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Research Article

Impact of thermal insulation on energy consumption in buildings

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ABSTRACT

This study examines the impact of thermal insulation on thermal comfort and energy consumption in an existing house that did not comply with building regulations. Thermal insulation included adding layers of polystyrene in the ceiling and floor, the areas with the highest heat gain and loss. After renovation, findings demonstrated a 55% reduction in heating energy required for winter. Reduction in air conditioning power was 18% during the summer. Simulations using the DesignBuilder software for the house revealed a 42% and a 17% reduction in the energy needed for heating and cooling. TRNSYS software simulation indicated a 500 kWh average annual energy consumption reduction. Experimental results measurements in two days of summer proved that the indoor temperatures of the house did not exceed 25.1°C and remained stable regardless of changes in external temperatures. Thermal insulation is a promising solution for reducing energy consumption and achieving thermal comfort in buildings.

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INTRODUCTION

Globally, buildings are the largest energy consumer, accounting for 36% of final energy consumption and 40% of primary energy consumption worldwide [1-3], making them the second biggest emitter of greenhouse gases. Shockingly, its annual CO_2 emissions have risen by an average of 1% per year since 2010.

Most building regulations worldwide focus on reducing energy consumption [2]. Thermal insulation is mandatory in buildings, it effectively reduces energy consumption in heating and cooling [2-7]. Insulation has been shown to be effective in numerous research [8-11]. Dombayci [12] investigated the environmental impact of optimal insulation thickness for exterior walls in Denizli, Turkey, using expanded polystyrene as an insulating material. Results showed that using optimal insulation thickness reduces energy consumption by 46.6%, leading to lower CO_2 and SO_2 emissions. Mishra et al. [13] discussed energy saving in different types of building walls: Brick, concrete, and stone, using optimum insulation thickness. They selected expanded and extruded polystyrene as insulation materials. They found that the optimum insulation thickness ranged from 5.2 to 7.4 cm, while energy saving varied from 2560 to 5510 Rs/m². Khoukhi and Tahat [14] investigated the relationship between temperature and thermal

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conductivity of polystyrene at various densities. Results indicated that high temperature leads to elevated thermal conductivity, and lower material density produces higher thermal conductivity. Yucel et al. [15] applied experimental tests on expanded polystyrene as an insulating and construction material which are homogeneous or close to homogeneous, grainy, multilayer, or porous. The panel method was used for experimental studies in compliance with standards. Findings proved that expanded polystyrene is affected by cell material composition changes. Fang et al. [16] conducted a comparative study between two experimental chambers - one designed with an external thermal insulation system for walls, hollow brick, and double-glazed windows "energy efficient," the other based on general building design in the 1980s and 1990s, consisting of brick and single-glazed windows ("basic" chamber). According to the study, an "energy efficient" thermally insulated chamber offered more comfortable conditions, was less affected by the outside environment, and saved up to 23.5% in air conditioning energy consumption compared with a "basic" chamber. Paraschiv et al. [3] also discovered that thermal insulation of exterior walls could reduce energy consumption by 13% -16%, depending on external temperature variations.

Many studies focus on improving thermal insulation in buildings, thus increasing thermal efficiency and saving more energy, especially when this energy source is non-renewable [17]. Kalbasi and Afrand [18] reported finding that adding phase change material (PCM) or thermal insulation in buildings effectively minimized energy consumption. Results showed that adding PCM to walls is better in summer, while insulation is preferable in winter. Furthermore, applying a combination of insulation and PCM worked well than either of them separately. Boobalakrishnan et al. [19] set out to reduce indoor temperature in metal roofs of single-story industrial buildings. They performed a comparative experimental investigation of two modes, the first without PCM in the roof (Plain Roof) and the second with encapsulated paraffin as PCM within the roof (PCM Roof). Findings showed that the second mode was preferable, reducing average daily indoor temperature by 5°C and peak indoor temperature by 9.5°C. Moreover, there is considerable interest in using phase change materials (PCM) in building construction, as they help to reduce energy consumption [20-24].

Aerogels are an eco-friendly material derived from gelled materials, offering an excellent insulating solution without any cost increase [25]. Bashir et al. [26] investigated aerogel and its use as thermal insulation material towards the sustainable design of residential buildings in tropical climates of Nigeria. They modelled a residential building using conventional materials, then modified it by applying aerogel on various surfaces of model. Their results indicated that it had a greater influence when aerogel was inserted in attic and floor slabs. Average indoor air temperatures and operating temperature were reduced by over 6%, energy consumption was cut by over 15% [27-32]. These indicate that using aerogel in buildings is a promising solution to improve thermal insulation efficiency.

It is interesting to use bio-based materials as thermal insulators since they are highly hygroscopic and renewable which can be used as an alternative to conventional materials for reducing energy consumption in buildings [33-37]. Mathews et al. [38] made thermal insulation panels from recycled cardboard and various biodegradable binders (corn starch, lime, and clay). Results suggested that the fabricated panels have good thermal conductivity due to their porosity and can be used as building insulation.

Adding thermal insulation to older houses can increase their energy efficiency, provide thermal comfort, and minimize energy consumption. To ensure that renovation complies with building standards, it is important to consider the climatic and ecological conditions of buildings and the financial resources available when selecting the appropriate type of insulation.

This paper examines the application of Algerian Thermal Regulations (DTR C 3.2/4) to a house in Oued Athmania-Mila. The aim is to determine whether or not the home complies with the regulation and to opt for renovation by adding thermal insulation in areas of high thermal loss and gain. The Regulatory Technical Document DTR C3.2/4 CNERIB 2016 defines the general building regulations for thermal design (heating and cooling), and energy needs assessment for winter and summer periods. TRNSYS software is used to simulate house temperatures throughout the year, and DesignBuilder software is utilised to find out the energy requirements of this house. After renovation, temperature values are also measured to demonstrate thermal insulation's effect on energy consumption.

DESCRIPTION OF HOUSE

The house is located in Hammam Grouz Oued Athmania-Mila in northeastern Algeria, with dimensions 6 m, 11 m, and 3.2 m (width, length, height). It consists of three chambers (kitchen, living room, room), see Table 1. Its geographical coordinates are 36°14'09 N6°17'25 E, Altitude is 729 m. See Figure 1.

