Enhancing Thermal Performance of Roofs Within Heavy-Weight Thermal Mass Residential Buildings in The Warm Mediterranean Climate of Lebanon

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Abstract

The research aims to analyze the thermal performance of the common practice roof construction types in fully exposed heavy-weight buildings in the coastal warm zone of Lebanon. Two roof types in one residential house, are monitored simultaneously during the summer of 2023, one with a reinforced concrete slab and the other with a steel structure covered by red clay tile. Once the house was simulated using Insight 360 software, results were compared to the recorded data of every room's indoor dry bulb temperature during the day and night. This is followed by further shading and spatial manipulation to enhance the construction materials' thermal properties, giving an in-depth overview of the thermal performance of those materials. The research concludes with practical design recommendations and solutions for keeping with the same construction material yet considerably reducing the annual cooling load and relying on scarce non-renewable energy. However, enhancing the roofs' thermal performance can decrease 56% of the energy used for indoor cooling.

Keywords: Thermal simulation, Thermal mass, Warm climate, Summer indoor cooling.

1. Introduction

The residential sector is responsible for 40% of global energy consumption (UNDP, 2022). This is due to the large heating and cooling loads that rely on scarce non-renewable energy resources to ensure indoor thermal comfort (Hooyberghs et al., 2017). Implementing measures to reduce carbon footprint and energy consumption is essential to mitigate the negative impact on the environment (Hachem-Vermette et al., 2019). While implementation of energy efficiency measures in residential buildings enables a decrease of 35% according to (ASHRAE, 2024). The energy used for cooling a building in a warm climate can be decreased through effective passive design techniques, choice of construction material, and enhancing the building envelope's thermal performance (Amaripadath, D et al., 2022). Lebanon relies on air-conditioning powered by diesel fuel oil electricity as a source of indoor cooling (Melki & Radan, 2005). Since Lebanon suffers from a daily power shortage. Thus, the supply cannot meet the demand.

In response to the increase of awareness on energy consumption overwhelming scarce non-renewable resources, numerous strategies and recommendations are available in Lebanon for buildings' envelope to reduce energy demands and consumption for each climatic zone issued by local and international bodies, targeting the development of low energy housing in warm climates (MOE/UNDP/GEF, 2015). It recommends highly insulated construction materials equivalent to a low U-value external envelope (external walls and roof). Moreover, the "Building Energy Codes Program" recommends thermal properties for each envelope within the four climatic zones of Lebanon that can reduce energy consumption and demand caused by cooling (Aznabaev et al., 2016). Thus, insulation is being used for hot climatic zones to reduce heat transfer and reduce heating loads (International Energy Conservation Code, 2011). However, the literature review does not support the use of insulation in hot and warm climates. Heavyweight construction materials such as concrete and their derivates are the common choice in warm environments to reduce internal temperature (ASHRAE, 2004). When it comes to the built-up fabric of Lebanon in all climatic zones combined, roofs are mainly made out of

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materials such as reinforced concrete or steel structures roof covered by red roof clay tile cladding.

The research studies the thermal performance of roof construction materials in Lebanon. Although Lebanon has 4 different climatic zones, the paper deals with the coastal warm zone which has cool and short winters, and hot, humid, and long summers (UNDP, 2005). The common roof construction type in Lebanon has reinforced concrete slabs and an optional steel-pitched roof covered by red clay tiles. These materials are labeled as heavyweight materials or thermal mass due to their capacity to absorb, store, and release heat (UNDP, 2005).

Del col Diaz et al. (2010) studied the concrete as a construction material to achieve an efficient thermal resistance in warm climates without an effective insulation property. The insulation has its impact on air flow within the unit's modeled interior space. Where it increases the thermal performance of the concrete. This research showed an increase of 42% through insulation. They showed the difference between insulated and non-insulated concrete slab. The next paper by Pierquet P. et al. (1998) compares eleven different slab systems to the lightweight insulated construction such as steel construction, and concrete construction. Concrete construction shows the best long-term energy performance compared to other construction materials in warm climate. Several studies have tackled the issue of reducing energy consumption by minimizing the demand for cooling in warm and hot climates (Visser et al., 2013), (Bretz et al., 1998), and (Prado et al., 2013). Their research outlined the reliance on passive strategies switching to being independent of fossil fuels. These strategies are natural ventilation, passive cooling, and reducing heat gain from the roof. Retrofitting has been addressed to improve indoor comfort conditions and reduce energy demand and consumption. (Blázquez et al., 2019) proposed retrofitting strategies for improving ventilation and adding insulation layers on 218 housing units. (Suárez et al., 2015) applied to retrofit strategies for a 68-apartment unit in a residential building in Cordoba, Spain. Results show that this reduced 38% of the total energy demand. (Suárez et al., 2015) highlighted a significant envelope improvement as increasing insulation and night ventilation. This led to a reduction of 27% of energy for indoor cooling. (Panayi, 2004) Investigated the impacts of different passive strategies for retrofitting on cooling energy consumption as insulation, glazing, thermal mass, and orientation of a house in Nicosia, Cyprus. The analysis was conducted through simulation software. Results showed that the most effective measure is double glazing, 25 mm of wall insulation, thermal mass, and roof insulation. (Florides et al., 2000) studied a house in Cyprus analyzing its cooling load throughout the year. Results showed that roof insulation reduces cooling demand by up to 57%.

