


Figure 4 3D view of the building model; (a) The apartment studied; (b) Simulation process using Designbuilder

The following numerical simulation equations were used to calculate and obtain heat transfer for the various cases proposed in this study [38]:

The total heat transfer per unit area:

$$q = \frac{dT}{R_{Total}} \quad (1)$$

R_{Total} Is equal to:

$$R_{Total} = \frac{1}{h_1 A} + \sum \frac{L}{\lambda A} + \frac{1}{h_2 A} \tag{2}$$

Where:
q : Is the heat transfer rate (W)
dT : Temperature difference (Tout – Tin) (°C)
h : Heat transfer coefficient by convection (W/m².k)

For the flat roof: h_{air} for outside = h_1=19.870 W/m².k & h_{air} for inside = h_2= 4.460 W/ m².k
For the exterior walls: h_1= 19.870 W/m².k & h_2= 2.152 W/m².k
For the intermediate floor: h_1= 4.460 W/m².k & h_2= 0.342 W/m².k [39]

$\sum \frac{L}{\lambda A}$: The resistance of composites by conduction

Where:
L : Is the thickness (m)
λ : Is the value of thermal conductivity (W/m.k)
A : The area of heat transfer (m²).

Thus, the schematization of the different thermal insulation systems for the flat roof studied are illustrated in Figure 5.

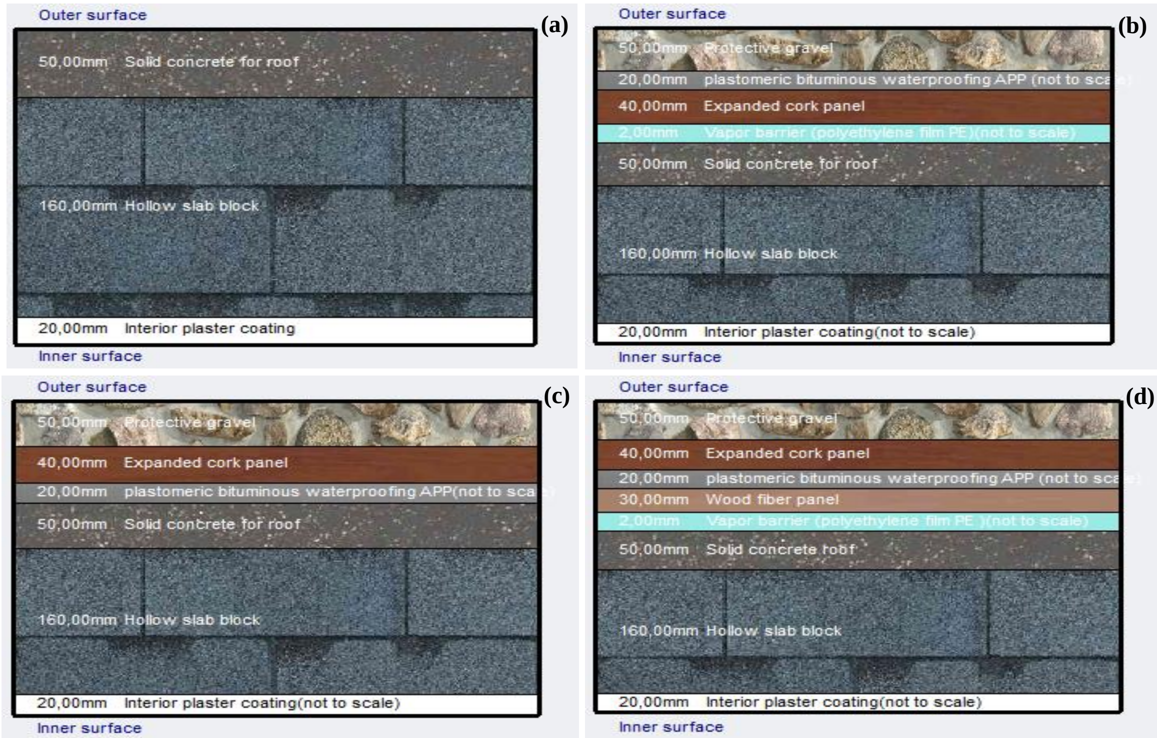


Figure 5 Thermal insulation systems proposed for the flat roof; (a) Reference roof; (b) Hot roof system; (c) Inverted roof system; (d) Combined roof system

