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Thermal Comfort Evaluation in Egyptian Residential Buildings: A Case Study to Determine the Problems of Excessive Electricity Consumption

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ABSTRACT

Residential buildings consume a large proportion of global energy consumption. This consumption burdens energy security greatly as it is not proportional to the produced energy. Efficient planning to meet building energy needs requires accurate, high spatial resolution information on energy consumption. To justify the high energy consumption, this study focuses on energy consumption breakdown and evaluates how it affected indoor thermal comfort inside existing residential buildings. As well as, evaluating the proposed retrofitting solution provided by the Egyptian energy code to provide the bases which work on enhancing thermal comfort in existing residential buildings in Egypt. This evaluation was done using building performance simulation tools. The paper's research methodology follows the experimental approach. This approach utilizes energy simulation (DesignBuilder) to evaluate the existing residential building's thermal performance in the current state and post retrofitting solutions. The evaluation is done by analyzing thermal comfort levels according to the acceptable ranges stated by the Egyptian Code for Improving the Efficiency of Energy Use in buildings. Residential buildings are built without taking appropriate design measures to protect the indoor environment from external weather conditions. researchs' importance is to study how this will affect indoor thermal comfort. The paper aims at clarifying the effect the lack of thermal comfort has on energy consumption in the existing residential buildings in Egypt.

1. Introduction

The building sector, specifically residential buildings, is a significant contributor to global energy consumption (1,2). In 2019/2020, Egypt's residential sector utilizes a whopping 42% of all generated power. (1). This percentage was the end consequence of a ten-year trend of increasing rates. In 2009/2010, it was 40%, and in 2015/2016, it was 44% (1). This consumption pattern results from the population growth rate of 1.31. This pace of increase resulted in the present population of 102,192,247 people. (2).

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Abbreviations

PMV	Predicted Mean Value
CDD	Cooling Degree Days
EREC	Egyptian Residential Energy Code
HBRC	Housing & Building national Research Center
DB	Design Builder
U-Value	thermal transmittance
R-Value	thermal resistance
PET	Physiologic Equivalent Temperature

The growing population necessitated the rapid development of residential structures. As a result, the majority of these structures were constructed without regard for environmental factors, resulting in low building thermal efficiency and poor internal thermal comfort. (3). The two main variables that contribute to an annual increase in energy consumption are the number of air conditioners installed and their operation hours to meet the demand for indoor thermal comfort in these bridlings (4). As a result, as indicated in Figure 1, the residential sector was the greatest energy consumer in 2019/2020 (1). Climate change caused such behavior, which is an important factor in such contexts because poor building thermal performance influences energy use to achieve comfort levels (4). Furthermore, the building envelope should be considered as a critical aspect in reducing energy consumption and bearing responsibility for solar and heat gains that impact internal comfort conditions. (5).

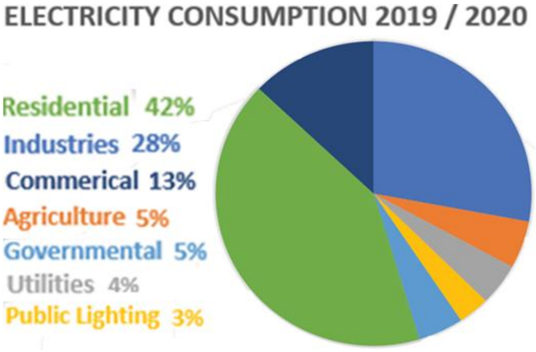


Fig. 1. Electricity consumption by sector 2019/2020

2. Literature Review

2.1. *Buildings Energy*

Cairo, Egypt's capital, is classified as Group B by the Köppen climate classification system, which means it is extremely hot and dry (6). Because of poor thermal resistance in buildings and Cairo's changing climate over the last 30 years, ventilation and cooling systems increasingly rely heavily on electricity. Over the period of the 30 years, hanan et al summarized that of the 10950 days (30 years), cooling systems were used in 4943 days of the total. Known as cooling degree days (CDD). At which the base temperature was 10° (7).

The previously mentioned data were corroborated further by an electrical usage breakdown performed by 2020 research. According to the report, 50 percent of the power consumed is for thermal comfort, with 45 percent for cooling and 5 percent for heating. (8).