- The house's walls comprise six layers. See Figure 2 and Table 2.
- The ceiling has three layers. See Figure 3 and Table 2.
- The ground consists of one layer. See Figure 4 and Table 2.

Table 1. Dimensions of the house before renovation

Location	Walls	Length (m)	Height (m)	Door gap (m²)	Windows gap (m²)	Orientation
Kitchen	1	3.76	3.20	1.67	/	S-W
	2	3.63	3.20	/	3.86	N-W
	3	3.76	3.20	/	/	N-E
	4	3.63	3.20	/	/	S-E
Living room	1	3.76	3.20	2.16	/	S-W
	2	3.80	3.20	/	2.26	N-W
	3	3.76	3.20	/	/	N-E
	4	3.80	3.20	/	/	S-E
Room	1	3.76	3.20	2.16	/	S-W
	2	3.89	3.20	/	2.28	N-W
	3	3.76	3.20	/	/	N-E
	4	3.89	3.20	/	/	S-E

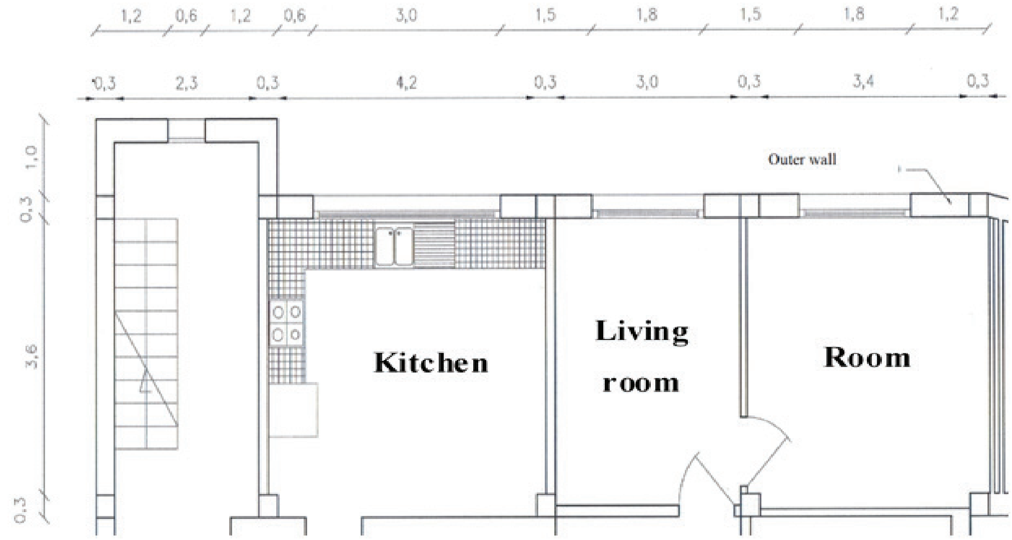


Figure 1. House plan.

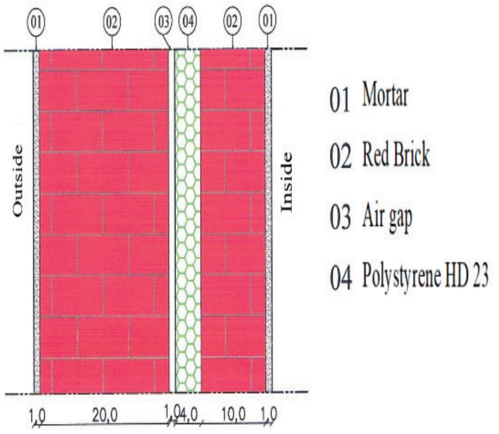


Figure 2. Outside wall components.

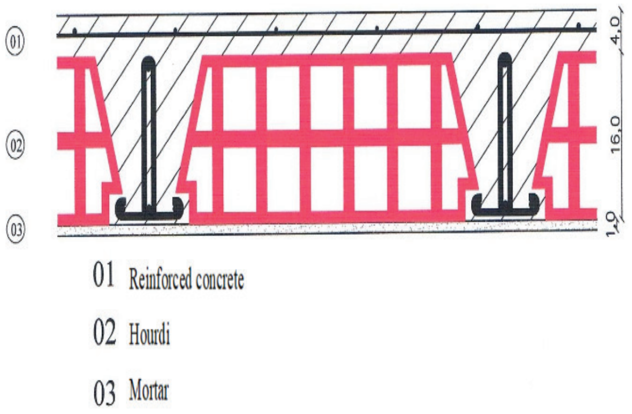


Figure 3. Roof components before renovation.

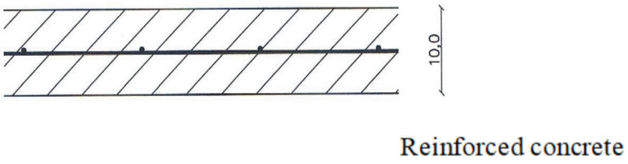


Figure 4. Ground before renovation.

Table 2. Components and properties of construction materials before renovation

Name	Construction materials	Thickness (m)	Thermal conductivity k (W/m.°C)	Thermal resistance R (m².°C/W)	ρ (Kg/m³)
Exterior wall	Mortar	0.01	1.4	0.0071	2200
	Red brick	0.20	0.48	0.4167	900
	Air gap	0.01	/	0.14	/
	Polystyrene HD 23	0.04	0.046	0.8696	23
	Red brick	0.10	0.48	0.2083	900
	Mortar	0.01	1.4	0.0071	2200
Roof	Reinforced concrete	0.04	1.75	0.0343	2500
	Hourdi	0.16	/	0.23	1500
	Mortar	0.01	1.4	0.0071	2200
Ground	Reinforced concrete	0.10	1.75	0.0571	2500

NUMERICAL ANALYSIS

Evaluation of Energy Needs During Winter

Total loss of a dwelling

Equations 1 to 9 were taken from the Regulatory Technical Document C3.2/4 [39].