This study investigates a building's roof as an external envelope by comparing two common construction materials in Lebanon to study their thermal properties during the summer of 2023. The aim is to monitor the internal dry bulb temperature of every room to assess each roof construction material's impact under the same conditions. Where, rooms are identical in windows' type and size, walls, construction materials, shutters, surroundings, and occupancy. The duration of the monitoring allowed weekly comparisons between results to experiment with random changes. The purpose was to test the behavior of each material during the day and night. Following an overview of previous studies that deal with temperature monitoring of each of the cited construction materials.

The research aims to assess the potential of decreasing energy consumption by enhancing the thermal properties of the roof's construction materials used in Lebanon to minimize cooling loads that depend on scarce non-renewable energy.

2. Methodology

This research is carried out on a residential house located in Jounieh area (33.9843° N, 35.6344° E), 20 km northeast Beirut, 60 m above sea level (Figure 1), monitoring its internal temperature for a period from August 2023 till September 2023 (summer of 2023). It is a two-floor residential house having two different external envelopes: limestone 30 cm for the external and internal walls and concrete masonry unit (CMU) 10 cm for the rooms that have been added lately. Part of the roof is a 15cm reinforced concrete, while the other part has a steel slab covered by clay roof tiles (Figure 2). The slab between the ground floor and the first floor is a steel structure covered with ceramic tiles. All the internal walls are plastered and painted, and the windows are single glazed with a wooden frame (Figure 4).

The house has two balconies, one towards the north (14 sq. m), while the other is towards the southeast and is closed with single-glazed curtain glass. The closed balcony is 25 sq. m, and its roof is made of steel structure covered with red roof tiles. The ground floor sums up to 113 sq. m, while the first floor is 37 sq. m. The living area and the dining area on the ground floor have a double height of 6 m. The bedrooms on the ground floor are covered with corrugated sheet shading elements to use the space underneath them as a storage area.

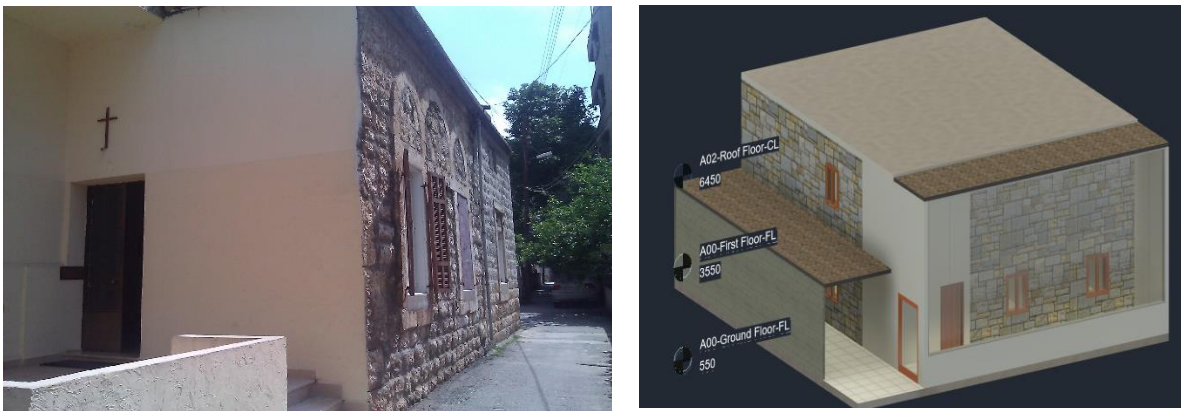


Fig. 1: Picture and isometric view showing the studied house. Source: Author.