In addition to the previous research findings, some of the most recent studies on building energy efficiency were reviewed and evaluated in order to discover the approach and techniques used in each study.

Hanan et al (7), examined the interior conditions and energy consumption of heritage residential structures, taking into account building thermal efficiency and climate changes that occurred over time According to the findings, the comfort hours in the reference building's base scenario accounted for 31.4 percent of the total hours.

Adly et al (9), Researchers investigated the energy consumption and internal gains of an existing residential complex in Greater Cairo on both the building and neighborhood sizes. The effect of integrating energy efficiency retrofitting approaches as a strategy for decreasing energy consumption by elevating interior thermal comfort in existing residential structures was investigated in this paper. Retrofitting the building envelope and lighting system, which saved 11.32 percent of the energy usage, and installing PV panels, which produced 77.36 percent of the used energy, were among the upgrading techniques used. Total energy consumption was reduced by 88.68%.

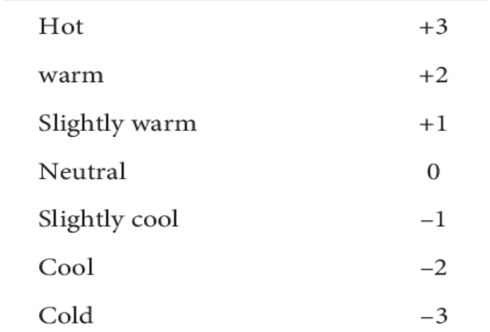
This highlights the significance of addressing thermal comfort concerns, and how increasing building thermal performance will result in significant energy savings.

2.2. *Thermal comfort*

A clear definition of thermal comfort is: "It represents the subjective state of mind satisfaction with the thermal environment and is assessed by subjective evaluation (10). So, comfort in the context of indoor climate is the degree of satisfaction experienced by the users which they would like to live or work with".

2.3. Ashrae Standard 55

The ranges of indoor environmental conditions to ensure acceptable thermal comfort for building occupants are established in ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy, an American National Standard issued by ASHRAE. It makes use of thermal indices, often referred to as predicted mean value, to assess interior thermal comfort (PMV). A thermal sensation vote (self-reported perception) is measured on a scale from -3 to +3, which corresponds to the categories of "cold," "cool," "slightly cool," "neutral," "slight warm," "warm," and "hot." The PMV index predicts the mean value of the thermal sensation votes (self-reported perceptions) of a large group of people on this scale.(10)



Thermal sensations	PMV
Hot	+3
warm	+2
Slightly warm	+1
Neutral	0
Slightly cool	−1
Cool	−2
Cold	−3

Fig 2. PMV Index

To summarize the thermal comfort ranges according to Ashrae standard 55 (10) in the case of 0.2 m/s for air velocity and -0.5 > PMV < 0.5 (Thermal comfort optimum conditions are between 0.5 & -0.5):

- Cold Temperatures: 20° > Temp. < 24.5°
- Hot Temperatures: 23.5° > Temp. < 27°

Previous temperatures were obtained by applying PMV interval (-0.5 > PMV < 0.5) on the acceptable ranges of operative temperature graph in Figure 3.

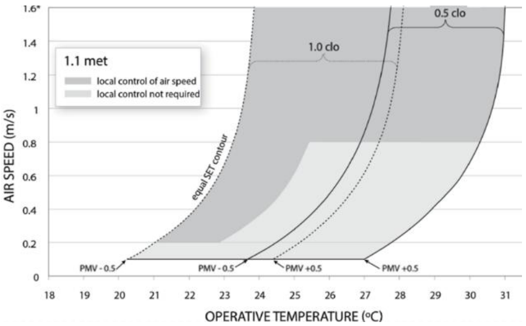


Fig. 3. Thermal comfort constraints

As previously stated, several studies and researches have been conducted to evaluate energy usage, thermal comfort, or both in existing residential buildings in Cairo. The majority of these researches concentrated on the building envelope and intended to improve indoor comfort levels and building energy efficiency in residential buildings. it was done by studying the effectiveness of retrofitting with renewable energy as an energy production source without solving the main issue causing the low thermal comfort and sequentially the high energy consumption. On the other hand, no clear guideline is offered that recommends viable passive retrofitting procedures for an existing building that would allow solving early design defects that cause the high energy consumption (such as poor building insulation).

