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Raising The Efficiency of The Middle-Income Residential Building Envelopes for Energy Reduction and Thermal Performance Improvement – Case Study

Nourhan M. Shawki[1], and Hala F. Saad[1]

1 Department of Architecture, Faculty of Engineering, October 6 University, 6th of October City, 12585, Giza, Egypt.

* Corresponding author's email nourhan.mohamed.eng@o6u.edu.eg

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Abstract – The research problem has emerged in the weak efficiency of the external envelopes in existing buildings, affecting the rate of energy consumption, as it has become involved in the largest proportion of the total energy consumption. The research aims to present a method for classifying techniques for increasing the efficiency of the building envelope, based on two aspects: energy conservation and renewable energy production, especially for middle-income residential buildings, and to clarify their impact in reducing the rate of energy consumption. The study conducted theoretical studies to clarify the problems of energy consumption in existing buildings, the importance of the envelope's contribution to saving it, and knowledge of the most important technologies that increase the efficiency of the envelope. Then, presented a case study for one of the existing middle-income residential buildings in Egypt and simulated it using Design Builder to determine the energy-saving rates. The research has reached a set of results that confirm the extent to which saving energy consumption in existing buildings is linked to raising the efficiency of their envelope through a set of technologies that can be integrated with the envelope to conserve energy and produce renewable energy.

Keywords: Existing Residential Buildings, Design Builder simulation, Conserve Energy, Cooling loads, Thermal Performance.

I. INTRODUCTION

Existing buildings account for 41.7% of total electrical energy consumption and contribute significantly to carbon emissions. In addition to the existing residential buildings representing the largest percentage of existing buildings compared to new buildings. The existing residential buildings alone constitute 34% of the total electrical energy consumption in residential buildings [1]. It is a tangible reality that requires more attention, study, and unconventional solutions.

Accordingly, it has opened areas for research into finding strategies to reduce energy consumption in existing buildings to get out of this crisis. The building is considered a system that includes several elements and integrated systems, each of which affects the other, and one of the most important of these elements is the building's envelope. The importance of the building envelope is that it is the first line of defense to protect the building from surrounding conditions. It controls heat exchange processes, the amount of heat received by the envelope, and the amount of energy needed to operate the building. Most of the existing buildings in the world, including Egypt, suffer from poor design and performance of the building's envelope, and some of them lack environmental treatments. As a result, such buildings require continuous, high-cost mechanical cooling systems in order to ensure a comfortable environment for the occupants of the space. Thus, focusing on treating existing building envelopes and working to raise their efficiency is one of the main solutions affecting energy consumption rates and confronting environmental changes.

The basic goal of the research can be derived in improving the current condition of the existing building envelopes, taking into account not disturbing the structure of the buildings. Therefore, the research proposes a classifying technology that helps raise the efficiency of the envelope between techniques that conserve energy and technologies that include energy production. Treating the existing buildings by integrating Some of the techniques that help raise the efficiency of the envelope are a low-cost method and a good solution to increase the energy efficiency of middle-income existing buildings and maximize the benefit from ventilation and natural lighting, while trying to integrate renewable energy generation technologies into the envelope to serve the goals of reducing and rationalizing energy consumption rates. Demolition and rebuilding are the solution. It is neither economically feasible nor environmentally friendly.

II. Literature Review

A. Factors affecting the energy performance of existing residential buildings

Some of the factors affecting energy consumption are fixed and cannot be changed except for the building envelope. Increasing the building envelope's efficiency improves the quality of the internal environment and provides comfort. This makes it one of the main solutions affecting energy consumption and confronting environmental changes [2]. *Fig. 1* shows the factors that affect the energy performance of existing residential buildings.