The observation was divided into two categories. The first one (category A) is the rooms that had the reinforced concrete roof. While the second category (B) contains the rooms that have steel structure with red roof tiles. The AC in both categories work according to the availability of electricity. This is due to Lebanon suffering from daily power shortages. Affected by the high demand for electricity and the inefficiency of power plants. According to (Fardoun et al. 2012, p.317), There is a lack of electricity to meet market demands, where the demand increases while the supply decreases.

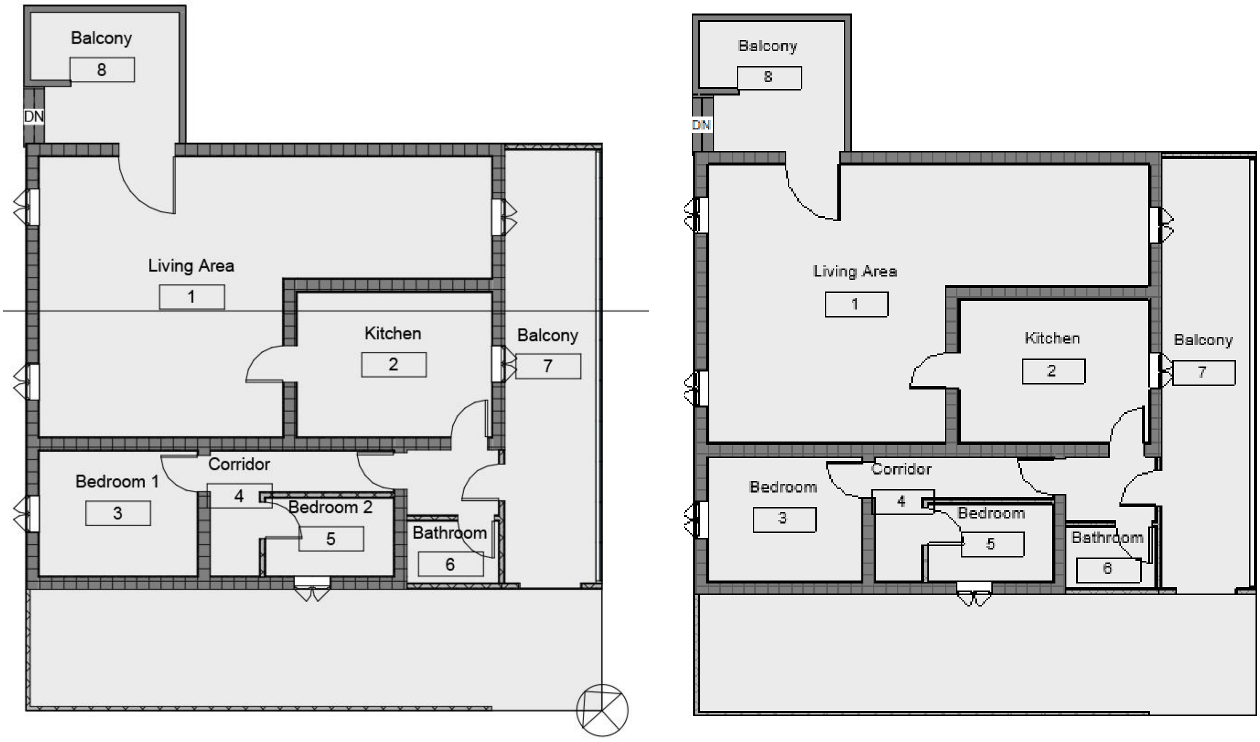


Fig. 2: Ground Floor and First Floor Plans of the Studied House. Source: Author through Revit Autodesk 2020

The current situation depends on the private sector supplying the required energy through diesel generator. The energy used for the residential sector shows that the main consumption is summer indoor cooling (MOEW/GEF/UNDP, 2015, p. 19).

Recorded temperature shows that peak temperature occurs after mid-day hottest peak when the solar radiation is directly hitting the room’s roof. Also, the temperature within the most exposed rooms to the sun is constantly higher than in the other rooms. This was shown during the observed period where the inside temperature is above the comfort band. This is in clear contrast with the recorded rooms that were least exposed to solar radiation where it was within the comfort band.

Fig. 3: Photos showing the instruments used for dry bulb data collection. Source: Author on August 2023.

In addition, the monitoring instruments consist of a Davis weather station which was installed on a nearby building’s roof to record the outdoor air temperature and solar radiation at hourly intervals in °C. Also, Tiny Tag data loggers were installed in each room of the house recording the dry bulb temperature at the hour in °C. All of these values are used in the analysis to compare internal and external temperatures. Moreover, a single-phase energy meter was installed to record the air-conditioning consumption in terms of electricity in Wh.