3. Research Problem

The researches reviewed above reveal a significant gap in the integration of thermal comfort, energy performance, and existing buildings. this lack of integration resulted in the existing residential buildings that were built without taking into consideration the building thermal performance and external conditions that affects indoor environment quality. This negatively affected occupant’s thermal comfort which led users to seek solutions that would enhance thermal comfort, such as air conditioners, which created an excessive domestic electricity usage.

4. Research Objective

As a result, the purpose of this study is to evaluate the present status of interior thermal comfort in existing residential structures. Furthermore, it attempted to determine the feasibility of using current passive retrofitting scenarios specified by the Egyptian Energy code (EREC) to improve interior thermal comfort in existing residential buildings.

5. Research Methodology

The anticipated methodology follows building performance simulation to apply the following research methodology:

- Experimental approach: Dynamic thermal simulations were conducted on a typical residential building in Egypt using DesignBuilder. Firstly, it is used to evaluate the building's thermal comfort state. This shows building thermal performance underlying problems and its consequences of high electricity consumption. Secondly, it is used to investigate passive retrofitting as a tool to increase comfort levels and decrease cooling loads with consequent energy reductions in the residential sector. The simulation starts by gathering design data and materials and thermal properties of the existing building. Then simulation is done on periods where cooling is required and periods where heating is required to obtain PMV values throughout the year. The results are analyzed through thermal comfort PMV values stated by HBRC and current electricity consumption. The result of this method is to determine the building efficiency, in its current state, in reducing used energy to reach thermal comfort levels. In addition to evaluating thermal performance enhancements feasibility by using retrofitting solutions stated by EREC. Modeling and simulations were carried out using DesignBuilder (DB) in its sixth version (V.6.1.0.006), To assure the most reliable data and accuracy, a validated software (DB) has been used (11).

6. Case Study

The evaluation is done on existing residential buildings in Cairo to analyze the reasons for the building's low thermal performance. The detailed step-by-step simulation is performed as follows:

6.1. *Reference Building Selection*

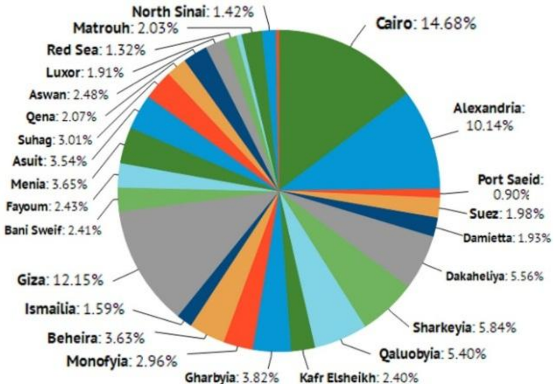


Fig 4. Total Regular Buildings for Housing Purposes - Urban

Egypt has 4,075,400 residential buildings. 14.68% of the total exists in Cairo which means 598,311 buildings. These numbers place Cairo at the top of the table as the city with the highest number of residential buildings as shown in Figure 4.

According to the census, apartments throughout Cairo can be classified into 4 classes based on apartment area (12):

Table 1. Cairo apartments classification (12)

Category	A	B	C	D
Area	> 130 m2	110 m2 > B < 130 m2	90 m^2 > C < 110 m^2	60 m^2 > D < 90 m^2
Percentage	7%	47%	23%	13%

Based on this classification, the majority of air-conditioned residential apartments are in class B. Therefore, the case study aimed to screen and select neighborhoods that fall in class B (12). According to this, the selected neighborhood was Mohandessin.

6.2. *Model definition*

The case study building is a 6-story residential building with two apartments per floor each with an approximate area of 122 m^2 and the total surface area of the building is 275 m^2. The building has one staircase acting as the core vertical circulation. Each apartment has a perimeter of 60.35m and a ceiling internal height of 2.8 m. It is rectangular and consists of three bedrooms, a living room, bathroom and Kitchen.

