Performance and Economical Analysis of Different Insulating Materials Used to Reduce the Heat Load of an Existing Residential Building

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Abstract: - The energy consumption from the residential sector is an important element which has an impact on the total energy consumption in any country. The heating and air conditioning loads can be reduced through many means. Using thermal insulation in buildings does not only contribute in reducing the required air conditioning system size, but also in reducing the annual energy cost for the whole building. In this case, the energy saving varies according to the building type, the climatic conditions at which the building is located as well as the type of the insulating material used. In the present study, an existing single family house has been studied by applying two main solutions to insulate the walls and the roof using six different materials on the exterior walls that have the most heat gain, such as silica aerogel, polystyrene foam boards (XPS), spray cork, glass ceramic, cool coating enforced by phase change material (PCM), and straw boards. The study took place in El-Shorouk city, Egypt. The energy analysis was estimated by using TRNSYS simulation for the total internal house loads in summer season (June, July, and August) to be 13410 kW. The prototype house is about 300 m^2 on two floors and a roof. The results showed that the aerogel has the best insulation followed by XPS then straw boards and glass ceramic which have efficiencies of 48.33%, 38.36%,36.46% and 34.38%. Because of its economical and environmental aspects, straw boards were selected to apply further investigations to indicate the relative efficiencies for the offered solution with the corresponding cost analysis.

Key-Words: - Energy efficiency, Energy consumption, bio-based materials.

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1 Introduction

Buildings are the largest consumers of energy all over the world. In areas with harsh climatic conditions such in Egypt which is located at latitude 26.82055 ^{o} and longitude 30.802498^{o}, a substantial share of energy goes to mainly cooling the buildings [1]. These air conditioning loads can be reduced through many means. The proper use of thermal insulation in buildings as one of the attractive methods used to reduce the energy gain in building does not only contribute in reducing the required air conditioning system size, but also in reducing the annual energy cost for the whole building. Moreover, it helps in extending the durations of thermal comfort without reliance on mechanical conditions. The magnitude of energy savings as a result of using thermal insulation vary according to the building type, the climatic conditions at which the building is located as well as the type of the insulating material used [2]. The amount of energy required to cool or even to heat a building depends on how well the building envelop isolates thermal energy. The thermal performance of the building envelop is determined by the thermal properties of the materials used in construction and characterized by its ability to absorb or emit solar heat [3]. Research and development activities should pay a great attention to the field of energy savings working on its dramatic reduction in both consumption and waste. One of the brilliant strongly coming technologies that can serve to achieve this goal is the investments in technologies used in building constructions. It is proved that halving of buildings energy consumptions is feasible and can be practically attained by the means of improving used utilities, materials used in construction or finishing like windows and doors, heating and cooling techniques, lighting systems and building design strategies as well [1]. Walls represent a high capacity of the building envelope, the walls are known to provide thermal and acoustic comfort in the building, without compromising the aesthetics of the building. An important factor is the thermal resistance of the wall as it greatly affects the building's energy consumption [4].

Using different materials to insulate walls has attracted researchers to investigate the behavior of these materials on the wall's thermal resistance. Bugaje et. al [6] reported that by adding aluminum to paraffin wax, the heating and cooling phase change time has decreased significantly. Two drawbacks of this method were analyzed: the increase in the weight and the high cost of the system. Desirable characteristics (low density, large specific surface area, high specific strength to density ratio and high thermal conductivity) could be achieved from metal foams that are being manufactured by sintering method, this makes them to be promising in heat transfer enhancement for PCMs (Phase change materials) [7].

The re-shaping of the panels on construction site has no effect on its thermal resistance. Bunge and Merkel [8] was able to develop an improved XPS foam with elevated efficiency and reduced thermal conductivity. They also studied in details the long term mechanical properties of their improved XPS foam. On the other hand, Vait et al. [9] studied the effect of the exposure time on XPS compression, claiming that alternation in XPS strength was observed after 45 days of monitoring. Enríquez [10] investigated glass ceramic and glaze based on laboratory experiments, where two cubes of glass ceramic and glaze with a thermometer at its center were placed on the roof of a building and left for two successive complete days. During mid-day period, the temperature difference between the two tiles showed approximately about 1.5℃ for glass ceramic confirming higher albedo of solar radiation and higher energy required to heat it up, in other words lower thermal diffusivity. During night period, the temperature difference between the cubes varied between 0℃ up to 0.5℃ difference because heat caused by solar reflection is stopped during night period. It was concluded that, the replacement of glaze by glass ceramic can save energy up to 20 %. It offers a unique solution to reduce heat transfer between the building.

A study was done by Martelli et.al. [10] concluded that combing a photovoltaic system with a biomaterial such as straw will decrease the thermal heat gain of buildings also will have a zero impact on the environment with low cost.

Various physical phenomena could be responsible for the simulation errors for example irreversible heat transfers between the system and the surroundings, air-to-air heat recovery, geographic location, timing of weather data for different operating conditions and unstable weather conditions [5].

2 Building Details

For the present work, a full study is offered for the energy analysis of an existing building located in El-Shorouk city in Egypt.