Fig. 4: Isometric Section showing the inner space of the House. Source: Author through Revit Autodesk 2020.

Furthermore, the house was modeled by using Revit Autodesk 2020 as thermal simulation software (Figure 5). Results were compared to the recorded temperature data. Subsequently, the model was constructed and simulated by retrofitting the roof in terms of enhancing the external envelope’s thermal properties to minimize cooling demand and adding shading devices. Insight 360 (Autodesk) and Green Building Studio (GBS) are energy simulation software that allows designing, analyzing, predicting, and evaluating energy consumed in models in a specific location, orientation, and climatic conditions (Fasi et al., 2015). The simulation allows a clear understanding of the impact of the building design, including retrofitting measures for existing buildings on energy consumption. A calibration was done to insure the correlation between the actual recorded data with the software simulation data. Adding to that, the simulation included the enhancement in the construction materials' thermal performance such adding insulation and reducing sun radiation exposure to the roof surface. This resulted to have an overview of the results that will occur in case of enhancement. Reaching 222 kWh/m^2/yr which is below the benchmark set by AHRAE 90.1 (252 kWh/m^2/yr).

The research uses also the method of degree hours of overheating above 30ºC to establish performance ranking of the various cases.

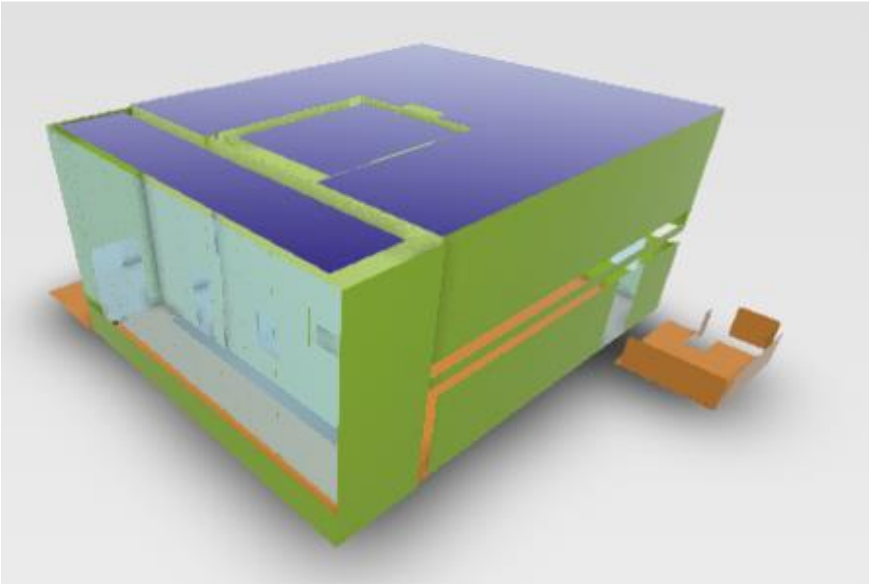


Fig. 5: Isometric Section showing the modelled House through Insight 360. Source: Author.

3. Results

The monitoring period showed that each room performed differently with significant day and night temperature differences, and with exposure to solar radiation (Figure 6). During the day, bedroom #4 (1st floor) had the highest indoor dry bulb temperature and recorded the hottest peak between the other rooms, while bedroom #2 (ground floor) recorded the warmest score and maintained the coolest (Figure 6).

Initially, during days 239 and 240 on the 27th and 28th of August 2023 (Figure 5), the highest outdoor temperature trend was recorded during daytime 32.8°C. This is reflected in the inner temperature of bedroom #4 where it recorded a peak temperature of 38.3°C. As soon as the air-condition (A/C) was turned on, the internal temperature of the room dropped to reach 27.8°C (day 239). Once the A/C was turned on (day 240), the room kept cooler than the previous day and reached a maximum of 34.9°C which is lower than day 239.

Observation showed that during day 239, the A/C was turned on for 12 hours simultaneously. While, during day 240, the A/C was turned on for 17 hours simultaneously. This reflects the indoor temperature of the room that differs between these two days while having almost the same outdoor temperature and solar radiation. According to figure 5, the A/Cs consumed 50 kWh at day 239 while on day 240 it consumed 56 kWh. Although, having an A/C running more than half of the day, the temperature of bedroom #4 did not drop below the outdoor temperature.