The number of occupants is an average of 5 persons. The typical floor plan and 3d model for the prototype are as seen in figure 6. The building is located in an average residential community in the Al-Mohandessin area with orientation North. A typical common building typology was identified among Class B, referred to as Typologies 1. for the case study's sake, the typical building identified in Al Mohandessin District was used for simulation due to being used as a typical cluster that is repeated throughout the district.

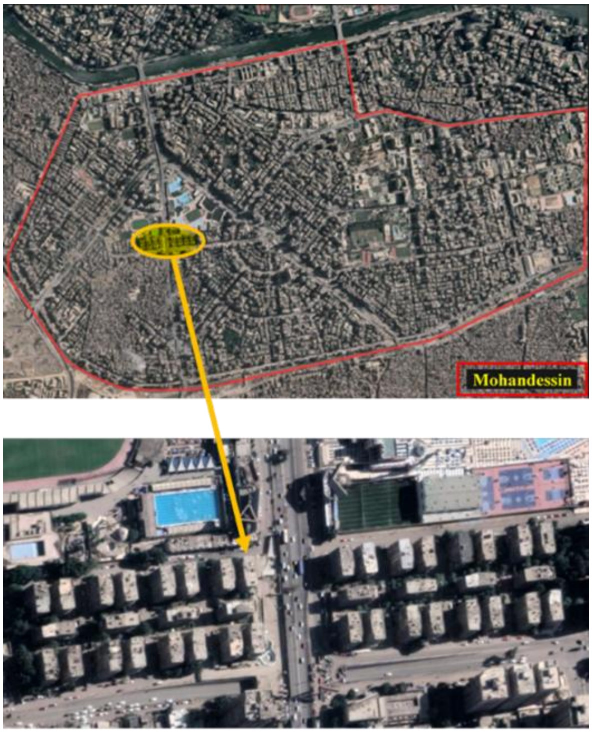


Fig 5. Typology 1 sample in Al Mohanseen District

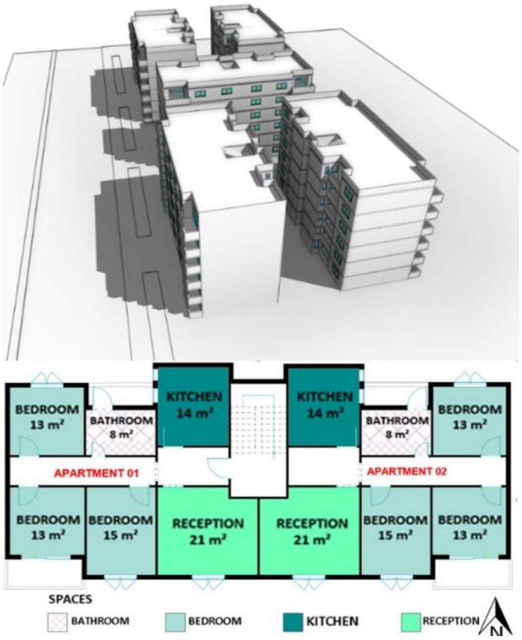


Fig. 6. Typology 1 Building Cluster and apartments
a. Cluster Layout, b. Floor Plan

6.3. Building materials specifications

The specifications for wall and floor constructions used throughout the building are presented in Table 2.

Table 2. Construction material thermal Specifications (13)

No	Location	Thickness	U-Value	R-Value
A	Internal Wall	125mm	1.9	0.4
B	External Wall	250mm	2.5	0.5
C	Floor Slab	200mm	1.58	0.63
D	Roof Slab	270mm	1.39	.72

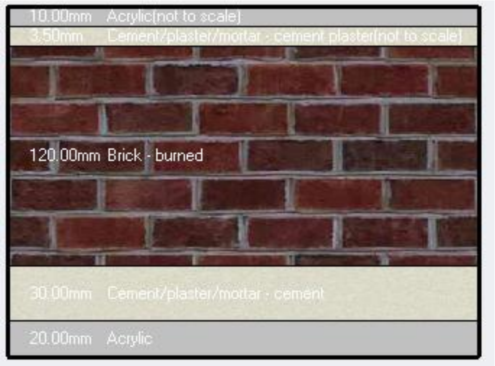
The thermal properties for the construction materials were obtained from EREC (13), and the Egyptian Specifications for Thermal Insulation Work Items. The used glass is single-glazed with a u-value of 5.76. The construction materials are shown in Figure 7.