The analysis will cover the following scenarios:

1. A full study for the original building structure. Tracking the heat gains and losses in the building and their implications on the energy consumption.
2. Integrating different insulation material to the building on the most heat gain walls in the building envelope.
3. Using a shading pergola with a PV power system.
4. Executing complete economic analysis for all materials.

The first original study aims to determine the heat required to reach the comfort temperature which is known to be 24˚C [11] for each floor as a whole and then to track the heat gains and losses through the 32 walls of the building shown in Fig 1. The period assigned for this analysis is planned to be during the three months of summer season (June, July and August) which are the hottest months where the most energy consumption is occurred.

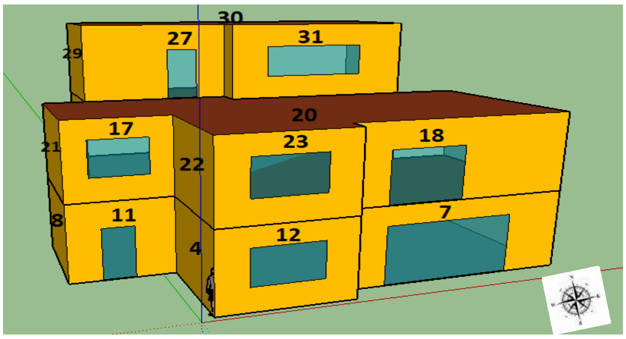

Fig 1: Front view of the model on Sketchup

3 Results and Discussion

The original building which is composed of three thermal zones is drawn according to the real building properties as listed below and shown in Fig 1:

1. Ground floor zone with total area of 130 m^2 with three openings represented by one door (1.97 m^2), a window (2.99 m^2) and a large terrace window (9.21 m^2).
2. First floor zone with a total area of 130 m^2 and three openings of two windows (2.45 m^2 and 2.99 m^2) and another large balcony window of area 4.73 m^2.
3. Roof zone with a total area of 42 m^2 which has one door (1.97 m^2) and one window (4.17 m^2).

The first stage was to study the original structure of the building. The simulation will depend on calculating the loads needed inside the building to reach the comfort temperature each hour all over the year. The heat gain was calculated using Fourier's Law as shown in Equation (1).

$$Q = \frac{K\ A\ \Delta T}{L} \tag{1}$$

Where

$k = Thermal\ conductivity\ \frac{kj}{m}.hk$

$A = Area\ m^2$

$\Delta T = Temprature\ difference\ K$

$L = Thickness\ m$

The exterior walls of the building are composed of different layers which are: plaster, cement mortar, red bricks, cement mortar and plaster. Moreover, the roof top is composed of: plaster, concrete tiles, cement mortar, sand, bitumen and reinforced concrete. Based on each layer's thermal conductivity, thickness, and internal and external surface temperatures, the U-value (Overall Heat Transfer Coeff.) can be obtained for each wall. Finally, the net heat transfer can be calculated.

Fig 2 shows the accumulative hourly heat gain in each wall over the three summer months, to investigate which wall has the highest heat gain and heat loss. The analysis showed that the roof top has the largest heat gain (wall 20), followed by the ceiling of the room in the roof (wall 30), and then the three largest walls that facing north (wall 5, 16, 26).

These major five walls should be treated to minimize the heat losses of the building because they represent almost 77.5% of the total heat gain inside the building.

3.1 Internal cooling loads calculations on TRNSYS simulation

All the heat gains from the building are categorized by: equipment (QEQUIP), lighting (QLIGHT), electronic equipment and building envelope due to solar radiation (QENV), occupants (QPERSON), ventilation (QVENT), and infiltration (QINF). These heat gains were contributed to the sensible cooling load output (QSENS); moreover, they were calculated in the simulation. TRNSYS use the transfer function method to simplify the arduous heat balance method for conductive heat gain at the surface of each wall in the building [12]. The heat gain by radiation and convection through each zone were calculated by the star network given by Seem's equation shown in Equation (2):

$$q_{comb,s,i} = q_{s,c,i} + q_{r,s,i} = \frac{1}{R_{equiv,i}\, A_{s,i}}(T_{s,i} - T_{star}) \tag{2}$$

Where:

$q_{comb,s,i}$=combined convective and radiative heat transfer $kJ\ h^{-1}$

$q_{r,s,i}$=long wave radiation heat flux on the surface of the wall $kJ\ h^{-1}$

$R_{equiv,i}$ =Equivelant resistance between the walls with a node h $m^2\ K\ kJ^{-1}$

$A_{s,i} = Inside\ surface\ area\ m^2$

$T_{s,i} = Inside\ surface\ temprature\ °C$

$T_{star} = Artificial\ temprature\ node\ °C$

Based on ASHRAE standers the building and occupants components were considered [13]. The building ventilation is considered to be 0.3 L/s.m^2 and occupant ventilation rate per person is considered to be 2.5 L/s. The infiltration rate of air exchange due to leakage air and door openings was assumed to be 0.1/h while AC operation.