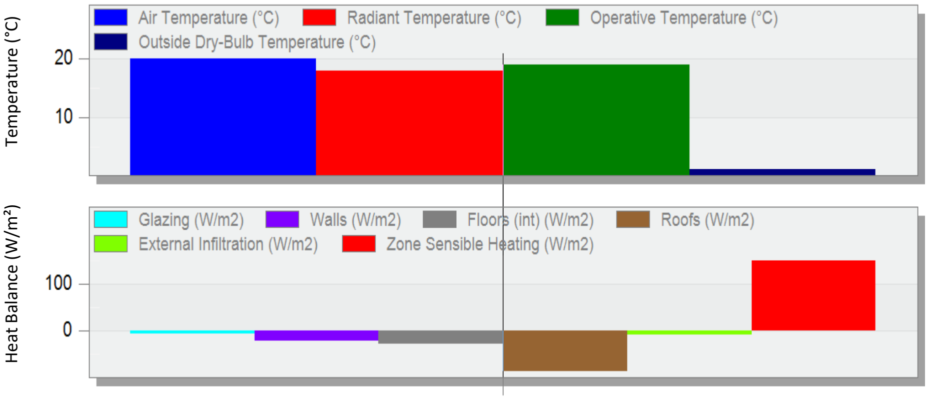
3. Results and discussion

The results of the numerical simulation of the heating system of the studied apartment (reference case) are represented in Figure 6. Note that a comparison will be frequently made with respect to the reference case, according to the three thermal insulation systems used. Understanding this concept allows for the selection of the best thermal insulation technique for the roof.

The analysis of the obtained results shows that a minimal heat loss at the level of the glazing and external infiltration is about 6.43 and 8.96 W/m² respectively. On the other hand, a relatively average thermal loss is observed for the exterior walls (22.20 W/m²) and the intermediate floor (26.76 W/m²). However, a very high thermal loss (86.80 W/m²) was recorded for the roof. It represents the greatest heat loss compared to the other envelope components (glazing, exterior walls, and intermediate floor) of the tested apartment. This can be explained by several reasons: the roof represents a large contact surface between the interior and exterior, it is constantly exposed to winds, sun, and harsh weather. Furthermore, the heat produced inside the apartment tends to rise because it is less dense and accumulates under the roof.

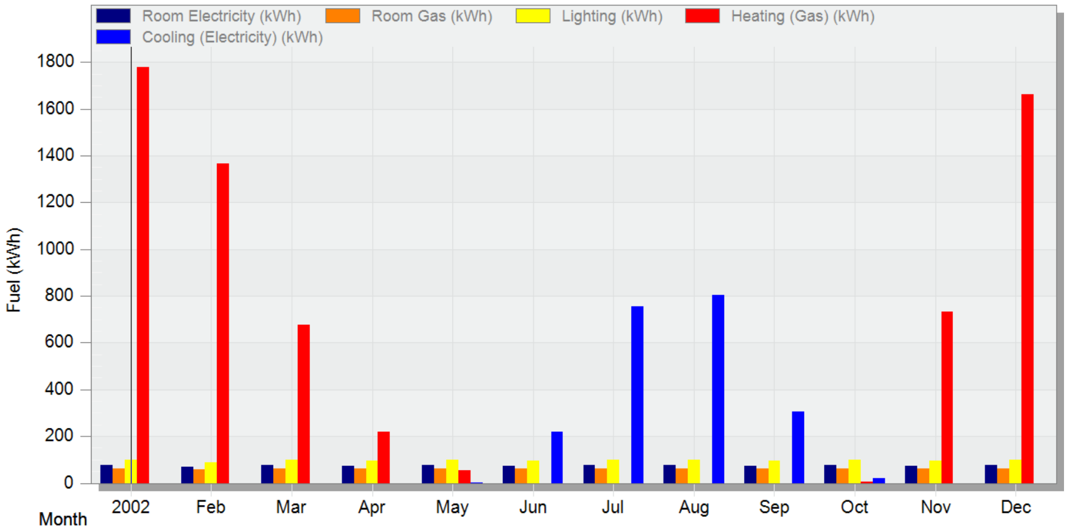
Indeed, the French Agency for the Environment and Energy Management (ADEME) [40], indicates that in a poorly insulated construction, between 25 and 30% of thermal losses occur through the roof, with almost one third of the energy being lost. Based on the preceding, it has been observed and explained that the roof is the first critical point of a dwelling in terms of thermal losses.