Total losses L for a dwelling containing several thermal volumes are given by:

$$L=\sum L_i \qquad (1)$$

$$\text{With: } L_i=(L_T)_i+(L_R)_i \qquad (2)$$

Transmission losses $(L_T)_i$ of a volume i are given by:

$$(L_T)_i=(L_s)_i+(L_{li})_i+(L_{gr})_i+(L_{uh})_i \qquad (3)$$

Regulatory verification

The losses by transmission L_T of the dwelling must be checked:

$$L_T \leq 1.05 \times L_{ref} \qquad (4)$$

Heating power installed

The heating power Q required for a dwelling is given by:

$$Q=(t,bi-t,bo)\times[(1+\text{Max}(Cr, Cin)) \times L_T+((1+Cr)\times L_R)] \qquad (5)$$

- t,bi= 21 [°C].
- t,bo= -2 [°C].
- Cr= 0 (dimensionless) is an estimated ratio of heat losses due to the possible piping network.
- Cin=0.1 (dimensionless) represents an overpower coefficient.

Assessment of Energy Needs During Summer

Total thermal gain

$$AT=(C\Delta as \times As)+AREN \qquad (6)$$

$$\text{With: } As=APO+AV+AI+AINF \qquad (7)$$

- $C_{\Delta as}$=1.05 is the increasing coefficient of sensible gains.

Regulatory verification

The sum of the thermal gain through the glazed walls and the overhead opaque walls must be verified in July at 3 p.m., for an interior dry temperature of 27°C, the equation below:

$$APO\,(15h)+AV\,(15h)\leq 1.05\,A_{ref}\,(15h) \qquad (8)$$

Air-conditioning power

$$W=APO+AV+AREN+AINF+AI \qquad (9)$$

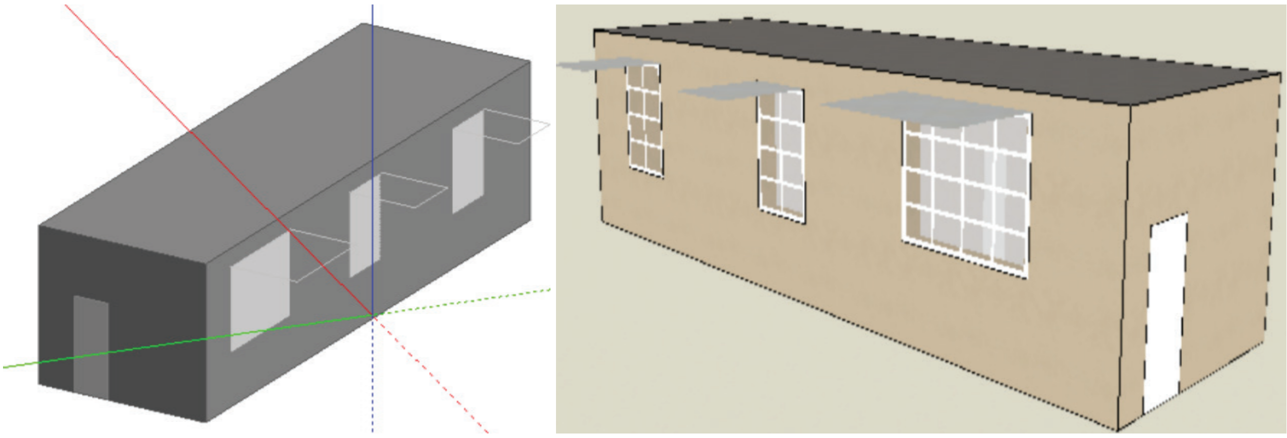


Figure 5. House visualization in DesignBuilder.

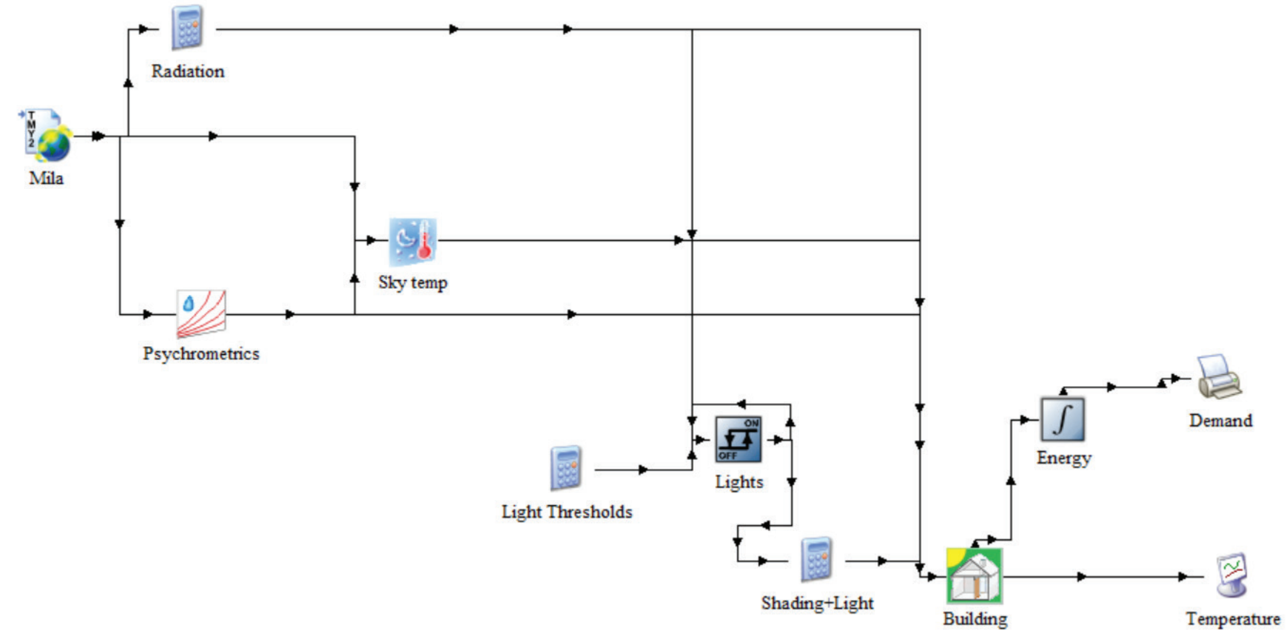


Figure 6. TRNSYS model chart.

Simulation Models

During this study, two simulator packages are used: DesignBuilder and TRNSYS, where:

DesignBuilder is software with a graphical interface for dynamic simulation and thermal modelling of buildings. Figure 5 Visualization of the house in DesignBuilder.

TRNSYS software simulates building's energy consumption using weather data generated by the meteorological software Meteonorm [40,41]. See Figure 6.