The internal loads needed in each floor (zone) to maintain the comfort temperature (24^{o}C) inside the building are shown in Fig 3. The ceiling of the first floor represents the roof top which exposed directly to the sun radiation almost all the day long as a result it consumes more energy than the rest of the house, followed by the roof which has the same conditions as the first floor then the ground floor. The percentage's distributions of heat gain in the whole building for each floor are 21.5%, 56.4%, and 22% for ground floor, first floor and roof respectively.

The second stage, different materials will be investigated to select the applicable material that can be installed on the outer surface of the building's walls with respect to their efficiency, saved internal loads, and minimizing energy consumption during summer time.

Some of the previously investigated insulation materials for exterior walls of buildings are classified as demonstrated in Table 1.

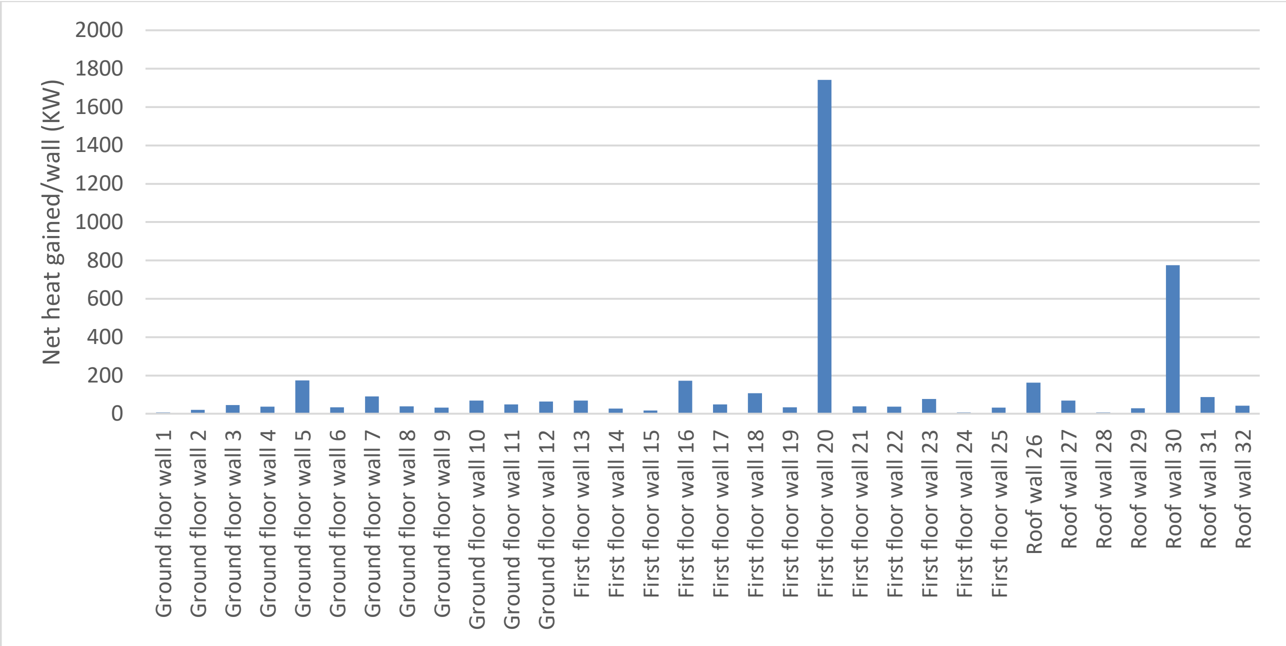

Fig 2: Total net heat gained by each wall in the three summer months

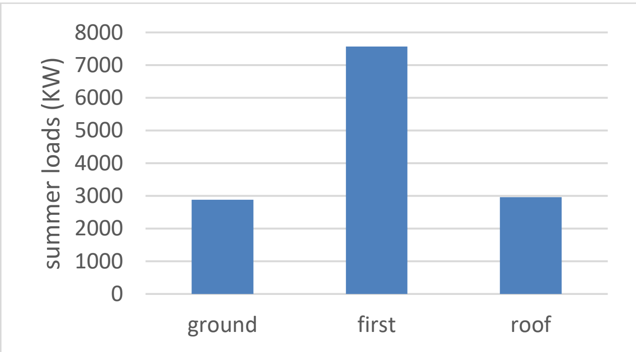

Fig 3: Loads needed in each floor to reach comfort temperature in kW

It has been agreed to select the following materials:

1. Aerogel, the worldwide most effective thermal insulating material.
2. Spray cork, a biomass spray material is selected due to its easy application.
3. Polystyrene wall boards, is selected due to their wide availability in the Egyptian market.
4. Glass ceramic, a reflective material which has been tested experimentally and showed a high effectiveness.
5. Cool coating, an innovative material that is widely found in the Egyptian market but with some modifications by adding PCM.
6. Straw boards, a recyclable biomass wall board material.

The materials were chosen based on their waterproof, and fireproof resistance. The six selected materials have thermal properties as show in Table 2.

3.2 Calculation of heat gain through walls

The overall heat transfer coefficients (U-value) of each wall and roof after inserting the insulation materials are shown in Table 3. The following section will discuss the behavior of each material.