The values of the monthly energy requirements of the apartment under study (without insulation system) are represented in Figure 7. It should be noted that these energy consumptions are distributed as follows: electricity for the zone, gas for the zone, lighting, heating, and air conditioning in order to provide a certain thermal comfort to the occupants inside the apartment during the two winter and summer periods of the year.



Air Temperature (°C)	20,00
Radiant Temperature (°C)	17,87
Operative Temperature (°C)	18,93
Outside Dry-Bulb Temperature (°C)	1,20
Glazing (W/m2)	-6,43
Walls (W/m2)	-22,20
Floors (int) (W/m2)	-26,76
Roofs (W/m2)	-86,80
External Infiltration (W/m2)	-8,96
Zone Sensible Heating (W/m2)	151,14

Figure 6 Temperature and heat losses of the reference apartment



Month	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Room Electricity (kWh)	75,80	68,47	75,80	73,36	75,80	73,36	75,80	75,80	73,36	75,80	73,36	75,80
Room Gas (kWh)	62,34	56,30	62,34	60,32	62,34	60,32	62,34	62,34	60,32	62,34	60,32	62,34
Lighting (kWh)	99,44	89,82	99,44	96,24	99,44	96,24	99,44	99,44	96,24	99,44	96,24	99,44
Heating (Gas) (kWh)	1778,23	1366,88	676,84	218,66	55,96	0,00	0,00	0,00	0,00	6,20	734,79	1664,01
Cooling (Electricity) (kWh)	0,00	0,00	0,00	0,00	1,39	217,95	756,66	803,76	305,83	22,31	0,00	0,00

Figure 7 Monthly evolution of energy consumption. Case study of the uninsulated residential apartment (reference roof)

The energy consumption of electricity, gas for the zone, and lighting varies in the range of 68.47 to 75.80 kWh for electricity, 56.30 to 62.34 kWh for gas in the zone, and 89.82 to 99.44 kWh for lighting. We can observe that there is a small difference in these energy needs throughout all the months, from January to December. This is explained by the same process of operation and use of these energies (electricity for the zone, gas for the zone, and lighting) by the occupants during all months of the year. However, the variation in heating needs for the winter period recorded a high value of 1778.23 kWh corresponding to the month of January, which signifies the coldest month. On the other hand, the increase in air conditioning needs for the summer period reached a value of 803.76 kWh corresponding to the month of August, which represents the most unfavorable month in this period. From this analysis, we can clearly see that there is a considerable energy consumption in terms of heating and air conditioning in order to maintain the thermal comfort level of individuals during winter and summer.