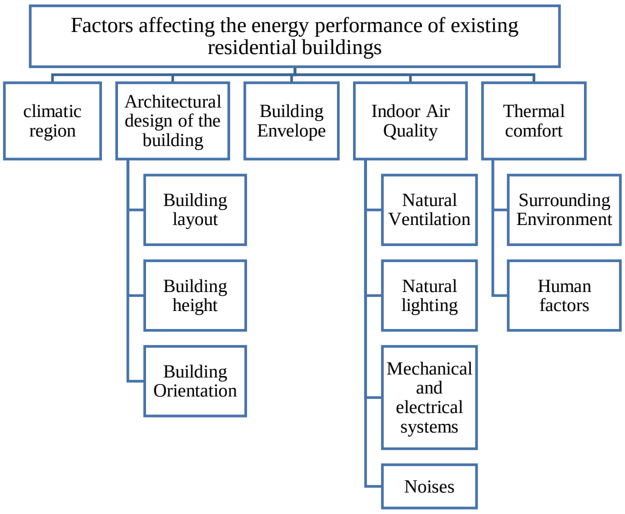

Fig. 1: Factors affecting the energy performance of existing residential buildings
Source: Krestein Nashat, 2018

The building envelope plays a major role in determining the amount of energy consumed. According to a report by (the United States Department of Energy), the building envelope affects 4 out of 11 end-use categories of energy, responsible for more than 57% of the building's thermal loads [3] as shown in *Fig 2*.

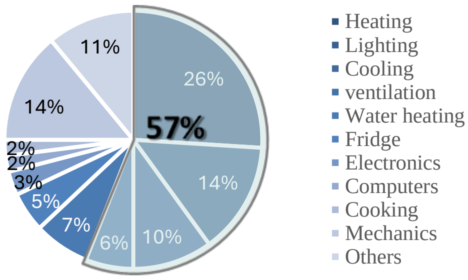

Fig. 2: Categories of energy affected by the performance behavior of the building envelope
Source: M. Patterson, et. al., 2014

B. Problems affecting the existing building envelopes

Existing buildings suffer from a variety of problems. Most existing buildings do not consider environmental standards. This is due to the poor design of the envelope that is not appropriate for climate considerations, and the lack of some treatments that increase the efficiency of its performance, thus affecting energy consumption, increasing emissions, indoor air quality, and its negative impact on the health of residents because of poor natural ventilation [4].

Existing buildings in Egypt are characterized by poor insulation, which leads to very poor thermal performance and low indoor air quality. The building's energy performance is poor, because the building is only insulated with traditional thermal insulation on the roof of the upper floor, and there is no shading above the windows to prevent sunlight. However, the single-glazed windows and most of their orientations are not suitable, in addition to being not tightly sealed, which caused air leakage from them, and thus the amount of thermal energy transferred from the outside to the inside is large [5]. Most of the problems found in existing building envelopes that affect their efficiency, thermal comfort for occupants, and energy consumption can be summarized in *Fig 3*.

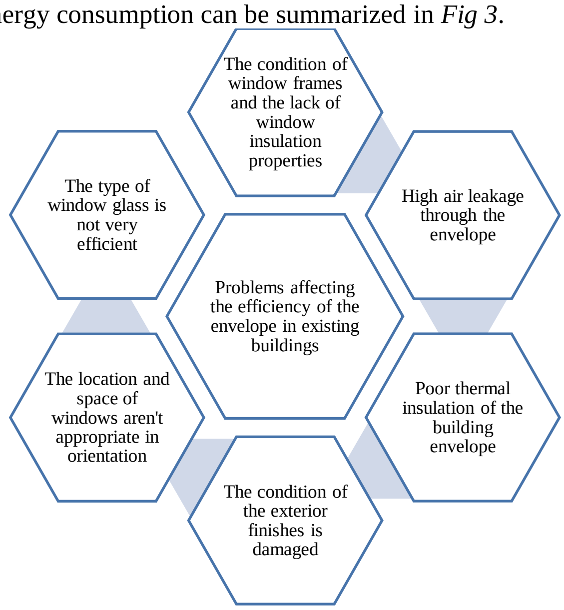

Fig. 3: Problems affecting the existing building envelopes
Source: M. Mahdy, et. al., 2017

C. Increasing the efficiency of the building envelope

A large percentage of the energy consumed is wasted, and much of the energy used in heating and cooling for a building is typically lost through the envelope due to low efficiency envelopes. It is estimated that about 8% of the energy used in buildings is wasted from the external walls, 6% from the ceilings, and 20% from the openings by increasing the thermal load of the building and thus increasing air conditioning loads. About 25% to 35% of the energy used in air conditioning is being wasted due to inefficient windows, this is equivalent to 6% of the total energy consumption. About 25% of the heat gained leaks through cracks and openings, 25% through glass, and 50%

through walls and ceilings. Simulation on many building types has shown that reducing air leakage can save 5–40% of heating and cooling energy [6].