3.2.1 Aerogel Blankets

The silica aerogel blanket is applied to the exterior chosen walls and roofs. The material was defined by its thermal property as shown in Table 2. The U-values of the walls and roof were calculated to be 0.333 W/m^{2}K for walls, and 0.616 W/m^{2}K for roof after adding the aerogel blankets as shown in Table 3. Then the simulation was done each hour during the three summer months to see the temperature difference between the outer and the inner surface of the wall to calculate the heat gain and loss. Equation (1) will be used to calculate the heat gain/loss though the five selected walls. Fig 4 shows a comparison before and after inserting the Aerogel on the walls. The Aerogel blankets showed a better efficiency by 18% comparing to the original model.

Table 1:Insulation materials for external walls and their suitability

Material	Suitability	Comments	Reference
Blanket: batts and rolls - Fiberglass - Mineral wool	No	Not very effective, get damaged with time Unfinished walls	[14]
Rock wool	No	Better in the interior walls	[15]
Spray Cork	Yes	Good thermal insulation, waterproof, sound proof	[16]
Extruded Polyurethane	Yes	Heat insulation boards, available in the Egyptian market	[14]
Cool coating	Yes	Reflective coatings, available in the Egyptian market	[17]
Thermochromics	No	Degradation problems	[18]
Hydrated salts	No	Toxic vapours with time	[19]
Aerogel	Yes	Waterproof, soundproof, excellent thermal insulation	[20]
cellulose insulation	No	Not waterproof, absorbs moisture so it gets damaged easily	[16]
Polyurethane foam board	No	Gas can leak out after time, flammable	[16]
Glass ceramic	Yes	Reflective coatings	[10]
Stone wool	No	Cavity insulation, negatively affected by water vapor condenses	[16]
Gas filled panels	No	Cavity walls	[14]
Straw boards	Yes	Bio-mass insulation material, recyclable widely available	[21]

Table 2: Thermal properties of the selected materials

Material	Thermal conductivity KJ/h.m.K	Density Kg/m^3	Specific heat capacity KJ/Kg.K
Aerogel	0.072	130	1
Spray cork	0.309	240	1.8
Extruded polystyrene	0.115	28	1.28
Glass ceramic	1.26	2630	0.765
Cool coating + PCM	1.548	1260	1.4
Straw	0.356	379	2

Table 3: The U-value for each wall after applying the insulation materials

Material name	U-value $W/m^2.K$
Basic wall	0.500
Basic roof	1.607
Aerogel wall	0.333
Aerogel roof	0.616
Spray cork wall	0.494
Spray cork roof	1.549
Extruded polystyrene wall	0.381
Extruded polystyrene roof	0.779
Glass ceramic wall	0.499
Glass ceramic roof	0.785
Cool coating + PCM wall	0.472
Cool coating + PCM roof	1.353
Straw wall	0.384
Straw roof	0.814

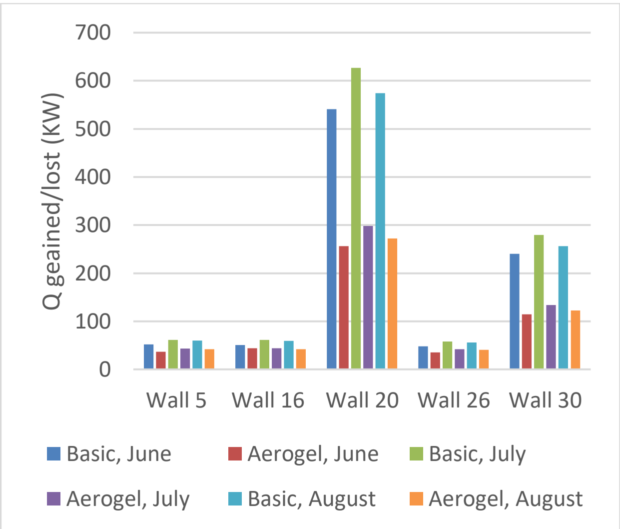

Fig 4: Basic vs Aerogel heat gained through walls

3.2.2 XPS
Similarly, the XPS wall board is applied on the highest heat gain walls of the building. The board thickness is 20 mm. The U-values obtained after applying the material were 0.381 W/m^2K and 0.779 W/m^2K for walls and roof respectively. Fig 5 shows the performance of the heat gain through the walls before and after inserting XPS. The polystyrene foam boards showed an improvement of 15% compared to the original model.