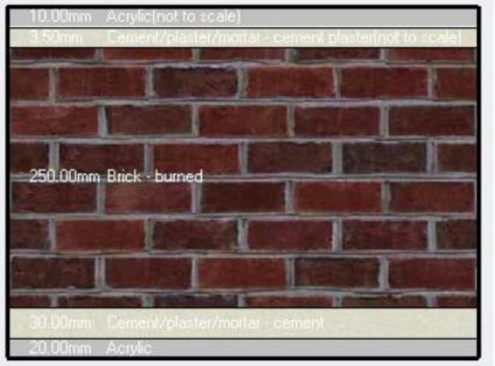
7. Base Case Thermal Comfort Performance

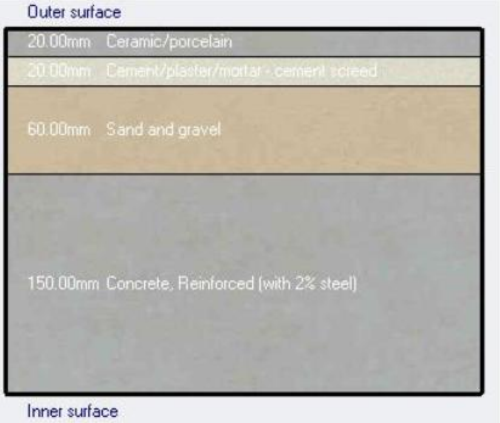
Thermal Performance is simulated by calculating PMV throughout periods where the occupant experience discomfort throughout the year. This helps to determine discomfort nature, whether heat or cold stress. This discomfort occurs when the temperature in the apartment's rooms will exceed a certain temperature limit stated according to thermal comfort boundaries stated by the PET index as shown in table 3.

Table 3. Thermal Perceptions

PMV	PET [°C]	Thermal perception	Grade of physiological stress
< -3.5	< 4	Very cold	Extreme cold stress
-3.5 - -2.5	4 - 8	Cold	Strong cold stress
-2.5 - -1.5	8 - 13	Cool	Moderate cold stress
-1.5 - -0.5	13 - 18	Slightly cool	Slight cold stress
-0.5 – 0.5	18 - 23	Comfortable	No thermal stress
0.5 – 1.5	23 - 29	Slightly warm	Slight heat stress
1.5 – 2.5	29 - 35	Warm	Moderate heat stress
2.5 – 3.5	35 - 41	Hot	Strong heat stress
> 3.5	> 41	Very hot	Extreme heat stress







Outer surface
20.00mm Ceramic/porcelain
20.00mm Cement/plaster/mortar - cement screed
60.00mm Sand and gravel
150.00mm Concrete, Reinforced (with 2% steel)
Inner surface

Fig. 7. Construction Material presentation in DesignBuilder

The level of thermal comfort and the temperature limits are calculated using the PMV (predicted mean vote). After simulating over a year, the results are shown in Figure 8 below. And the following remarks are noted:

7.1. *May to October*

Ranges of air temperatures in hot weather are around 27 - 35°C which resulted in six months where the comfort zone is not reached, during May, June, July, August, September, and October as seen in figure 8. Depending on PMV index for these months obtained through DesignBuilder simulation of the current case study, results showed 1.59 (Moderate heat stress), 3.02 (Strong heat stress), 3.58 (Extreme heat stress), 3.89 (Extreme heat stress), 2.86 (strong heat stress) and 2.14 (Moderate heat stress) respectively which exceeds thermal comfort range of -0.5 > PMV < 0.5 (No thermal stress). as they indicate high temperatures (heat stress) as indicated in thermal perception shown in table 3.

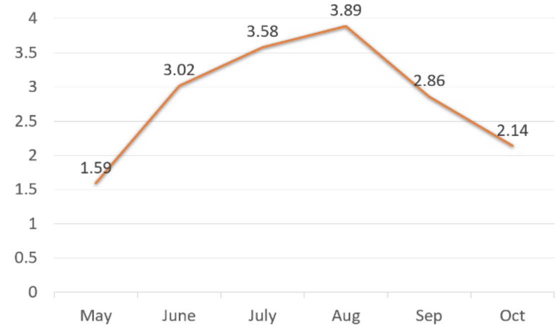


Fig. 8. Base Case Thermal comfort simulation throughout months of high PMV (Warm to Hot sensation)

According to the PMV index and the corresponding thermal sensation, starting from May, Residents will thermally perceive indoor conditions as "Slightly Hot".