Raising the efficiency of the building envelope is defined as intervening in the elements of the building envelope by adding or replacing modern materials, systems, or technologies to the existing building envelope. The efficiency of the building envelope is also increased by improving the physical, optical, and thermal properties of the envelope elements. The process of raising the efficiency of the building envelope is preceded by the process of examining it in terms of the problems present in it that cause a lack of thermal comfort internally and high energy consumption [7].

D. Classifying the envelope raising efficiency techniques

In existing buildings, the techniques options for increasing the efficiency are limited according to 1) the condition of the building, 2) the percentage of energy savings required the possibly of energy-saving from a technical, economic and environmental standpoint, 3) the limitation to improve the quality of the indoor environment without the need to make radical changes to the building according to a specific budget and material cost of the project [8].

The concept of classifying the technologies that help raise the efficiency of the existing residential building envelope is based on two main aspects. First is saving and preserving energy, and second is generating renewable energy as shown in *Fig 4*. Both aspects are important, which will be reflected in reducing the building's energy use with the integration of renewable energy systems into the existing envelope. But they are overlooked due to the reliance on traditional building technology and the ambiguity of renewable energy systems [9].

1. Technologies that conserve energy

It aims to improve the internal thermal behavior of the building and reduce energy consumption, and relies on:

- Increase the thermal resistance of the fabric by using insulation materials.
- Improved sealing to reduce air leakage.
- Effective control of heat transfer.
- Retrofitting windows with applying necessary shading devices.
- Determine the ratio of openings to the walls and their locations to control air flow and natural lighting.

2. Technologies involve energy production

They are technologies that combine the production of renewable energy and the provision of thermal insulation for the building envelope by creating shaded places. Among the most popular energy-producing systems in residential buildings are integrated solar systems, including photovoltaic panels and solar water heaters, and they can be integrated with the building through the roofs, external walls, and shading means.

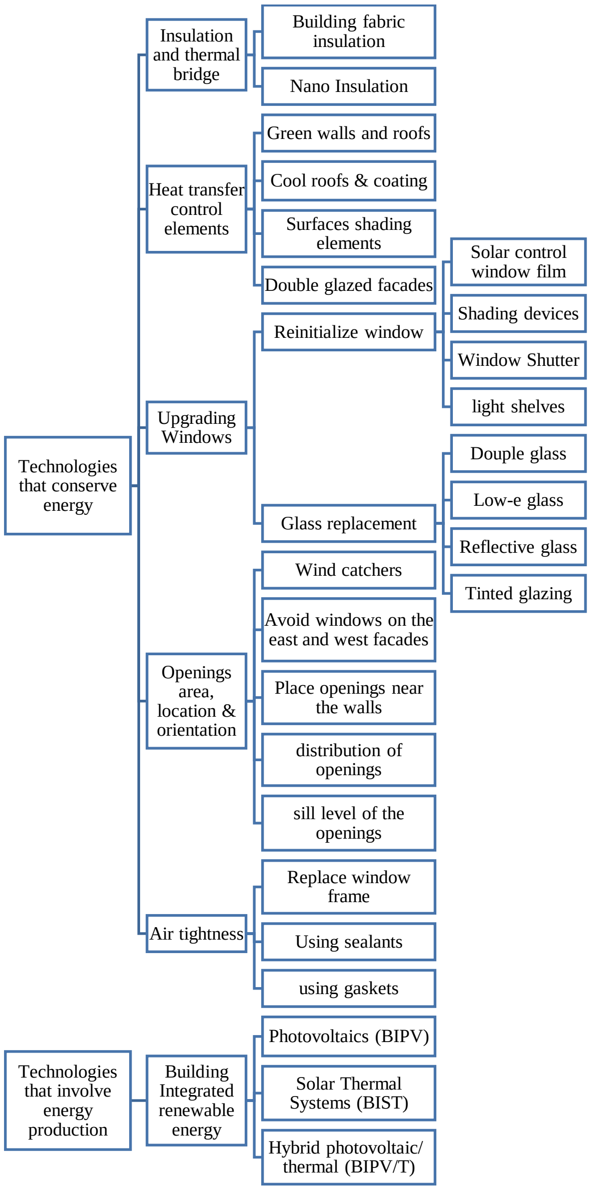

Fig. 4: Classifying the technologies that raise the efficiency of the middle-income residential building's envelope Source: Author