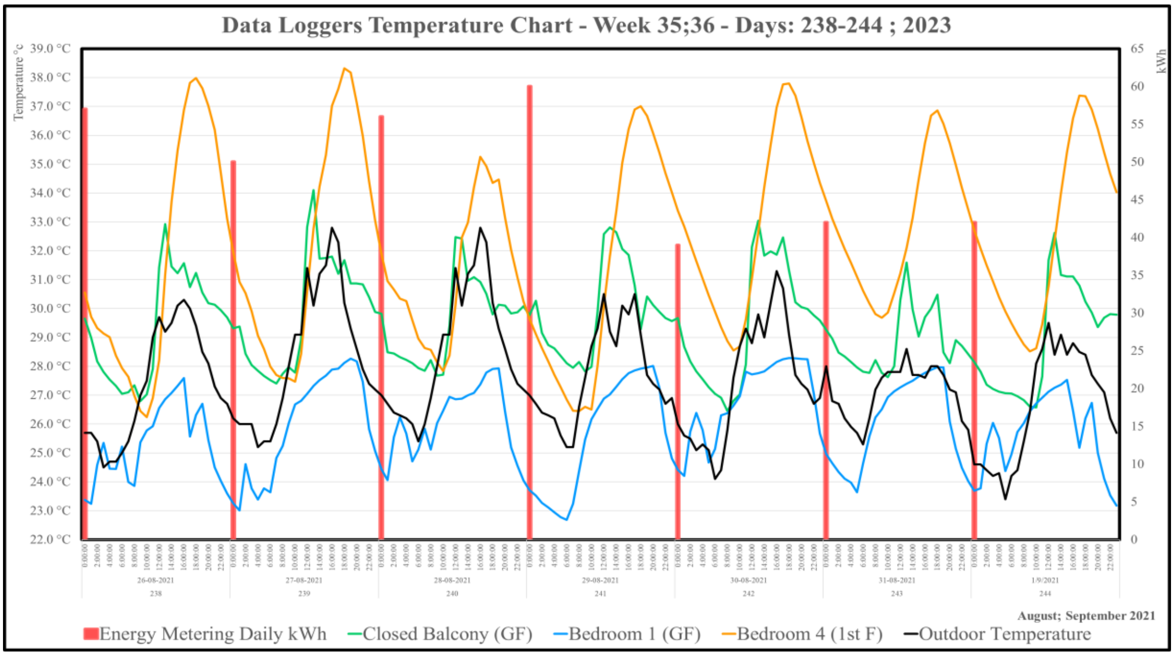


Fig. 6: Comparison between indoor and outdoor Temperature. Source: Author.

The observation of the closed balcony showed that during noon, the internal temperature started increasing. This is due to the orientation of the room which is towards the southeast (Figure 6). This was evident during the study period, where temperature started increasing until it reacheed its peak during the day. This is where the A/C was turned on and started decreasing the internal temperature. Accordingly, with a minimum of 12 hours of A/C running, also the closed balcony did not reach a temperature below the outdoor temperature during the day.

Internal peaks and fluctuation happened at various times during the day; this occurred due to the electricity blackout. As shown in figure 6, when the electricity is cut off, the internal temperature of the closed balcony increases rapidly. Bedroom #1 (below bedroom #4 on the ground floor) has the coolest temperature compared to the rooms that use an A/C in the house.

Observation shows that during day and night, this room had its inner temperature below the outdoor temperature. The daily temperature peaks sharply afternoon. This is due to the orientation of the bedroom towards the west. When the internal temperature starts rising, the A/C was turned on to decrease the room