RESULTS AND DISCUSSION

Numerical Results

Numerical analysis (Equations 1 to 9) revealed that our building did not comply with Algerian Building Thermal Regulations DTR. This necessitated a home renovation. To achieve thermoregulation, good thermal insulation was applied to the ceiling and the floor to reduce losses in winter and thermal gain in summer. Three new layers were added to the ceiling (0.12 m polystyrene HD 23, 0.01 m aluminum, and 0.013 m plasterboard), see Figure 7. Two layers

(a) **(b)**

Figure 7. Thermal insulation layers of the ceiling. (a): Fixing two-layer polystyrene of thickness 4 cm of each layer below the ceiling. (b): Attachment of the last 4 cm polystyrene layer with 1 cm aluminum layer.

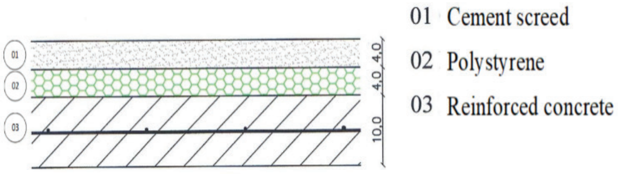


Figure 8. Ground layers and components after renovation.

Table 3. Construction materials of roof and ground after renovation

Designation	Composition	Thickness (m)	Thermal conductivity k (W/m.°C)	Thermal resistance R (m².°C/W)	ρ (Kg/m³)
Roof	Reinforced concrete	0.04	1.75	0.0343	2500
	Hourdi	0.16	/	0.23	1500
	Mortar	0.01	1.4	0.0071	2200
	Polystyrene HD 23	0.04	0.046	0.8696	23
	Aluminum	0.001	230	/	2700
	plasterboard	0.013	0.35	0.0371	750
Ground	Reinforced concrete	0.10	1.75	0.0571	2500
	Polystyrene	0.04	0.046	0.8696	23
	screed	0.04	0.5	0.08	600

on the floor (0.04 m polystyrene, 0.04 m cement screed) see Figure 8. The properties of additive insulation materials were described in Table 3.

Figure 9 illustrates loss variations (Luh, Lli, Ls, Lgr, LR, LT, Ltot) before and after the home's renovation during the winter period. The renovation results are starkly evident, with a 77% reduction in ground losses and a 59% reduction in surface losses (ceiling and walls), leading to a more than twofold drop in total losses. Thermal losses are influenced by environmental conditions surrounding the building (temperature, wind, humidity, etc.), so the appropriate design minimizes this effect. Therefore, thermal insulation is an effective energy-saving measure that significantly reduces thermal losses and ensures greater thermal comfort regardless of external climatic conditions.

Figure 10 shows thermal gain before and after house renovation during summer. It should be noted that the changes in thermal gain occurred only at the APO level

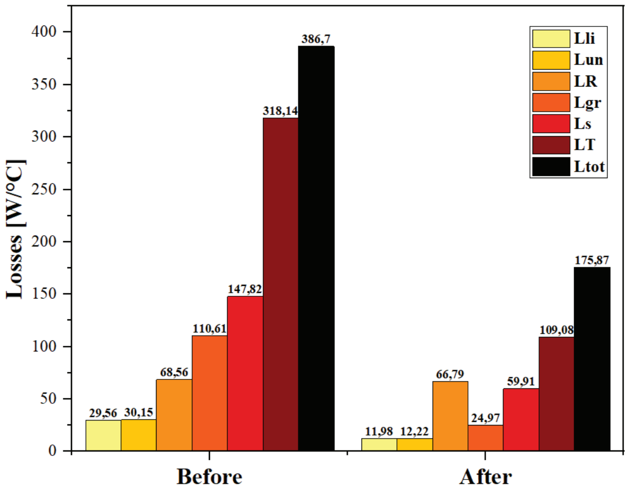


Figure 9. Thermal losses of a building during winter before and after renovation.

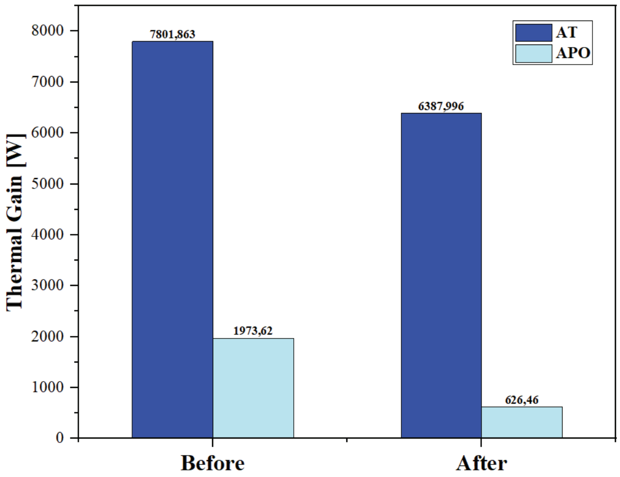


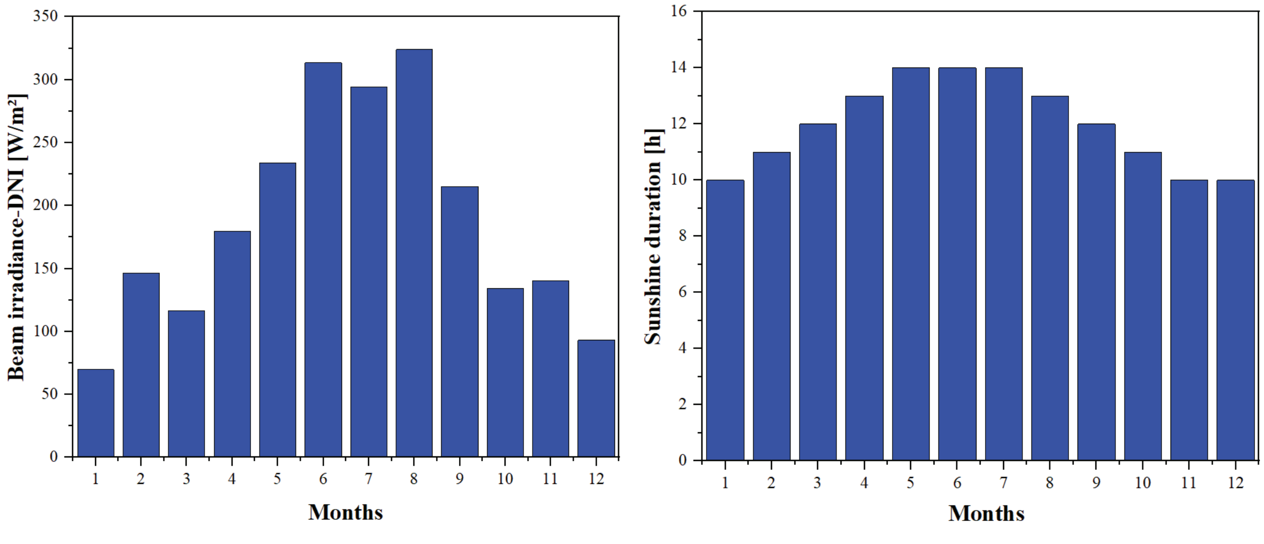
Figure 10. Thermal gain during summer before and after renovation.