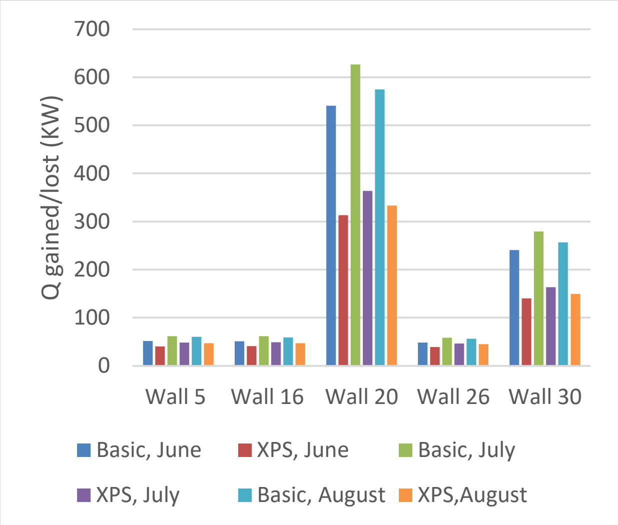

Fig 5: Basic vs XPS heat gained through walls

3.2.3 Glass Ceramic
Similar to the previous materials the glass ceramic coating with a thickness of 1 mm was tested. The material was then applied on the three exterior walls and two roofs. The U-values were obtained for the walls and roof to be 0.499 W/m^2K, 0.785 W/m^2K respectively. The inside and outside temperatures were determined through the simulation to each wall. Fig 6 shows a comparison between the heat gain trough the walls before and after inserting the glass ceramic. The glass ceramic coating showed an efficiency of 14% compared to the original model.

3.2.4 Cool Coating + PCM
The cool coating with a PCM were placed on the exterior surface of the walls with a thickness of 5mm. The walls and roofs U-value were found to be 0.472 $W/m^2.K$ and 1.353 $W/m^2.K$ consecutively as shown in Table 3. Fig 7 shows the heat performance through the walls before and after inserting the cool coating + PCM. This material showed an efficiency of 5.4% compared to the original model.

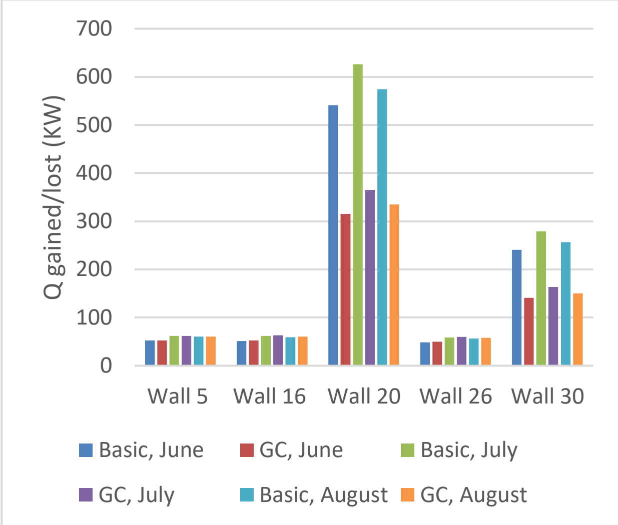

Fig 6: Basic vs Glass Ceramic heat gained through walls

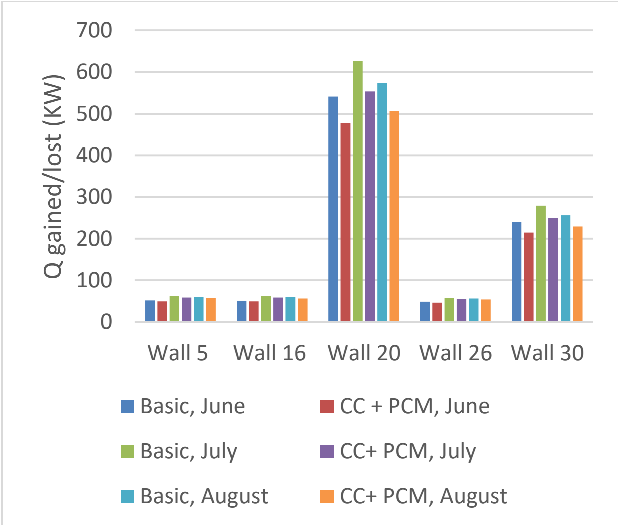

Fig 7: Basic vs Cool coating + PCM heat gained through walls

3.2.5 Spray Cork
The spray cork material was examined on the exterior of the five selected walls and roofs with 2 mm thickness. The U-values for the walls and roofs were obtained from the software to be 0.494 $W/m^2.K$ and 1.549 $W/m^2.K$ consecutively. Fig 8 shows a comparison between the heat performance of the walls before and after inserting the spray cork. The spray cork showed an efficiency of 2.2% compared to the original model.