III. CASE STUDY

Implementing the theoretical study on an existing project provides the opportunity to study the evolution from being analytical research to a practical experiment, as the applied study revolves around proposing the application of bio-reaction technology to existing university buildings and testing it to determine the rate of saving energy consumption, reducing carbon emissions, and improving its performance during operations. Then simulate the energy performance using Design Builder energy simulation software for the existing building sample and compare it to the modified case to show the amount of energy saved.

E. Methodology

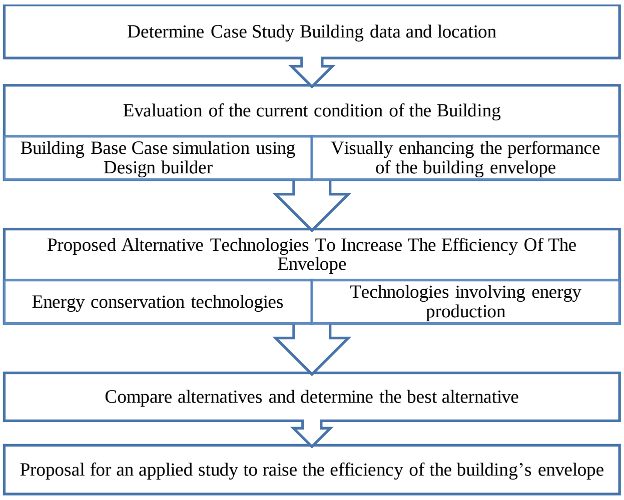

Fig.5: Applied study methodology
Source: Author

F. Case Study Building data and location

The building is located in 6th of October City, Egypt. The southern façade is the main facade of the building and overlooks a street with a width of 30 meters. The building consists of 4 main residential floors and the ground floor is a Carparking. Each floor contains two apartments, and the area of each apartment is 170 m^2 and with height 3m. The simulation was conducted on the 4th Floor. *Fig 6* and *Fig 7* show the case study building data and location

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Fig.6: The general location of the building Source: Author

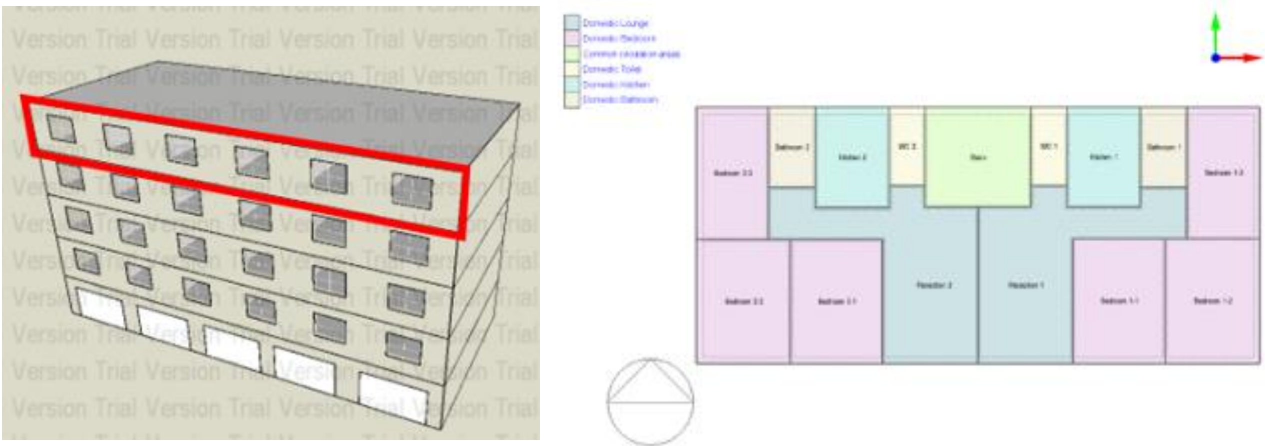


Fig.7: The main facade of the building and the Floor plan Source: Author

G. Enhancing the performance of the building envelope

The building's performance is evaluated by conducting a field visit to the site to monitor the building's operations, verify the final energy consumption, review the electricity bills, take pictures of the building, and conduct interviews with the building's occupants. *Table I* shows the visual enhancing of the building's current condition.