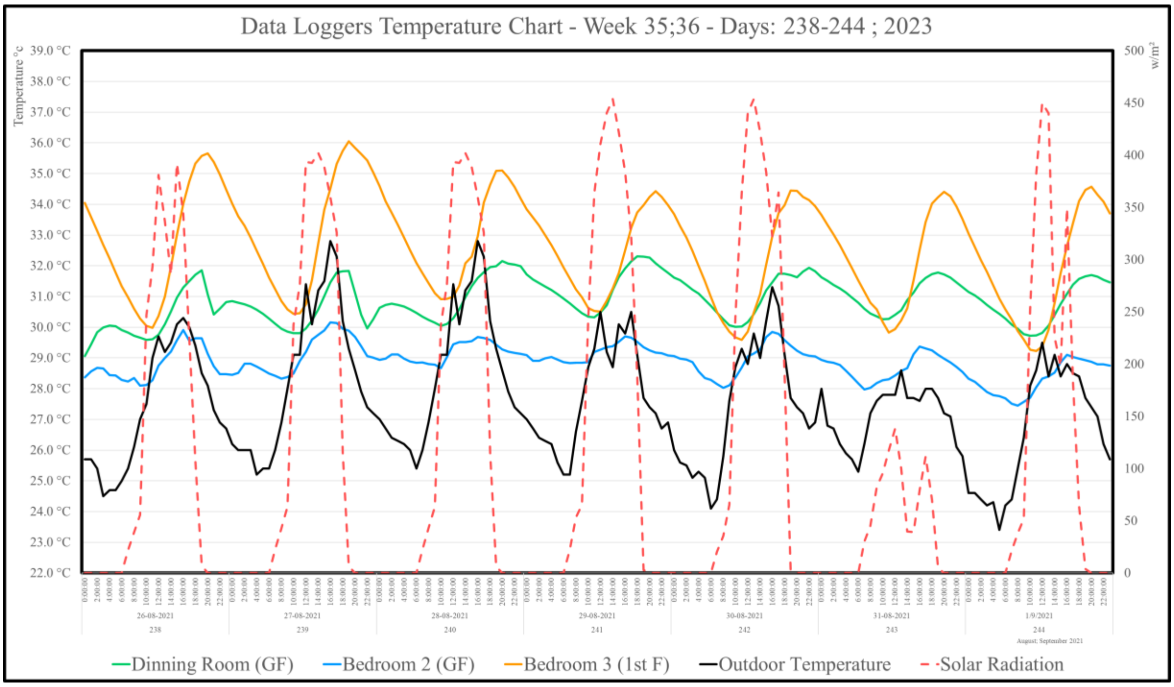


Fig. 7: Comparison between indoor and outdoor Temperature. Source: Author.

temperature. Accordingly, the temperature drops until the A/C was shot-off. Internal peaks and valleys happened at various times; as a general trend, they occurred due to electricity blackout with a malfunction of the A/C. So far, these three rooms showed that the direct exposure of the solar radiation on the roof highly affect the indoor temperature. In order to assess the impact of the external envelope on the internal temperature, a comparison of bedroom #2 which is situated on the ground floor, where the solar radiation doesn't hit the room due to the shading platform on its elevation, and bedroom #3 which is situated on the first floor where its roof is totally exposed to the solar radiation during the day (Figure 7).

Days 239 and 240 recorded the highest temperature during the studied period compared to day 243 which has the lowest temperature recordings and lowest solar radiation at that week. Figure 6 shows that bedroom #2 has almost a daily repetitive fluctuation of 1.5°C temperature difference between day and night. While bedroom #3 has a difference of 5.7°C between day and night. Subsequently, when the outdoor temperature reaches its lowest recording which is 24.5°C, the internal temperature of bedroom #2 drops to reach 28.1°C. Yet bedroom #3 recorded a 30°C. However, when the outdoor temperature reaches its daily peak which is 32.8°C, the internal temperature of bedroom #2 records 29.6°C while bedroom #3 reaches a 35.7°C. It is noticeable that the internal temperature of bedroom #2 does not exceed the external temperature where it