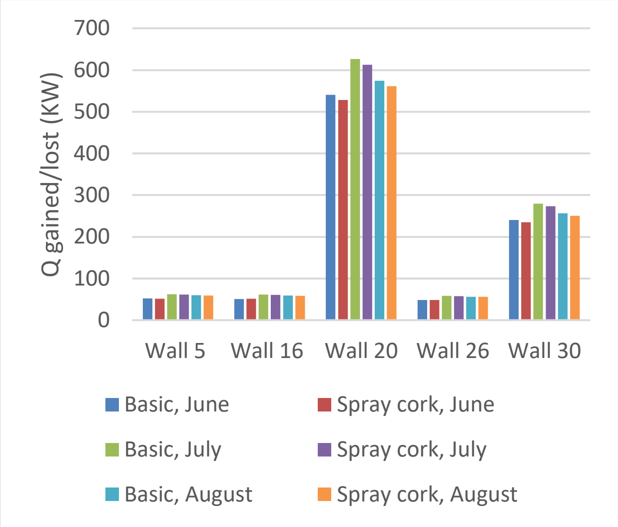

Fig 8: Basic vs Spray Cork heat gained through walls

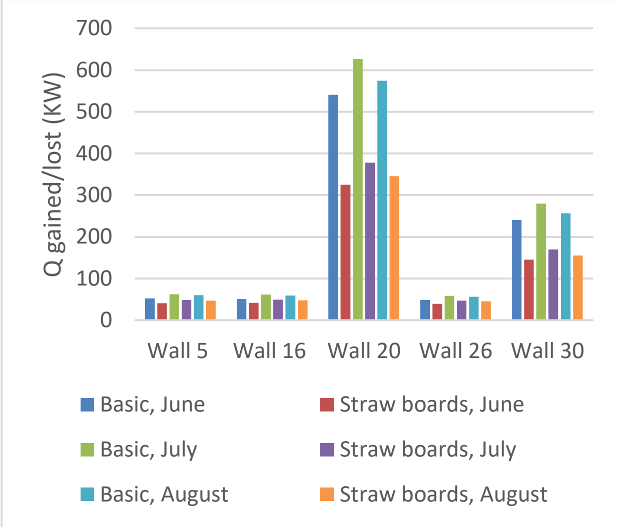

Fig 9: Basic vs Straw Boards heat gained through walls

3.2.6 Straw Boards
The studied straw boards have a thickness 60 mm based on the commercial boards. The U-values of walls and roofs were obtained to be 0.384 $W/m^2.K$, 0.814 $W/m^2.K$ respectively. Fig 9 shows a comparison between the performance of the walls before and after inserting the insulation material. The straw boards showed an efficiency of 14.5% compared to the original model.

3.3 Comparison based on the internal loads
The thermal performance with insulation layer located on the five external walls was compared in order to assess the best heat performance. Fig 10 shows the effect of different insulation materials in improving the efficiency of the prototype building during summer period, also it will offer a comparison between the solar heat gain through each material. The lower Q, the better the insulation material. Moreover, Fig 10 will represent the efficiency of each material (percentage of heat loss) during summer season. Aerogel showed the highest efficiency (48.33%) compared to basic model. Followed by Polystyrene wall board that showed (38.36%), then Straw boards (36.46%), and Glass ceramic (34.38%). The least efficiencies were found to be (10.26%) and (2%) for cool coating + PCM and spray cork which respectively.

3.4 Comparing the internal loads for each material
Fig 11 shows the internal loads (energy used by air-conditioning) needed for each floor to reach the comfort temperature after inserting the proposed insulation materials. Apparently, the best four materials which reduce the total heat gain are aerogel, XPS, straw boards and glass ceramic. The least two materials which are cool coating + PCM and spray cork didn't offer a remarkable change in the energy reduction. It is very clear that the first floor consumed the largest loads followed by the roof then finally the ground floor. This is very expected as the roof area is half of the first floor, therefore it requires the lower energy to reach the comfort temperature. The ground floor is the least affected by the heat as most of heat is being stored in the first floor before reaching the ground floor, also its exposure to the direct solar radiation is limited.

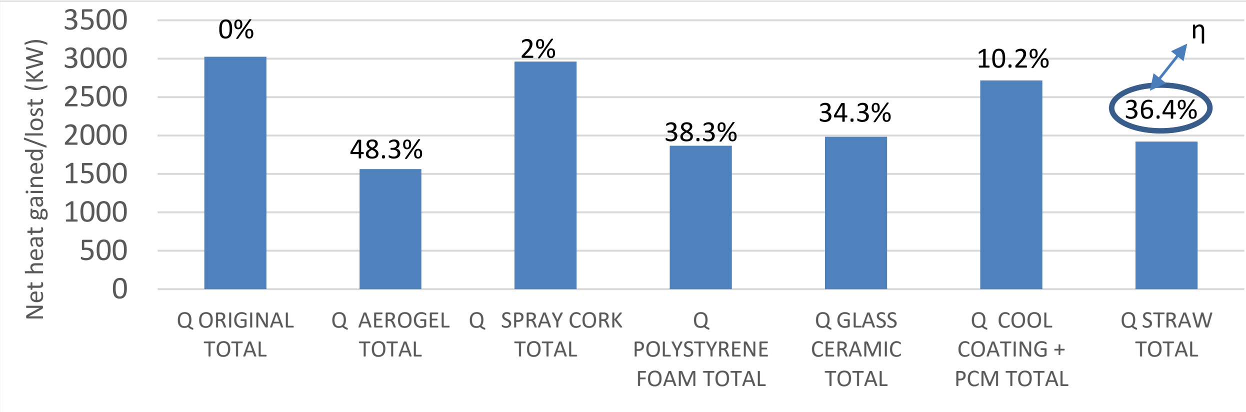

Fig 10: Comparison of the net heat transfer gained in summer season with efficiencies of each insulation material to reduce the heat transfer (η)