This feeling will be worsened throughout the following three months to be "Warm" during June and reaches its peak during July and August to be "Hot". During September and October thermal perception slightly decline to get back to being perceived as "Warm".

The thermal comfort results throughout the summer months have a direct impact on electricity consumption. Figure 8 shows the period of low thermal comfort from May to October. Such low PMV values force the user's high dependence on conventional cooling systems to reach thermal comfort acceptable ranges. This can be seen in figure 9 where electricity consumption for cooling purposes during the summer months is plotted. August has the highest consumption of 1260 kWh to compensate for the low PMV value of 3.89.

By analyzing the case study simulation data of and through visual investigation, it was found that the building's energy performance can be categorized as poor due to the following:

- The building is only insulated by the traditional thermal insulation on the roof of the top floor.
- Not considering building orientation at early design stages resulted in adding thermal gains on external envelopes that wasn't treated to prevent such gains.
- There is no shading over the windows to prevent direct sunlight from entering the interior space.
- The windows are single glazed which increases the amount of heat energy transferred from the outside to the inside significantly.

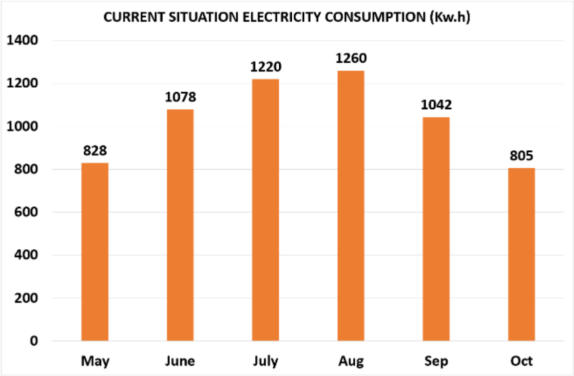


Fig. 9. Electricity consumption of conventional cooling systems

8. Retrofitting

An efficient envelope retrofit for cooling load dominant climates requires a reduction of solar gains through the envelope. walls are the most important component of the buildings' envelopes that are exposed to direct solar gain. The main concept for wall retrofitting is about increasing the thermal resistance (R-value) of the external walls. however, the current wall construction has a low R-Value of 0.4 W/m^2.k.

According to EREC (13), the recommended external walls R-values in north Cairo to provide a well-insulated indoor environment are shown in Table 4.

Table 4. EREC recommended Thermal Resistance values (9)

Orientation	North	South	West	East
R-Value	0.7 - 0.82	0.89 - 1.18	1.0 - 1.5	
U-Value	1.4-1.2	1.12 – 0.8	1.0 – 0.67	

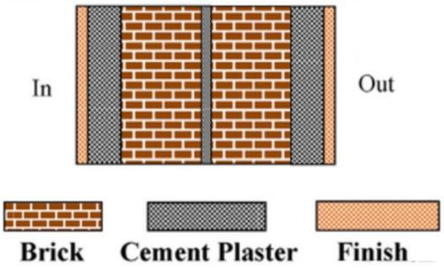
This can be verified by investigating the impact of these values on indoor thermal comfort. The EECRB identified techniques to help reach the previously mentioned values, these techniques are as follows, Figure 10 (13);

1. Using light sand brick as a part of double walls.
2. Adding extruded polystyrene (XPS), expanded polystyrene (EPS), fiberglass roll, rock wool, or polyurethane.
3. Creating a cavity wall with an air gap (a cavity between two walls of 10 cm).

Simulation results are compared to the thermal comfort values during the summer months of the base case, which has shown the lowest comfort levels (heat gain; worst case scenario).