The Figure 8 below shows the evaluation of thermal losses (W/m²) at the level of the flat roof of the apartment studied according to the different proposed case studies: reference roof (not insulated), hot roof, inverted roof, and combined roof. The following observations can be drawn from the reading of the histograms:

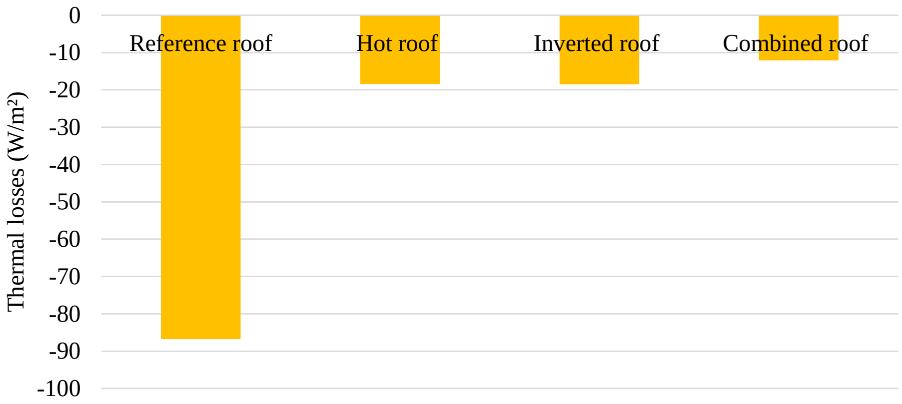


Figure 8 Evaluation of thermal losses at the roof level for the three studied thermal insulation techniques

In the first case where the tested apartment is not insulated, the thermal losses at the roof level (reference roof) are very high and recorded a maximum value of 86.80 W/m². After the application of external thermal insulation systems for the roof (inverted, hot, and combined roof), a very significant reduction in thermal losses at the roof level was observed. For the two improvement techniques concerning the inverted and hot roofs, the thermal losses are reduced to 18.53 and 18.40 W/m² respectively. In contrast, for the third technique of thermal insulation (combined roof system), the thermal losses through the roof are reduced and recorded a minimal value of 12.05 W/m², and consequently, this technique represents the top thermal insulation system for the roof among all the other studied insulation techniques, with a difference in thermal losses compared to the reference roof reaching 74.75 W/m². The explanation for the considerable reduction in thermal losses at the roof level between the reference case (uninsulated roof) and the one insulated by the three different proposed systems (inverted, hot, and combined roofs), is mainly linked to the optimization of the thermal transmittance coefficient U (W/m².K) of the roof such as: U (Reference roof) = 2.976 W/m².K, U (Inverted roof) = 0.691 W/m².K, U (Hot roof) = 0.686 W/m².K, and U (Combined roof) = 0.453 W/m².K. Simultaneously, a similar study conducted by Shaik and Talanki [41], indicates that the thermal transmittance coefficient U (W/m².K) is an assessment of heat loss through conduction, convection, and radiation across a wall or roof thickness.

Furthermore, the composition of each insulation technique has a significant impact on the variation of reduced thermal losses from one insulation system to another, due to several important factors, including the nature and thickness of the thermal insulator used.

The annual heating and air conditioning energy requirements (kWh/year) of the apartment studied, according to the different cases followed (reference, inverted, hot and combined roof), are illustrated in Figure 9.

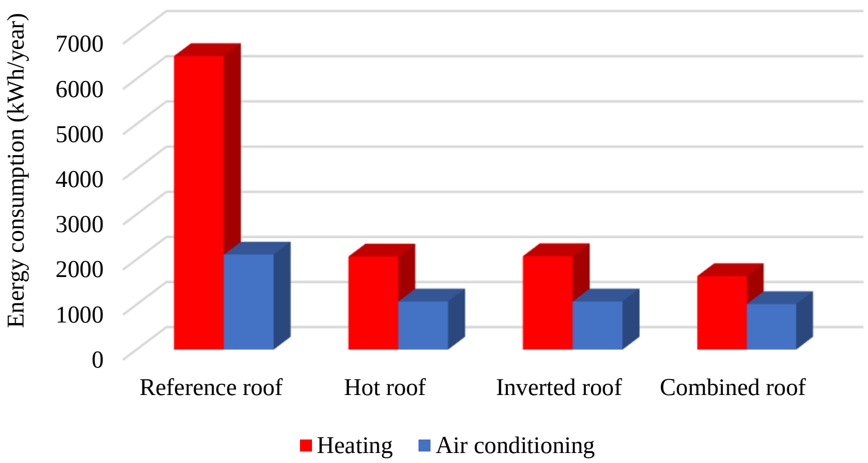


Figure 9 Annual energy consumption for heating and air conditioning of the apartment under the various studied techniques