TABLE I: Visual enhancing the building's current condition Source: Author

Building performance	The current situation
Building materials	Traditional building materials of brick and reinforced concrete
Air leakage	High air leakage due to the presence of openings around windows, air conditioner outlets, and connection outlets, and some cracks in the external walls.
External windows	The window frames are wooden, most of them damaged Poor thermal resistance of the glass used in windows due to the use of single transparent glass.
Reflectivity of external walls	Light-colored exterior paints, but low due to dust
Thermal insulation	No insulation is installed on the outside or inside of the casing
Shading means	shutters as an external shading method in windows
Natural lighting and ventilation	Increasing the intensity of illumination affects the visual comfort of the occupants of the space. This is because of the size of the window and the type of glass on the amount of heat and light passing through, which leads to closing most of the windows, affecting the rate of natural ventilation.

H. Base Case Simulation Using Design Builder

In order to correctly simulate the existing condition of the building, all data related to the building must be entered, including specifying the location, building materials, proportions of wall openings, type and lighting, ventilation and air conditioning systems, specifying the building's operating schedules, the rate of air leakage, defining the activities of the building's occupants, and the density of occupancy used. *Table II* describes the external envelope, and the data that were considered to simulate the base case of the building.

TABLE II: Description of the external envelope, and the data that were taken into account to simulate the base case of the building Source: Author

Data	Description
Wall U-Value	2.1 W/m2-K
Roof U-Value	2.3 W/m2-K
Glass type	Transparent single, 3 mm thick
Glass Heat transfer coefficient	5.89
Glass (SHGC)	0.86
Glass Light emission	0.9
Frame type	Painted wood frame with shutters
Opening Ratio	16% for the openings of the southern facade
Air leakage	0.7 ac/h at 24/7
Natural ventilation	The minimum ventilation rate per person is 3 l/s per person in the southern rooms 10 l/s per person in the northern rooms 12 l/s per person in the kitchens & bathrooms Permissible temperature under natural ventilation = 24
Air conditioning	Split air conditioning system
lighting (lux)	Bedrooms = 100, Salon = 200, Bathrooms = 100, Kitchens = 150

The base case simulation shows that the total energy annual consumption is 29974 kwh, the cooling represents the largest percentage of annual electricity consumption by 15119 kwh, the CO_2 Production throughout the year is 18164 kg of carbon, the highest radiant Temp. is 32°C and the solar gain exterior windows is 18387.10 kwh. From *Fig 8* to *Fig 12* shows the charts of the base case Design Builder simulation's results.