After simulation, the enhancement of thermal comfort levels from the wall retrofitting process reached almost 50 %. Such improvements succussed in placing May in the comfort zone. June, September, and October PMV values indicate the possibility for improvements to achieve comfort zone values since they are close to reaching them. This was achieved by applying an insulating material with thermal resistances (R-value) = 1 to 1.5 as stated in EREC (13). The following are the materials' thicknesses with the same thermal resistance that also achieved similar results: expanded polystyrene 4 cm, polyurethane 5 cm, and light sand brick 12 cm. Furthermore, if any of these materials with the specified thickness are used in the wall retrofitting process, energy modelling results guarantee an improvement.

a. Double Wall



b. Insulation Material C. Air gap: a cavity between two walls

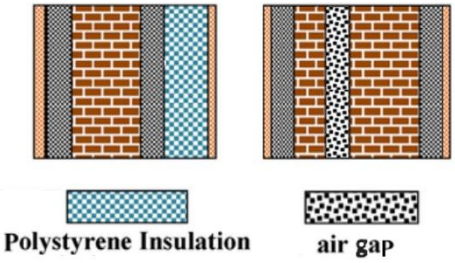


Fig. 10. Wall retrofitting techniques.

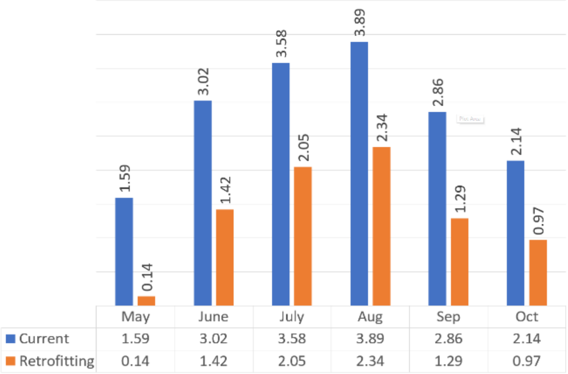


Fig. 11. Wall retrofitting Simulation PMV results in comparison to the current state

These improvements can also be witnessed in the suppression of electricity consumption titled for cooling as shown in figure 12. Electricity used by conventional cooling systems was lowered by 20 – 40%, where May has the peak savings and August has the least savings.

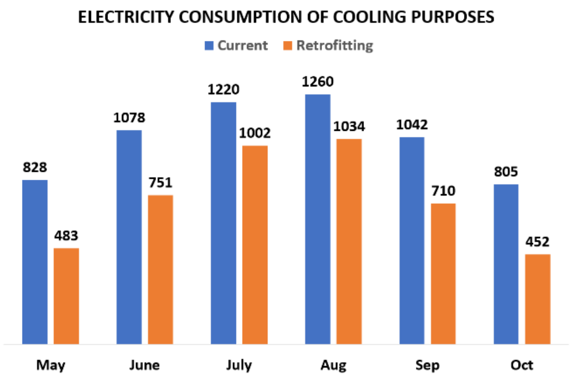


Fig. 12. Electricity consumption of cooling purposes, Current scenario vs Retrofitting.

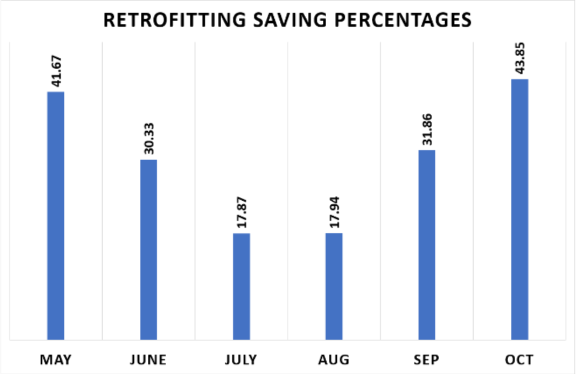


Fig. 13. Electricity consumption saving percentages due to retrofitting actions.

9. Discussion

The base case results elaborated the reason for high electricity consumption during the summer months. As it can be seen that the existing residential building performs poorly in protecting occupants from external weather conditions.

This is ought to the built envelope lacking the means of well-insulated construction materials. The used materials for external walls have low R-Value (high U-Value) that which lower performance to maintain its main function of acting as a shield for the indoor environment. In return, this resulted in high cooling loads to reach thermal comfort as compensation for the high negative impact outdoor temperatures have on the indoor environment.