The first case where the apartment is not insulated (roof reference), the energy consumption values are around 6501.57 (kWh/year) for heating and 2107.9 (kWh/year) for air conditioning. However, the application of external thermal insulation systems for the roof allows for a remarkable reduction in excessive energy consumption. For both the inverted and hot roof insulation systems, the heating and air conditioning needs are reduced with minimal phase shift between the two techniques, resulting in a total annual need of 3140.31 kWh for the inverted roof and 3131.56 kWh for the hot roof. This can be explained by the fact that both thermal insulation systems (inverted and hot roof) have almost identical compositions with the same insulating material represented by expanded cork (0.04 m thick). On the other hand, the combined roof technique recorded a better reduction in energy needs among all the proposed solutions, with a value of 1630.13 kWh for heating and 1009.37 kWh for air conditioning. This is due to the use of double thermal insulation materials represented by expanded cork and wood fiber with a total thickness of 0.07 m. In addition, the thermal insulation systems studied previously show their energy efficiency by reducing annual heating and air conditioning needs, and consequently significant thermal gains have been achieved in the studied apartment.

In order to assess the environmental impact of the tested apartment before and after the application of external thermal insulation to the roof, we have grouped in Figure 10 the distribution of CO_2 gas emissions (kg/year) according to each studied thermal insulation system (reference, inverted, hot, and combined roofs).

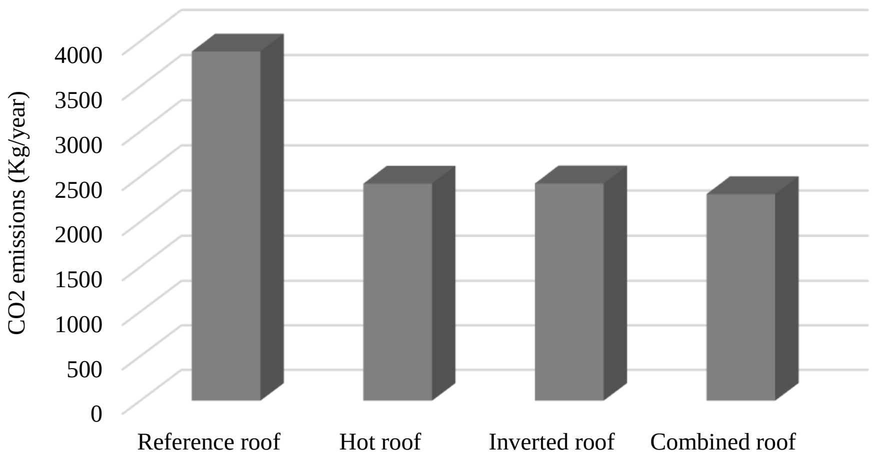


Figure 10 Evolution of the annual CO_2 emissions from the apartment under the various studied insulation techniques

The data show that the annual carbon dioxide (CO_2) emissions from the studied apartment (case of the reference roof) reach a maximum value of approximately 3884.89 kg/year. However, a very remarkable reduction was observed during the thermal insulation of the roof. Regarding the two systems of inverted and hot roof insulation, the emissions were reduced to approximately 2423.82 and 2421.92 kg/year, respectively. For the third case study, where thermal insulation was applied using the combined roof technique, the CO_2 emissions continued to decrease, reaching a minimum value of 2305.49 kg/year. It can be observed from the above that reducing the energy requirements for heating and air conditioning in the studied apartment allows to limit the generated CO_2 emissions, and this depends on the technique of the applied thermal insulation system.

In order to better understand and analyze the various results obtained above, as well as to make a comparison between the proposed thermal insulation systems for the roof and that of the reference case of the studied apartment (without thermal insulation), the aim is to determine the most effective thermal insulation system. We have summarized the following results of our study in Table 2.