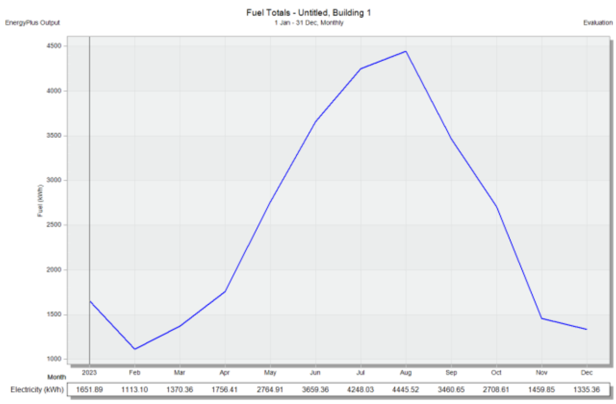
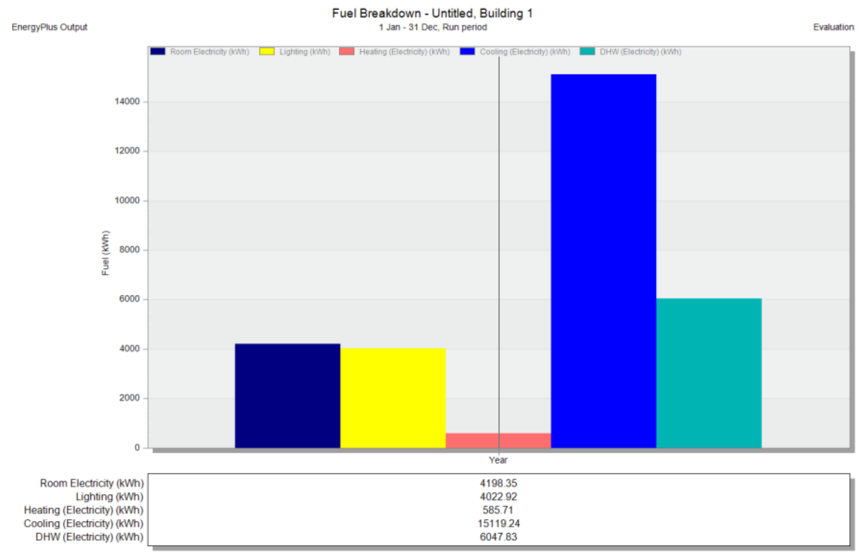
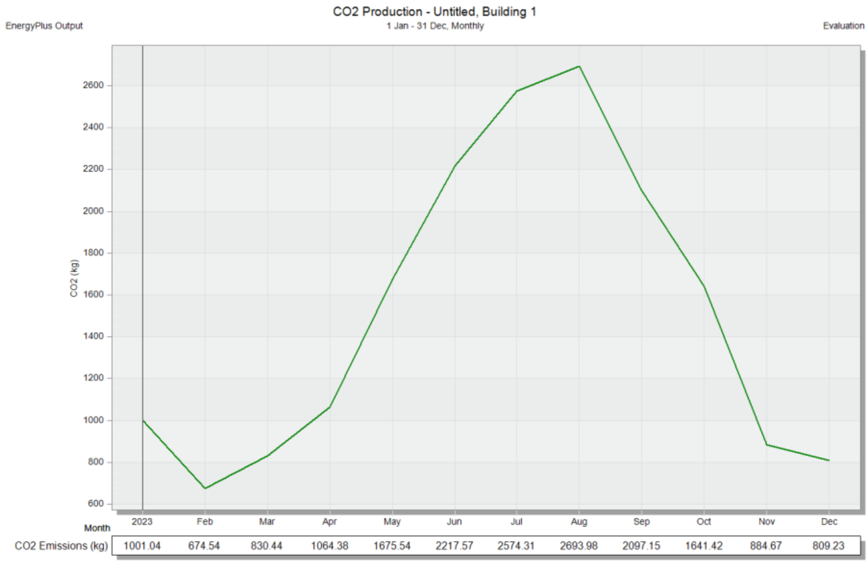


Fig.8: base case Total energy consumption through the year Source: Author



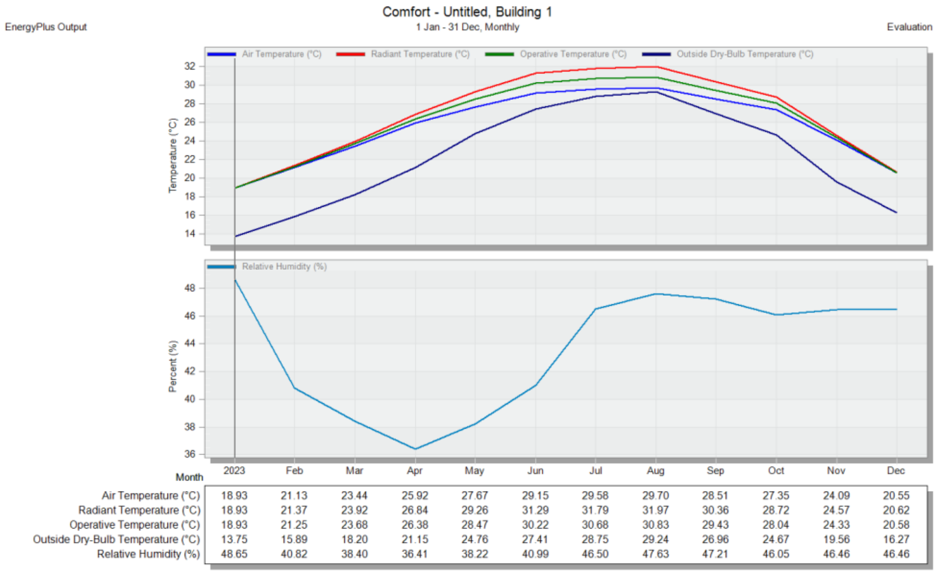
	Year
Room Electricity (kWh)	4198.35
Lighting (kWh)	4022.92
Heating (Electricity) (kWh)	585.71
Cooling (Electricity) (kWh)	15119.24
DHW (Electricity) (kWh)	6047.83