from 1973.62 [W] to 626.46 [W]. This can be explained by the fact that the renovation of the ceiling and floor levels reduced the thermal gain of the opaque walls, which mainly explains the 18% decrease in AT, with no variations in other parameters (Table 4). The thermal gain during the summer period is rather large. This can be attributed to the region's hot climate, which has a high solar radiation of 323 [W/m^2] and receives at least 10 hours of sunshine per day (Fig. 11).

Figure 12 demonstrates variation in the calculated heating and cooling power required to maintain thermal comfort in a house before and after renovation. As shown, there is a significant decrease in heating power in the winter of over 55% and cooling power in the summer of 18%. This is explained by the reduction in thermal losses and gains due to the thermal insulation of the building (Figures 9 and 10). Moreover, the house requires more air-conditioning power 2000 [W] than heating energy after renovation due to the regional climate and considerable heat gains in summer.

Table 4. Thermal gains unchanged

Thermal gain [W]	Before	After
AV	1231.86	1231.86
AI	3217.36	3217.36
AINF	550.50	550.50
AREN	483.84	483.84



(a) (b)

Figure 11. Average monthly change. **(a)** Beam irradiance-DNI, **(b)** Sunshine duration [h].

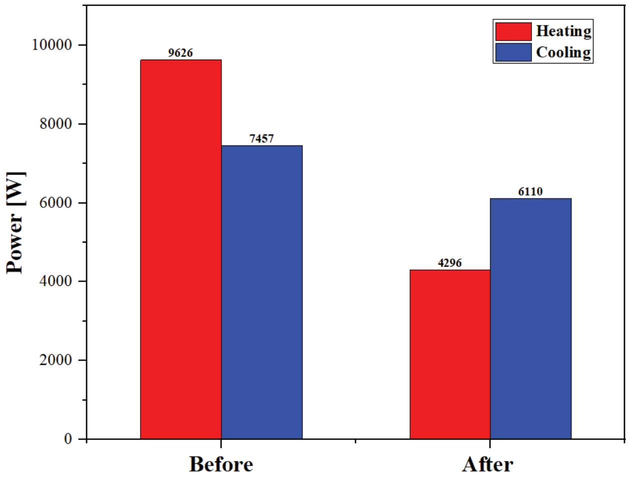


Figure 12. Energy needs for heating and cooling (numerical analysis).

After renovation, it appeared that the house complied with thermal regulations for buildings during winter and summer (based on equations (4) and (8)). The reason lies in the application of effective insulation (12 cm of polystyrene on the ceiling and 4 cm on the ground), which achieved the objective of this study.

Simulation Results

Figure 13 shows the results of the TRNSYS software simulation of temperature change in the three chambers (kitchen, living room, and room) over a period of 8760 hours. It is observed that the ambient chamber temperature throughout the year is between 6 and 32°C without heating or cooling. The average room temperature during the cold period is around 14-15°C, while the warm period ranges between 30-32°C. The results of these simulations suggest that the house is not thermally comfortable, so heating and air-conditioning are necessary to maintain a comfortable temperature. To achieve this, energy must be consumed to cool and heat the house as seen in Figure 14 which shows the average annual consumption before and after renovation of the dwelling. We find that thermal insulation is the cause of the decrease in annual consumption by more than 500 [kWh].

Figure 15 illustrates results from a simulation using DesignBuilder software, displaying the power required to heat and cool the house before and after renovation. The data demonstrate a 42% and 17% decrease in energy needs

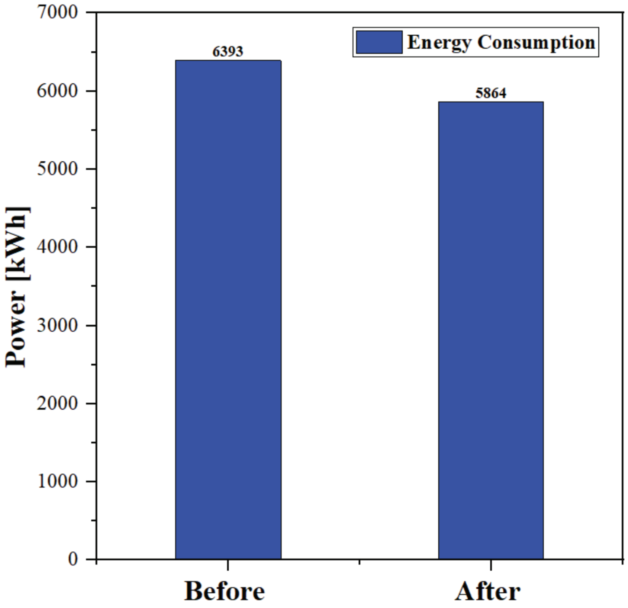


Figure 14. Average annual energy consumption for heating and cooling the house.