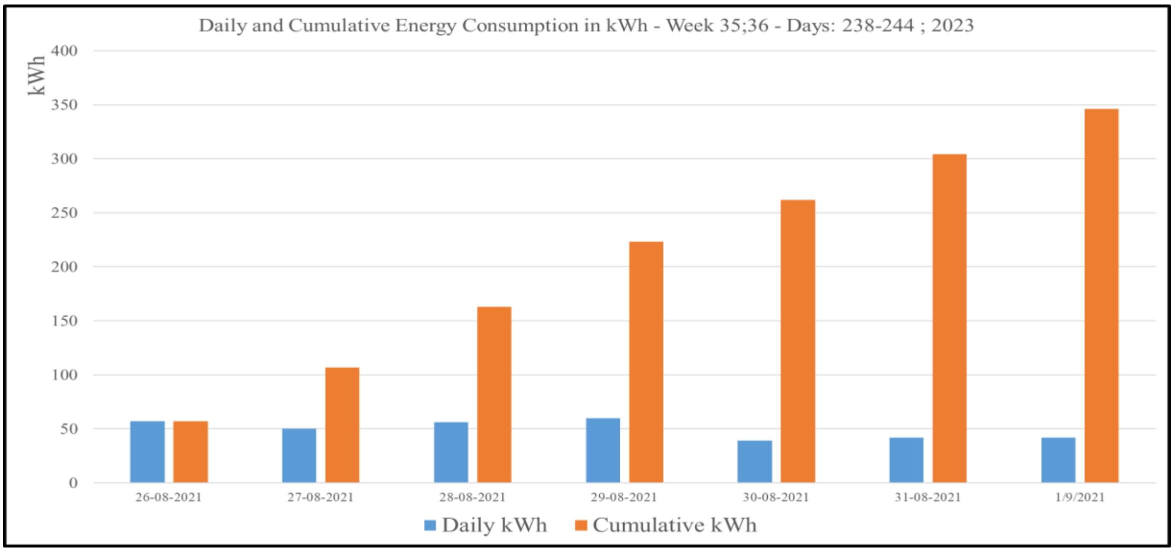
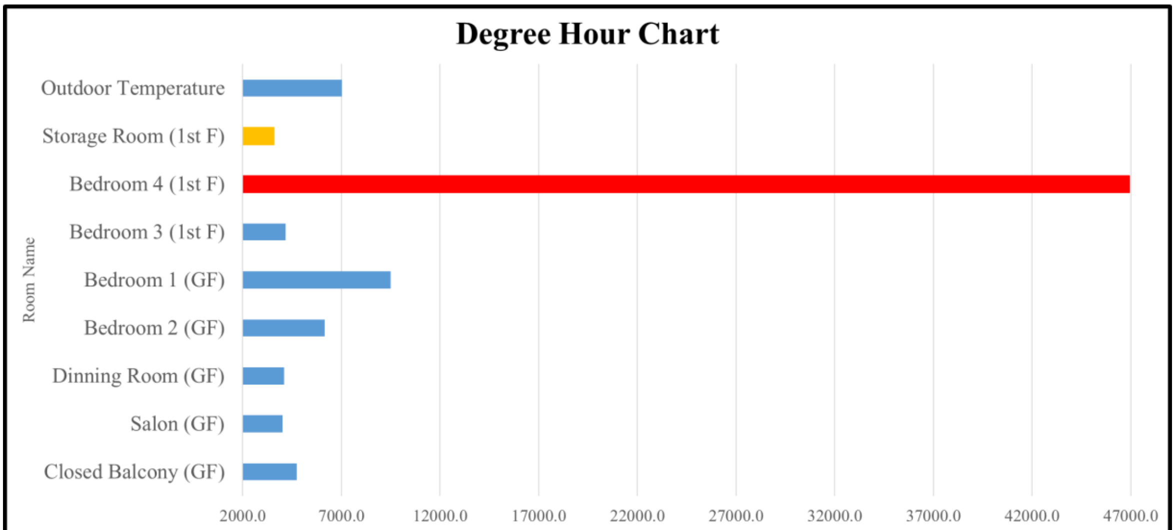


Fig. 8: Comparison between daily and cumulative energy consumption. Source: Author.

fluctuates at a constant temperature. Whereas the lowest temperature recorded in bedroom #3 is higher than the outdoor temperature.

Besides, the dining room temperature monitoring showed that internal temperature is affected by the solar radiation hitting its roof. The gap between the lowest and the highest internal temperature is around 2°C difference. Observation shows that the peak internal temperature occurred in the afternoon, this is due to the external envelope facing the west orientation and exposure to the sun radiation. This can be shown during each day of the studied period. Throughout days 238 and 239 (Figure 7), the temperature at 12:00 pm recorded 29.9°C. The internal temperature starts increasing until reaching an indoor temperature of 31.9°C as a peak



	Closed Balcony (GF)	Salon (GF)	Dinning Room (GF)	Bedroom 2 (GF)	Bedroom 1 (GF)	Bedroom 3 (1st F)	Bedroom 4 (1st F)	Storage Room (1st F)	Outdoor Temperature
Degree Hour	4732.4	4017.3	4097.9	6157.1	9504.4	4175.8	46944.2	3581.7	7023.7

Fig. 9: The recorded degree hour. Source: Author.

dry-bulb temperature at 7:00 pm. this is when the sunset during the summer season. After this action, a decrease in internal temperature occurred until reaching a temperature of 30°C.

To establish the performance ranking of the various studied rooms, degree hour method was implemented. It shows the proper situation in such context that has the higher thermal properties in providing coolest internal temperature among all rooms.

Saleh P. (2019) emphasized that degree hour is more relevant to such study. Where the purpose of such method is to use a benchmark temperature to compare the overheating hours. In this study, the benchmark is taken 30 ºC due to insure of having a wide difference between the minimum accepted by the publication, where according to UNDP (2005), temperature in the coastal area of Lebanon should not fall above 24 ºC.