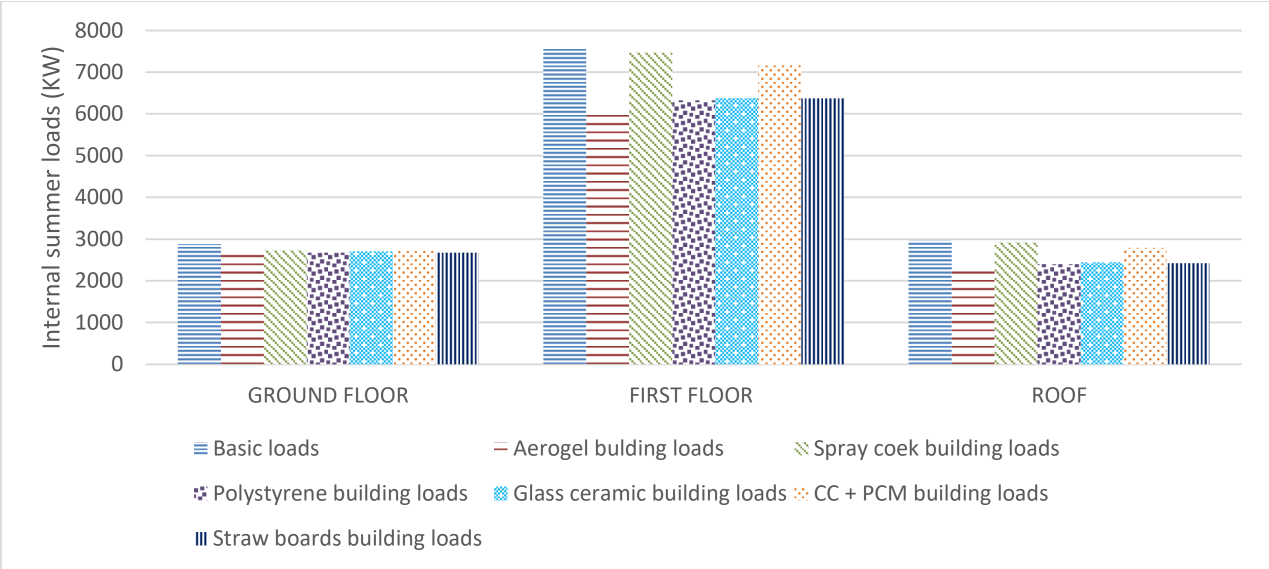

Fig 11: Internal building loads in summer season in each floor for each material

3.5 Payback period based on the material efficiency

Table 4 shows a comparison between the best four insulation materials in efficiency from the economical point of view. The payback periods were found to be 0.84, 1.8, 11.13, 15.5 years for Glass ceramic, Straw boards, XPS and Aerogel respectively. It can be seen that the relationship between the cost and the performance contradicting each others. The efficiency of the first three materials have almost the same range, but the first two offers a reasonable payback period. According to the operational and environmental point of view the best choice will be “Straw boards”.

Table 4: the efficiency and payback period for the best five materials

Material	Payback period (years)	Efficiency (%)
Glass Ceramic	0.84	34.38
Straw Boards	1.8	36.46
XPS	11.13	38.36
Aerogel	15.5	48.33

Nowadays the world attention is grabbed by the recycling processes to reduce the disposed waste material in an environmentally friendly way. It is very brilliant to re-use the waste material to produce new useful ones with newly added properties to serve usefully [22]. Straws supplied form wheat, rice and barley are considered a sustainable supplier to multiple construction products such as roofs, board sheets and bales. It has been proven all over that world by the means of many actual projects that straw boards are very effective in thermal insulation when installed as an external envelope on a building surfaces. The straw boards won their reputation to be a thermal insulating material which can be applied on building surfaces due to their hollow structure, low density and good heat insulation properties [23]. In Egypt, rice is a main crop in terms of whole production, moreover, rice production is associated with large quantities of straw. Rice straw is being produced in high quantities in Egypt which are about 4.4 million tons yearly and this amount increases with increasing population and rice cultivation yield. Agricultural field burning is the regular process for disposal of rice straw, but it results in great impact on the greenhouse aspect as gas emissions as well as air pollution and consequently affects public health [24] [25]. Solutions like recycling from biomass wastes will be so useful [26].

3.6 Reducing loads by using shading pergola with PV system.

In this part of the study, it is suggested to reduce the heat gain by testing a shading pergola with PV panels to see the effect on the internal house loads. Afterwards, a combination of straw boards with the shading-PV method will be investigated then the loads will be compared for the entire house during the summer season. By employing shading effect of the pergola with PV system, the sun radiation will be blocked from reaching the roof top of the first floor additionally will provide the house with power to reduce the house energy consumption. As the straw boards have good insulation properties and the shading pergola with PV panels are a renewable solution with no harm effect on the environment, and it will help in the thermal blockage with a grate architectural design. This solution will be implemented and tested to achieve better results for the existing building.

A 453W panel as dimensions of 1x2m and an area of 2 m^2 will be installed. According to the available pergola area which is 50 m^2 the maximum panels the pergola could take after leaving space for installation and maintenance will be 16 panels. The 16 installed panel will generate 7 kWp (16x435) as shown in Fig 13 this will approximately cover 80 % of the total home consumption.