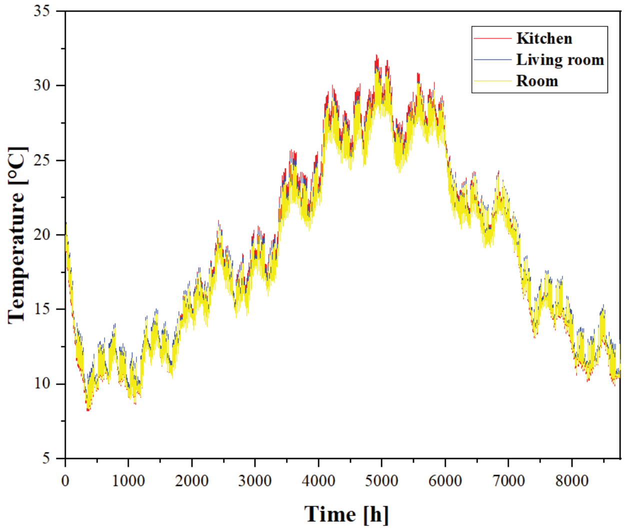


Figure 13. Indoor air temperature of house.

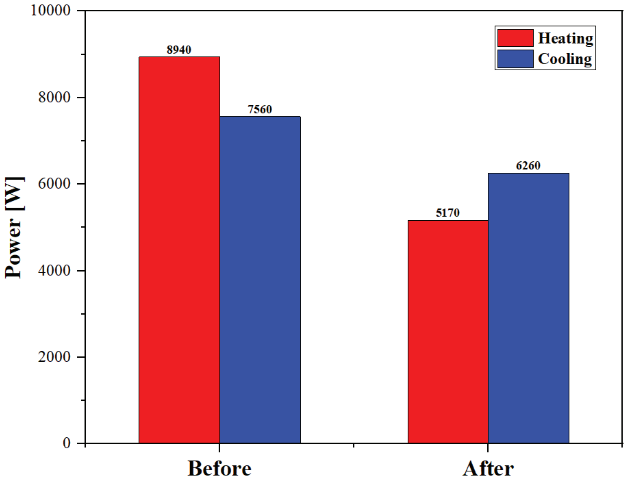


Figure 15. Energy needs for heating and cooling the house using DesignBuilder software.

for heating and cooling the house, respectively. In addition, the accuracy of the DTR-derived calculations of heating and air-conditioning powers was verified. This significant drop is attributed to the building's superior thermal insulation, which provides maximum comfort while reducing consumption and increasing savings.

Implemented Measures

After calculating thermal losses and gains for the home, it was insulated with compressed polystyrene, as indicated in Figures 7 and 8. To determine the effectiveness of thermal insulation and confirm the results of this paper, house temperatures were measured and compared to those outside. Two thermometers (IHM-MOINEAU TPM-10, measurement range: - 30/50°C) were used, one installed next to the chamber window at a distance of 1.5 m from floors, another suspended just outside the chamber. Measurements were taken every hour manually, starting at 11:00 a.m. Before using thermometers, we calibrated them with a digital probe thermometer, the difference between them being less than 0.1°C.

Temperatures measured inside and outside the building on 14/06/2021 from 11.00 to 19.00 are presented in Figure 16. Clearly, outside temperatures rise gradually until they reach their maximum at 3:00 p.m., then fall as winds blow across the region. Despite these external changes, internal temperatures remain almost constant at 24± 0.5 °C. This stability is due to thermal insulation applied in this home, which prevents gains from penetrating the interior, thus protecting the building. At 6:00 p.m., the indoor temperature drops to 23.0 °C as the bedroom window is opened to renew the air.

Figure 17 represents thermal insolation's effect on interior temperature for 8 hours (12.00 to 20.00). Although exterior temperatures are high (between 35- 37.2°C), interior temperatures stay below 25.1°C. As mentioned in Figure 16, good insulation ensured that internal temperatures were maintained constantly. However, the biggest losses and gains came from roofing, which was insulated with a 0.12 m thick layer of compressed polystyrene. Considering the average indoor/outdoor temperature difference of 11°C, with the results of two consecutive days analyzed, it is unnecessary to use air conditioning to soften the atmosphere. Natural ventilation is sufficient during night periods and early mornings when outdoor temperatures are low, significantly reducing electricity consumption.

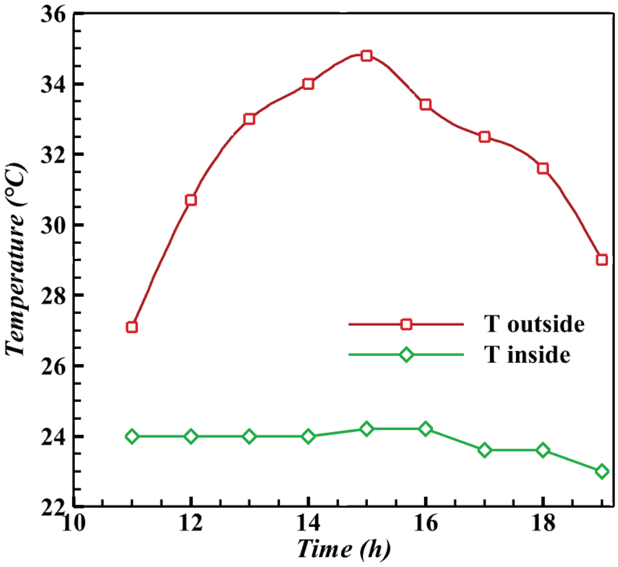


Figure 16. Variations in indoor and outdoor temperatures from 14/06/2021.

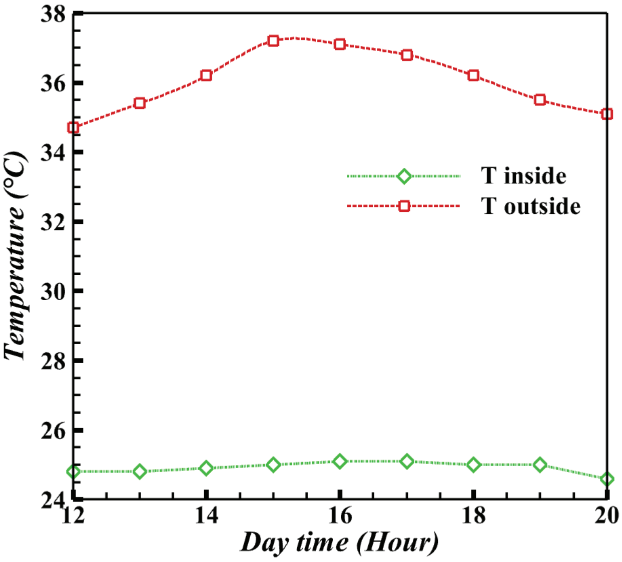


Figure 17. Outdoor and indoor temperature on 15/06/2021.