The outdoor temperature degree hour of the studied area according to the weather station is 7023.7 Dh during the study period based on a selected benchmark 30 °C. Also, the bedroom #4 which is situated on the 1st floor, where it is exposed directly to the solar radiation recorded the hottest degree hour between all studied rooms which is 46,944 Dh of overheating above 30ºC. Followed by bedroom #1 which recorded 9,504 Dh. Then, bedroom # 2, closed balcony, bedroom #3, dining room, and salon recorded respectively 6,157 Dh, 4,732 Dh, 4,175 Dh, 4,098 Dh, 4,017 Dh. It can be observed that there is a huge gap between the room that has the hottest Dh compared to the other rooms (Figure 9).

4. Discussion

So far, house monitoring has shown the impact of solar radiation exposure and roof construction materials' actual thermal properties on the internal dry bulb temperature. Observation showed that the room with no exposure to solar radiation has the coolest internal day and night peaks and temperature, whereas the more the solar radiation hits the roof, the more the room is warmer.

The source of energy requirement for summer indoor cooling is based only on electricity. Figure 6 shows an overview of the current situation. The effect of the high internal temperature required an average of 50 kWh of daily electricity consumption to decrease the internal dry bulb temperature in only three rooms which constitute 58 sq. m. This leads to energy consumption of 0.86 kWh/m² (for each m²). Whereas, projecting this number on the studied house which is 150 sq.m. if it was cooled during summer will end up consuming 129 kWh daily electricity (multiplying the energy consumption of each m² by the total house area).

Given that the thermal performance of the house was directly affected by the solar radiation and the absorbance of the roof. Therefore, the model simulation depends mainly on installing shading elements and enhancing the external envelope’s thermal properties to reduce heat gain to help the cooling process.

In the enhancement of the current situation thermal and energy consumption of the studied house, the construction is altered to insulated construction method to increase thermal resistance and minimize heat loss. In addition to these alterations, an increase in the ventilation also was proposed to regulate the internal temperature was also simulated.

To begin with the construction material enhancement, the roof thermal properties where improved. Where it was a 15 cm reinforced concrete roof. Thermal insulation was added on top of the slab with a 50 cm earth to have a green roof. This enhanced its U value from 5.4 kWh/m²/year to 1.3 kWh/m²/year which is 76%. By this, the elimination of solar radiation hits the roof surface. In addition, insulation was added to the roof cladding construction material to prevent heat transfer to the inside and increase the indoor temperature.

By doing such enhancements and changes and according to the simulation software, the energy use intensity (EUI) of the house was reduced by 56% from 506 kWh/m²/year to 222 kWh/m²/year. Insight 360 gives results in EUI (Energy Use Intensity) per unit of the built area. It means that this software provides an evaluation of the building’s annual energy consumption according to the gross floor area. This process is applied to all types of energy used in the building, such as space heating, and space cooling. For this reason, these measurements should be taken into consideration while selecting the external envelope building’s material according to the benchmark set by Insight 360, which is ASHRAE 90.1.

The positive impact of minimizing solar radiation contact with the roof and enhancing the house envelope thermal components on both the electricity consumption and the energy use intensity. Furthermore, it shows the impact of the reducing cooling load. The values of the above for the indoor cooling electricity consumption changed from 350 kWh as an average in a warm and hot week to 194 kWh after the retrofitting enhancements. While for the EUI, it dropped from 506 to reach 222 kWh/m²/year which is a decrease of 56%. The benchmark set by Insight 360 is 257 kWh/m²/year.

The external envelope varies considerably within the different parts of the house which affects the needed energy for indoor cooling. Whereas, whenever the house area increases, the cooling load increases. Accordingly, the need for energy will increase. The energy simulation of the house indicates that retrofitting could achieve a sufficient energy status by enhancing the envelope’s thermal properties and using the roof only for electricity generation, under the given climate conditions.

5. Conclusion

This research made an investigation into all aspects of heavyweight thermal mass roof with comparison to the red roof tile and the impact of solar radiation and effect of each construction material on the internal temperature through data recording of the internal dry bulb temperature and through software simulation in the warm Mediterranean coastal area of Lebanon reaching the following key conclusions:

The first factor deals with enhancing the thermal properties of the external envelope can decrease energy consumption and cooling load. The second factor is to incorporate shading devices to protect the envelope from direct solar radiation. These two strategies showed that 56% of cooling demand could be reduced.

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