The internal summer loads were calculated for the proposed method as shown in Fig 12. The best efficiency is 23% for the combined solution of using shading pergola with the PV panels and straw boards, then straw boards only (14.5%) followed by the shading effect of the pergola with the PV panels (10.8%). This is due to the fact that the shading of the pergola with the PV panels affect only the roof top of the first floor (wall 20) and has some shading on the roof that is why it has a small effect of the internal loads. Moreover, after adding the straw boards on the five walls the efficiency has increased more than the double, because of the double effects on the roof top which are the shading effect plus the insulating boards as shown in Fig 13.

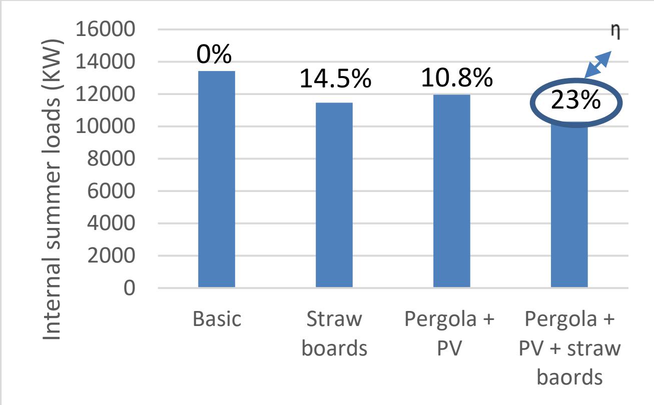

Fig 12: Summer loads and efficiencies (η) for the new solutions.

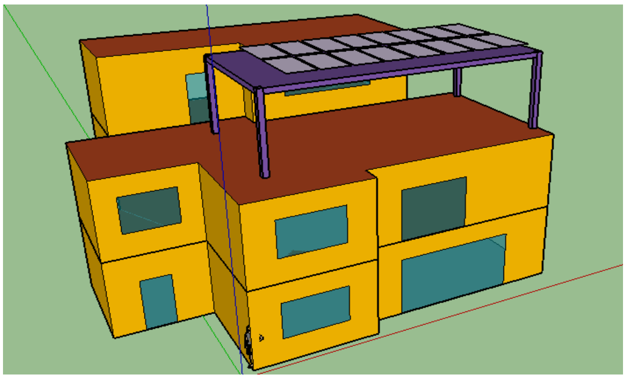

Fig 13: Pergola and PV shading on top of the building

3.7 Cost analysis

Table 5 shows the payback periods, monthly loads consumption (to achieve comfort temperature) and the efficiencies of the previously studied solutions. The table also shows the monthly saving (kW) for each solution compared to the original model. The cost is the price of the insulation system. From Table 5 The aerogel and the XPS will be excluded from the choices because they have a high payback period which are 15.5 and 11.1 years respectively. The best choice from the efficiency and payback point of view is the combination of the shading pergola with the PV on top plus the straw boards on the five selected walls. This solution has a reasonable price and optimum efficiency compared to the other solutions.

Table 5: comparing loads efficiencies of the best solutions

Material	Payback Period (years)	Monthly consumption (kW)	Monthly saving (kW)	Monthly saving (EGP)	Total Savings (EGP)	Cost (EGP)	Cost (USD)	Loads efficiency %
Basic building	N/A	4470.017	N/A	N/A	N/A	N/A	N/A	0%
Aerogel	15.5	3666.642	804	1165	3495	54141	3383	18%
XPS	11.1	3795.895	675	978	2934	32661	2041	15%
Glass Ceramic	0.84	3842.982	628	910	2730	2300	144	14%
Straw Boards	1.8	3821.385	649	941	2823	5055	316	14.5%
Shading + PV	3.88	3985.402	1955	2834	27687	107,500	6718	10.8%
Shading + PV + Straw boards	3.7	3430.583	2510	3639	30102	112,555	7034	23%

After investigating and comparing all the previous solutions, the applicable solution was using a shading pergola with PV system in addition to straw wall boards. The shading pergola and the PV system are widely available in the Egyptian market. The manufacturing of straw boards in Egypt will be an appreciated solution from the efficiency, environmental and economical point of view.
These solutions will be beneficial for the people working in the HVAC systems, civil engineering, energy efficiency industries.

4 Conclusion

The results of the comparative analysis concerning the daily thermal performance of an existing family house in Egypt are reported in order to show the influence of the insulation material on the thermal performance in Summer period. The best four materials in efficiency were found to be silica aerogel (18%), XPS (15%), glass ceramic (14%) and straw boards (14.5%). Going to the direction of renewable systems and bio-based materials, a new method was investigated which is a combination of straw boards with a shading pergola with PV panels. This method showed 23% efficiency on the internal comfort of the building compared to the original model. Moreover, it is proved to be environmentally and economically friendly.

5 Future Research

The future research agenda will focus on implementing experimentally the final results of the previous solutions to be integrated with other solutions such as solar thermal, geothermal, cold water and windows shutters in improving the domestic and electrical energy consumption inside any building to reach a sustainable development.

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Contribution of individual authors to the creation of a scientific article (ghostwriting policy)

Author Contributions: Please, indicate the role and the contribution of each author:
Example
Radwa Amr carried out the simulation and the analysis.

Ahmed Abdel-Rehim revised and reviewed the simulation results.

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