Fig.9: Base Case Electrical Usage throughout the year Source: Author



Month	2023	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
CO2 Emissions (kg)	1001.04	674.54	830.44	1064.38	1675.54	2217.57	2574.31	2693.98	2097.15	1641.42	884.67	809.23

Fig.10: Base Case CO2 Production throughout the year Source: Author



Month	2023	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Air Temperature (°C)	18.93	21.13	23.44	25.92	27.67	29.15	29.58	29.70	28.51	27.35	24.09	20.55
Radiant Temperature (°C)	18.93	21.37	23.92	26.84	29.26	31.29	31.79	31.97	30.36	28.72	24.57	20.62
Operative Temperature (°C)	18.93	21.25	23.68	26.38	28.47	30.22	30.68	30.83	29.43	28.04	24.33	20.58
Outside Dry-Bulb Temperature (°C)	13.75	15.89	18.20	21.15	24.76	27.41	28.75	29.24	26.96	24.67	19.56	16.27
Relative Humidity (%)	48.65	40.82	38.40	36.41	38.22	40.99	46.50	47.63	47.21	46.05	46.46	46.46

Fig.11: Base Case Temperature and Humidity Source: Author

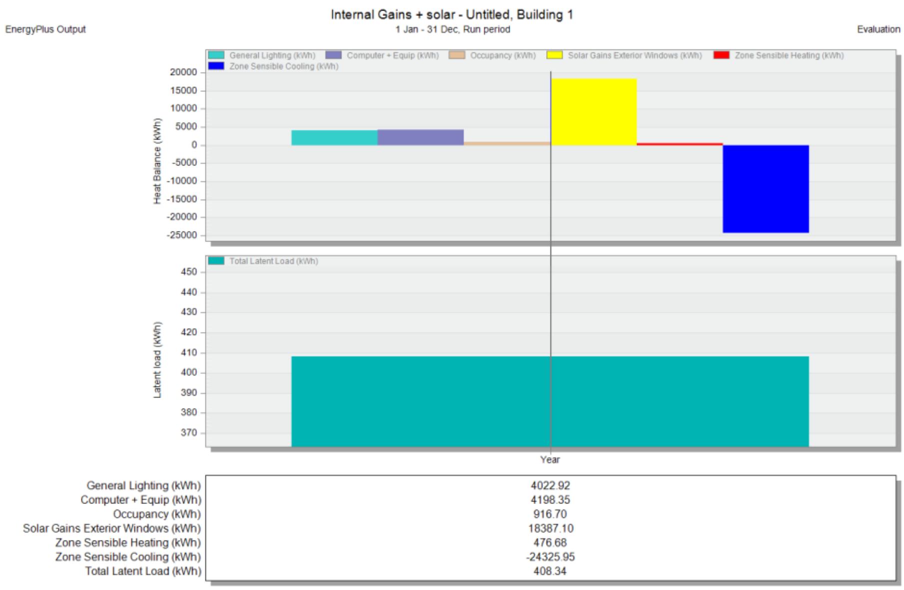


Fig.12: Base Case Internal Gains + Solar Source: Author

I. Proposed Alternatives

After reviewing the analytical results of the current situation, it was found that there was an increase in internal temperatures, which affects the thermal comfort of the occupants of the space and increases cooling loads. By studying the conditions of the building and the structural requirements of the study site to identify the permissible limits for intervention in terms of modification or addition, the following is revealed:

- The need to preserve the architectural composition of the building.
- It is not allowed to change the internal space areas by creating a double facade or making concrete protrusions in any direction from the envelopes.
- It is shown that it is possible to change the window glass and seal the windows to prevent air leakage.
- It is Possible to add shading elements to the openings.

The proposed alternative methods include technologies that conserve energy and technologies that include energy production. They are compared with each other, then the performance of each alternative is evaluated, and the energy-efficient alternative methods are selected, thus determining the most effective method of modifying the envelope in terms of energy efficiency for buildings. To determine the methods, a study was conducted of the construction market in Egypt to determine the best available technologies for walls, roofs and windows that can be applied for medium-income residential buildings in Egypt with medium, distinctive and social standards.