Table 2 Summary of the various results obtained

Consumption	Reference roof	Hot roof	Inverted roof	Combined roof
Electricity [kWh/year]	4171.29	3130.43	3131.05	3072.75
Gas [kWh/year]	7235.52	2798.46	2806.59	2364.08
Total [kWh/year]	11 406.81	5 928.89	5 937.64	5 436.83
Total [kWh /m².year]	194.69	101.19	101.34	92.79
Ieco [kWh/m². year]	-	93.50	93.35	101.90
Reduction %	-	48.03	47.95	52.34
CO_2 emissions [kg/year]	3884.89	2421.92	2423.82	2305.49
Reduction in CO_2 emissions [kg/year]	-	1 462.97	1 461.07	1 579.4

The hourly evolution of the average air temperature, indoor relative humidity of the south zone (living room), and outdoor dry air temperature during a year (winter and summer period) under the different thermal insulation systems of the previously studied roof (reference case, hot roof, inverted roof, and combined roof) are shown in Figures 11(a)-(d) respectively.

From these representations, we notice in the first place that the dry outside air temperature varies within a range of (-0.6 to 38.38 °C) throughout the year and for all the different test cases. On the other hand, the average indoor air temperature in the study zone (living room) under the various proposed thermal insulation systems showed a significant optimization compared to the reference case during both winter and summer periods. For the winter period, the indoor temperature for the different systems is significantly higher than that recorded at the reference case temperature, with a maximum phase shift of about 4.10 °C. However, in the summer period, the indoor temperature under the insulation systems was reduced compared to the reference case temperature, with a phase shift of 1.77 °C. Furthermore, a variation in indoor relative humidity was observed between these systems and the reference case of about 3.32%. We can see that the proposed natural-based thermal insulation systems present a remarkable improvement in thermal comfort for both study periods (winter and summer).