Despite the wall retrofitting effect on the building's thermal performance, the improvement achieved managed to partially solve the issue of low thermal comfort. As it can be seen that months of high values (June, July, August, September, and October) were improved and got closer to the acceptable ranges of comfort by almost 50%. This calls for EREC to provide a framework that is specified for existing buildings to facilitate the implementation of environmental solutions in existing buildings. As well as, this will immensely relieve the high pressure on the electricity national grid. Such benefits can mainly be gained by focusing on the existing buildings since they are the problem and the solution at the same time.

10. Conclusion

Existing residential structures in Egypt have inadequate insulation levels, which raises the amount of energy required to achieve thermal comfort within the building. By examining current residential building thermal efficiency throughout the year, this study identified the root cause of the problem. Summer months in Cairo are essential for thermal comfort, according to simulation. During the summer, the building's poor thermal performance manifested itself in the form of high monthly power consumption due to high cooling loads to provide thermal comfort, which was compensated for by the use of traditional cooling systems. This research also looked at envelope retrofitting as an option, using thermal insulation levels recommended by EREC.

Wall thermal performance retrofitting improvements resulted in up to a 50% increase in comfort hours. It also saved a 17 to 30% of the overall energy use.

11. Recommendation

Building performance results can be improved even more by upgrading the energy code with up-to-date materials which has low thicknesses and higher efficiency and can fulfil the requisite U-Values in efficient manners. This will result in improved building energy performance, increased energy savings, and improved indoor thermal comfort.

References

[1] Egyptian Electricity Holding Company, “Annual Report 2019/2020. Arab: Republic of Egypt”, Cairo: Ministry of Electricity and Energy, 2020.
[2] Central Agency for Public Mobilization, “The residential growth in Egypt”, Retrieved from http://www.capmas.gov.eg/Pages/populationClock.aspx, 2021.
[3] Aldali K., Moustafa W., “an attempt to achieve efficient energy design for High-Income Houses in Egypt”,

International Journal of Sustainable Built Environment, Vol. 5, No. 2, PP. 334-344, 2016.

[4] Fadel M., Scoccia R., Filippini G., and Motta M., "Cooling Energy Use Reduction in Residential Buildings in Egypt Accounting for Global Warming Effects", Climate 9, Vol. 9, No. 3, PP.45, 2021.

[5] Bellia L., Alfano F.R., Giordano J., Ianniello E., Riccio G., “Energy requalification of a historical building: A case study”, Energy Build, Vol. 95, PP. 184-189, 2015.

[6] Köppen W.P., Geiger R., Klimatologie H., “Gebrüder Borntraeger”, Berlin, Germany, 1930.

[7] Ibrahim H., Khan A., Mahar W., Attia S., and Serag Y., "Assessment of Passive Retrofitting Scenarios in Heritage Residential Buildings in Hot, Dry Climates" *Energies* 14, Vol. 14, No. 11, P. 3359, 2021.

[8] Nafeaa S., Mohamed A., Fatouha M., “Assessment of energy-saving in residential buildings using energy efficiency measures under Cairo climatic conditions”, Engineering Research Journal, Vol. 166, No., PP. 320-349, 2020.

[9] Adly B., El-Khouly T., “Combining retrofitting techniques, renewable energy resources, and regulations for residential buildings to achieve energy efficiency in gated communities”, Ain Shams Engineering Journal, Vol. 13, No.6, PP. 101772, 2022.

[10] Ashrae, “ASHRAE Standard 55”, American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2017.

[11] DesignBuilder, “DesignBuilder Simulation + CFD Training Guide 2008-2011”. Design-Builder Manual, 2011.

[12] CAPMAS, “The final results of the population and housing census 2017”, Cairo: Central Agency for Public Mobilization and Statistics, 2017.

[13] Housing and Building National Research Center, “Egyptian Code for Improving the Efficiency of Energy Use in buildings. Part 1: Residential Buildings (306/1)”, 2006.

[14] Hegazy I. & Qurnfulah E., “Thermal comfort of urban spaces using simulation tools exploring street orientation influence of on the outdoor thermal comfort: a case study of Jeddah, Saudi Arabia”, International Journal of Low-Carbon Technologies, Vol. 15, No.4, PP. 594–606, 2020.