CONCLUSION

This study investigated the impact of thermal insulation on the energy consumption of an existing house in north-eastern Algeria. This research aimed to verify if the house was compatible with the construction codes of Algerian thermal regulations DTR. A simulation model was also presented using DesignBuilder and TRNSYS software. Results showed that the house did not satisfy the regulations and had considerable thermal losses on the ceiling and floor. Therefore, thermal insulation (0.12 [m] polystyrene HD 23, 0.01 [m] aluminum, 0.013 [m] plasterboard) and (0.04 [m] polystyrene, 0.04 [m] screed) were applied to the ceiling and floor, respectively. Renovating the house with thermal insulation enabled it to comply with thermal regulations in both winter and summer. In addition, the numerical values for the energy required to heat and cool the house decreased by 55% during winter and 18% in summer.

The results of the DesignBuilder software simulation indicated that heating and air-conditioning power demands were significantly reduced after insulation, confirming the validity of the calculations. Furthermore, TRNSYS software proved that renovating the house lowered average annual energy consumption by 500 kWh. To ensure the results of our calculations and simulations, temperatures inside the house were measured and compared with outside temperatures. Temperatures were found not to exceed 25.1 °C and stayed almost constant throughout the day. That is due to thermal insulation, which prevents heat exchange between the inside and outside.

Thermal insulation is an effective way to increase energy efficiency in buildings. We hope that the idea of applying it in older homes will spread throughout the world, as it has the characteristic of containing heat inside buildings in cold countries, preventing heat from entering buildings in warm countries, thereby reducing energy consumption. In the future, we will try to use insulation materials such as cork instead of polystyrene and carry out practical measurements throughout the year to determine the actual percentage of energy consumption.

NOMENCLATURE

A	Gain, [W]
AI	Internal gain, [W]
AINF	Gain due to air infiltration, [W]
APO	Gain by opaque walls, [W]
AREN	Sensitive part due to ventilation of premises, [W]
As	Sensible gain, [W]
AT	Total thermal gain, [W]
AV	Gain through the glazed walls, [W]
e	Thickness, [m]
K	Conductivity, [W/m.K]
L	Losses, [W/°C]
L_{gr}	Losses through the walls in contact with the ground (low floor), [W/°C].
L_{li}	Losses through the links (thermal bridges), [W/°C].
L_R	Losses by air renewal, [W/°C].
L_S	Surface losses through common parts of walls in contact with outside, [W/°C].
L_T	Transmission losses, [W/°C]
L_{uh}	Losses through walls in contact with unheated rooms, [W/°C].
Q	Heating power, [W]
R	Resistance, [m^{2}°C/W]
t,bi	Indoor base temperature, [°C]
t,bo	Outdoor base temperature, [°C]
W	Air-conditioning power, [W]
ρ	density, [Kg/m^{3}]

Subscripts

gr	Ground
i	Indoor
li	Links
o	Outdoor
R	Renewal
Ref	Reference
s	Surface
T	Transmission
tot	Total
uh	Unheated rooms

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] Skovajsa J, Drabek P, Sehnalek S, Zalesak M. Design and experimental evaluation of phase change material based cooling ceiling system. Appl Therm Engineer 2022;205:118011. [CrossRef]

[2] Lee J, Kim J, Song D, Kim J, Jang C. Impact of external insulation and internal thermal density upon energy consumption of buildings in a temperate climate with four distinct seasons. Renew Sustain Energy Rev 2017;75:1081–1088. [CrossRef]

[3] Paraschiv S, Paraschiv LS, Serban A. Increasing the energy efficiency of a building by thermal insulation to reduce the thermal load of the micro-combined cooling, heating and power system. Energy Rep 2021;7:286–298. [CrossRef]

[4] Huang H, Zhou Y, Huang R, Wu H, Sun Y, Huang G. Optimum insulation thicknesses and energy conservation of building thermal insulation materials in Chinese zone of humid subtropical climate. Sustain Cities Soc 2020;52:101840. [CrossRef]

[5] Zilberberg E, Trapper P, Meir IA, Isaac S. The impact of thermal mass and insulation of building structure on energy efficiency. Energy Build 2021;241:110954. [CrossRef]

[6] Simona PL, Spiru P, Ion IV. Increasing the energy efficiency of buildings by thermal insulation. Energy Procedia 2017;128:393–399. [CrossRef]

[7] Alhefnawi MA, Abdu-Allah Al-Qahtany M. Thermal insulation efficiency of unventilated air-gapped facades in hot climate. Arab J Sci Engineer 2017;42:1155–1160. [CrossRef]

[8] Zhao K, Jiang Z, Huang Y, Sun Z, Wang L. The method of reducing heat loss from thermal bridges in residential buildings with internal insulation in the hot summer and cold winter zone of China. J Build Engineer 2022;62:105421. [CrossRef]

[9] Wang Y, Wang C, Gao S, Zheng X, Darkwa J. The impact of thermal insulation on cooling energy consumption and optimal insulation thickness for underground tunnel. Sustain Energy Technol Assess 2021;47:101495. [CrossRef]

[10] Yuan L, Kang Y, Wang S, Zhong K. Effects of thermal insulation characteristics on energy consumption of buildings with intermittently operated air-conditioning systems under real time varying climate conditions. Energy Build 2017;155:559−570. [CrossRef]

[11] Lakrafli H, Tahiri S, Albizane A, el Houssaini S, Bouhria M. Effect of thermal insulation using leather and carpentry wastes on thermal comfort and energy consumption in a residential building. Energy Effic 2017;10:1189−1199. [CrossRef]

[12] Dombaycı ÖA. The environmental impact of optimum insulation thickness for external walls of buildings. Build Environ 2007;42:3855−3859. [CrossRef]

[13] Mishra S, Usmani JA, Varshney S. Energy saving analysis in building walls through thermal insulation system. Int J Eng Res Appl 2012;2:128−135.

[14] Khoukhi M, Tahat M. Effect of temperature and density variations on thermal conductivity of polystyrene insulation materials in Oman climate. J Eng Phys Thermophys 2015;88:994−998. [CrossRef]

[15] Yucel KT, Basyigit C, Ozel C. Thermal insulation properties of expanded polystyrene as construction and insulating materials. 15th Symposium in Thermophysical Properties; 2003. pp. 54−66.