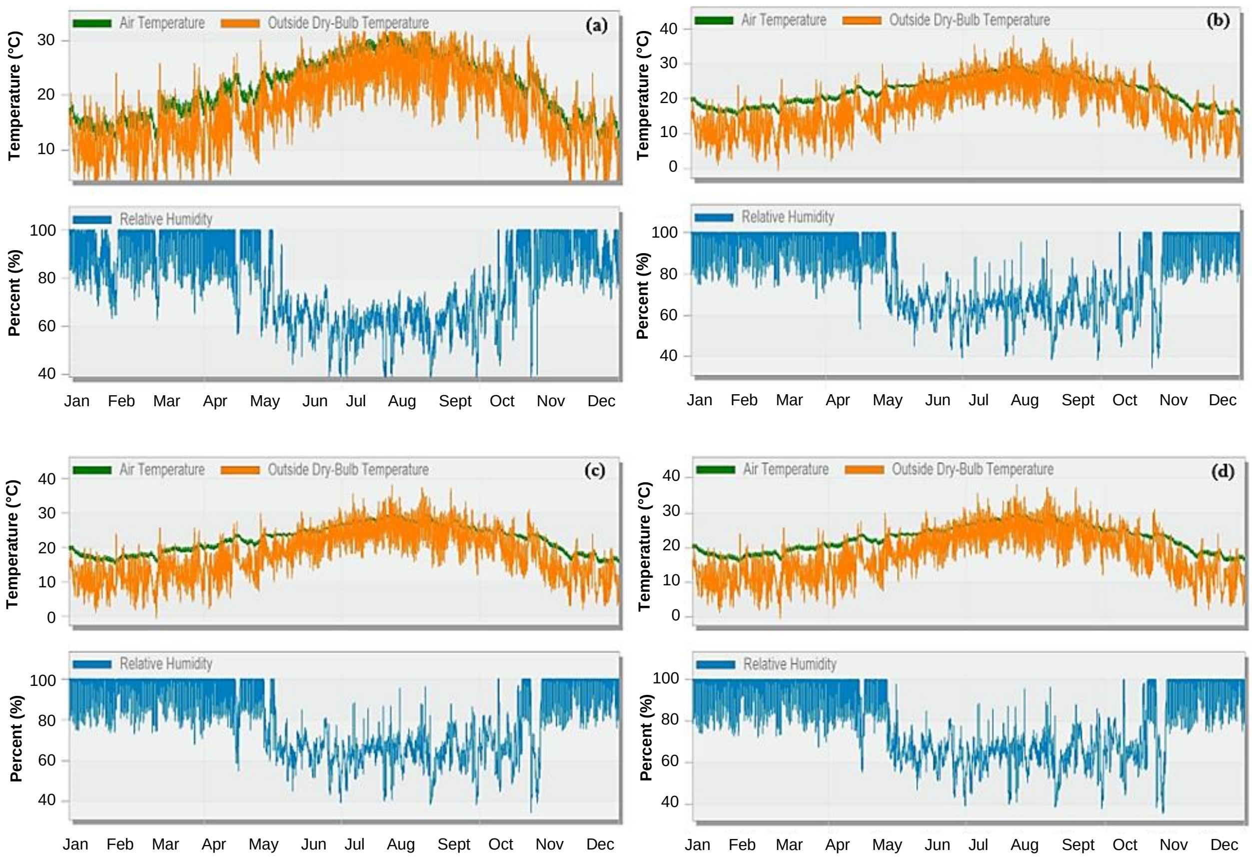


Figure 11 Evolution of the average air temperature and indoor relative humidity as a function of time under the various insulation techniques studied for the southern zone (Living Room); (a) Reference roof; (b) Hot roof; (c) Inverted roof; (d) Combined roof

This last part was dedicated to presenting an economic investigation based on energy savings (gas and electricity) through the application of roof insulation systems (hot, inverted, and combined roofs). An economic study is necessary to confirm the economic viability of these previously studied techniques. To do this, we present in Table 3 and Figure 12 an economic comparison, taking into consideration the cost of thermal insulation used [42], the cost of the applied insulation technique (ETI) [43], the total investment cost (insulation and technique), and the annual savings according to each insulation system based on current gas and electricity tariffs in Algeria [44].

Table 3 Total investment cost and savings achieved for the studied External Thermal Insulation systems (ETI)

Case studies	Studied Roof Systems (ETI)			
	Reference roof	**Hot roof**	**Inverted roof**	**Combined roof**
Material of thermal insulation used	-	Expanded cork (4cm)	Expanded cork (4cm)	Expanded cork (4cm) + Wood fiber (3cm)
Cost of insulation [DZD]	-	1974.21	1974.21	2 548.66
Cost of the ETI technique [DZD]	-	7421.85	4453.11	5937.48
Total investment cost [DZD/m²]	-	9396.06	6427.32	8486.14
Gas consumption [kWh/year]	7235.52	2798.46	2806.59	2364.08
Electricity consumption [kWh/year]	4171.29	3130.43	3131.05	3072.75
Gas price per tranche/year [0,384 DZD/kWh]	2778.44	1074.61	1077.73	907.81
Electricity price per tranche/year [5,340 DZD/kWh]	22274.69	16716.50	16719.81	16408.49
Total price of gas and electricity [DZD /year]	25053.13	17791.11	17797.54	17316.30
Savings achieved [DZD/year]	-	7262.02	7255.59	7736.83

Note: DZD = Algerian Dinar

From Table 3, it is clear that there is a variation in the investment costs between different insulation systems. This variability in the total investment costs of these insulation systems can be mainly explained by: the type of applied insulation technique, the nature of the thermal insulation used including their thermo-physical properties (thermal conductivity, thermal capacity, and density) as well as its thickness, so that the cost of insulation increases as its thickness and quality improve (low thermal conductivity), and consequently, the total investment cost of the insulation system increases.

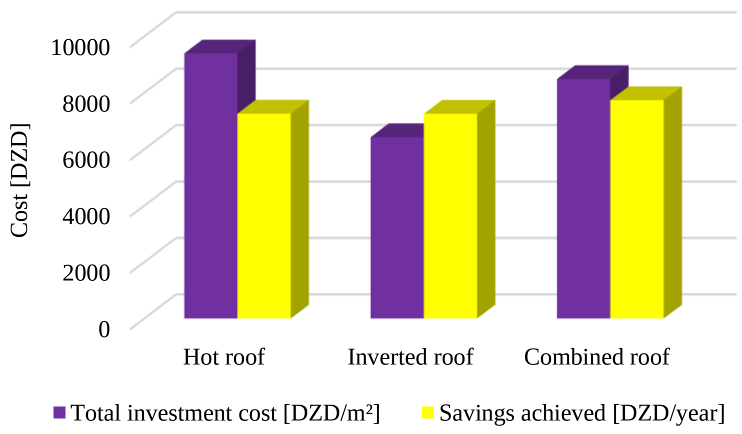


Figure 12 Total investment cost and savings achieved for the studied systems (ETI)

It should be noted that the investment prices of these insulation systems seem significant at first, but the thermal insulation of the building is indispensable in order to save the cost of its energy consumption, so the installation of such ETI systems allows to reduce the energy bill (electricity and natural gas) in the long term. Moreover, the selection of the optimal thermal insulation system depends on important factors, including the total installation cost and the savings achieved by the insulating system. Based on these factors, we recommended the combined roof system, which has a relatively medium investment cost and significant energy savings compared to other systems (hot and inverted roofs).

4. Conclusions

As part of this article, we have proposed different techniques of efficient external thermal insulation systems (ETI) for flat roofs, allowing to reduce high heat losses, maintain a comfortable indoor temperature while reducing reliance on heating and air conditioning systems and minimize greenhouse gas emissions. (CO_2). Note that the numerical simulation was carried out on one unfavorable case during winter and summer: very cold in winter and hot in summer. This allows, on the one hand, to validate the thermal optimization techniques used, and on the other, to evaluate the different numerical results of the study such as: heat losses at envelope level in particular the roof, energy consumption for heating and air conditioning, CO_2 gas emissions and thermal comfort values (indoor temperatures and relative humidity). Therefore, an economic investigation was conducted to estimate the cost of installing these systems as well as the savings achieved annually.

The analysis of the different results obtained, allows us to draw the following conclusions:

- In the reference case or the non-isolated apartment, the large amount of thermal losses was recorded at the roof level (86.80 W/m²) compared with the other envelope components (glazing, external walls and intermediate floor) of the tested apartment, with an orderly total energy consumption (194.69 kWh/m^2.year). This confirms the need for priority intervention regarding the thermal insulation of the roof;
- The proposed ETI insulation systems (inverted roof, hot and combined), offer an indispensable contribution to the reduction of thermal losses at the level of the roof of the studied apartment. For both the inverted and hot roof systems, thermal losses are reduced to 18.53 and 18.40 W/m² respectively, while for the combined roof system the loss is reduced up to 12.05 W/m². On the other hand, a very significant reduction in total energy consumption was recorded compared to the reference case of 47.95% for the inverted roof, 48.03% for the hot roof and 52.34% for the combined roof;
- The thermal insulation techniques used, allowing to reduce CO_2 emissions up to 37.61%, 37.66% and 40.65% for the three types of roof (inverted, hot and combined) respectively, leading to the preservation of a sustainable and healthy environment in the long term;
- The optimum thermal insulation system among all the systems tested for the roof is presented by the technique of the combined roof, taking into account the important criteria (energy, environmental and economic).

In perspective, this study opens a new way for many works, which allow to propose to the future (in the short and long term), in particularly:

- Characterize the different natural insulation materials utilized in the design of the tested ETI systems;
- Confront previously obtained numerical results with experimentation;
- Dimensioning the optimum thickness of thermal insulators for roofs in different climatic regions in Algeria, particularly desert regions.

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