[16] Fang Z, Li N, Li B, Luo G, Huang Y. The effect of building envelope insulation on cooling energy consumption in summer. Energy Build 2014;77:197−205. [CrossRef]

[17] Aliakbari K, Ebrahimi-Moghadam A, Ildarabadi P. Investigating the impact of a novel transparent nano-insulation in building windows on thermal comfort conditions and energy consumptions in different climates of Iran. Therm Sci Engineer Prog 2021;25:101009. [CrossRef]

[18] Kalbasi R, Afrand M. Which one is more effective to add to building envelope: Phase change material, thermal insulation, or their combination to meet zero-carbon-ready buildings? J Clean Prod 2022;367:133032. [CrossRef]

[19] Boobalakrishnan P, Kumar PM, Balaji G, Jenaris DS, Kaarthik S, Babu MJP, et al. Thermal management of metal roof building using phase change material (PCM). Mater Today Proc. 2021;47:5052−5058. [CrossRef]

[20] Al-Yasiri Q, Szabó M. Experimental study of PCM-enhanced building envelope towards energy-saving and decarbonisation in a severe hot climate. Energy Build 2023;279:112680. [CrossRef]

[21] Saffari M, Roe C, Finn DP. Improving the building energy flexibility using PCM-enhanced envelopes. Appl Therm Engineer 2022;217:119092. [CrossRef]

[22] Alshuraiaan B. Efficient utilization of PCM in building envelope in a hot environment condition. Int J Thermofluids 2022;16:100205. [CrossRef]

[23] Wu D, Rahim M, El M, Bennacer R, Djedjig R, Liu B. Dynamic hygrothermal behavior and energy performance analysis of a novel multilayer building envelope based on PCM and hemp concrete. Constr Build Mater 2022;341:127739. [CrossRef]

[24] Ajour MN, Abduaal MJ, Hariri FA, Abu-Hamdeh NH, Karimipour A. Reducing electricity demand by integrating a sustainable pack into HVAC-adding PCM in sustainable pack as well as building envelopes. J Build Engineer 2022;57:104915. [CrossRef]

[25] Balaji D, Sivalingam S, Bhuvaneswari V, Amarnath V, Adithya J, Balavignesh V, et al. Aerogels as alternatives for thermal insulation in buildings - A comparative teeny review. Mater Today Proc 2022;62:5371−5377. [CrossRef]

[26] Bashir AW, Chaves B, Leite C. Performance of aerogel as a thermal insulation material towards a sustainable design of residential buildings for tropical climates in Nigeria. Energy Built Environ 2022;3:291−315. [CrossRef]

[27] Lucchi E, Becherini F, Di Tuccio MC, Troi A, Frick J, Roberti F, et al. Thermal performance evaluation and comfort assessment of advanced aerogel as blown-in insulation for historic buildings. Build Environ. 2017;122:258−268. [CrossRef]

[28] Niu Y, Wang S, Zhu Z, Su M, Wang Y, Yan L, et al. Robust composite aerogels with excellent flame retardant and thermal insulation properties based on modified hollow glass microspheres. Polym Degrad Stab. 2022;202:110030. [CrossRef]

[29] Belloni E, Buratti C, Merli F, Moretti E, Ihara T. Thermal-energy and lighting performance of aerogel glazings with hollow silica: Field experimental study and dynamic simulations. Energy Build 2021;243:110999. [CrossRef]

[30] Leung CK, Lu L, Liu Y, Cheng HS, Tse JH. Optical and thermal performance analysis of aerogel glazing technology in a commercial building of Hong Kong. Energy Built Environ 2020;1:215−223. [CrossRef]

[31] Jiang S, Zhang M, Jiang W, Xu Q, Yu J, Liu L, et al. Multiscale nanocelluloses hybrid aerogels for thermal insulation: The study on mechanical and thermal properties. Carbohydr Polym 2020;247:116701. [CrossRef]

[32] Yang J, Wu H, Xu X, Huang G, Xu T, Guo S. Numerical and experimental study on the thermal performance of aerogel insulating panels for building energy efficiency. Renew Energy 2019;138:445−457. [CrossRef]

[33] Palumbo M, Lacasta AM, Giraldo MP, Haurie L, Correal E. Bio-based insulation materials and their hygrothermal performance in a building envelope system (ETICS). Energy Build 2018;174:147–155. [CrossRef]

[34] Torres-rivas A, Palumbo M, Haddad A, Cabeza LF, Jiménez L. Multi-objective optimisation of bio-based thermal insulation materials in building envelopes considering condensation risk. Appl Energy 2018;224:602–614. [CrossRef]

[35] Fedorik F, Zach J, Lehto M, Kymäläinen HR, Kuisma R, Jallinoja M, et al. Hygrothermal properties of advanced bio-based insulation materials. Energy Build. 2021;253:111528. [CrossRef]

[36] Ismail B, Belayachi N, Hoxha D. Hygric properties of wheat straw biocomposite containing natural additives intended for thermal insulation of buildings. Constr Build Mater 2022;317:126049. [CrossRef]

[37] Platt SL, Walker P, Maskell D, Shea A, Bacoup F, Mahieu A, et al. Sustainable bio & waste resources for thermal insulation of buildings. Constr Build Mater 2023;366:130030. [CrossRef]

[38] Mathews JM, Vivek B, Charde M. Thermal insulation panels for buildings using recycled cardboard: Experimental characterization and optimum selection. Energy Build 2023;281:112747. [CrossRef]

[39] CNERIB. Réglementation Thermique du Batiment (DTR C 3.2/4). Available at: https://www.normadoc.com/french/dtr-c-3-2-4.html. Accessed June 28, 2024.

[40] Abdou N, El Mghouchi Y, Jraida K, Hamdaoui S, Hajou A, Mouqallid M. Prediction and optimization of heating and cooling loads for low energy buildings in Morocco: An application of hybrid machine learning methods. J Build Engineer 2022;61:105332. [CrossRef]

[41] Azkorra-Larrinaga Z, Erkoreka-González A, Flores-Abascal I, Pérez-Iribarren E, Romero-Antón N. Defining the cooling and heating solar efficiency of a building component skin: application to a modular living wall. Appl Therm Engineer 2022;210:118403. [CrossRef]