1. Technologies that conserve energy

Green roof, Extruded polystyrene (XPS) and cool roof with XPS are compared with each other to rooftop efficiency raising. The results of simulating energy consumption and annual cooling loads for alternatives techniques in *Fig 13* shows that the best alternative for cooling loads and energy consumption is to combine thermal insulation XPS with thickness 8 cm in an inverted roof style, with a layer of cold roof to reflect radiation and heat.

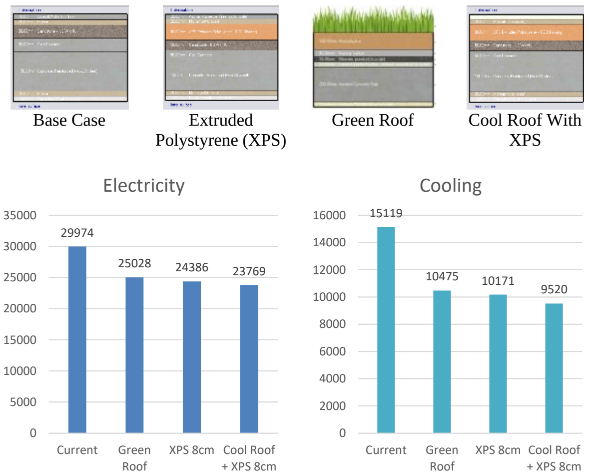


Fig.13: Results of simulating energy consumption and annual cooling loads for alternatives to rooftop efficiency raising techniques Source: Author

Expanded-polystyrene (EPS) with thicknesses 2cm and 5cm and light-colored finish are compared with each other to walls efficiency raising. Combining the addition of thermal insulation with light-colored finishes helps reduce the building's energy consumption and cooling loads. Large-thick insulation reduces thermal transfer and thus contributes to higher internal temperatures. *Fig14* shows the results of simulating energy consumption, annual cooling loads for the alternatives techniques.

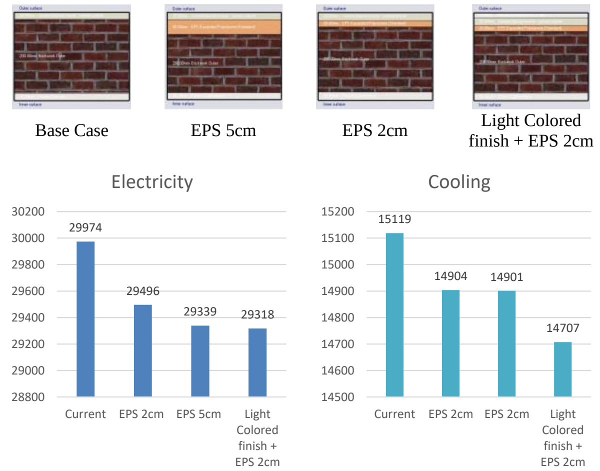


Fig.14: Results of simulating energy consumption and annual cooling loads for alternatives to wall efficiency raising techniques Source: Author

Single Low-E, double glass, single reflective glass and louver shadings are compared with each other to windows efficiency raising. The results of simulating energy consumption, annual cooling loads and solar heat gain for alternatives techniques in *Fig 15* and *Fig 16* shows that the single reflective glazing is the least heat-gaining type of glass and the least energy-consuming and cooling-load type, which contributes to lowering internal temperatures.

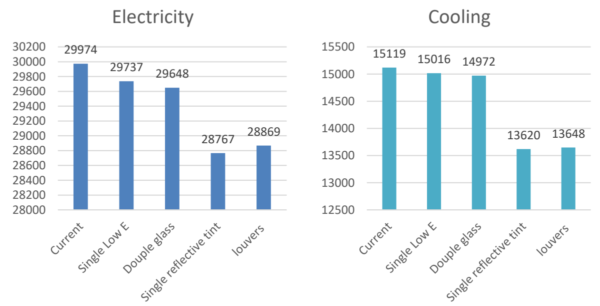


Fig.15: Simulation results of heat gain, energy consumption, and annual cooling loads for the proposed glass alternatives Source: Author

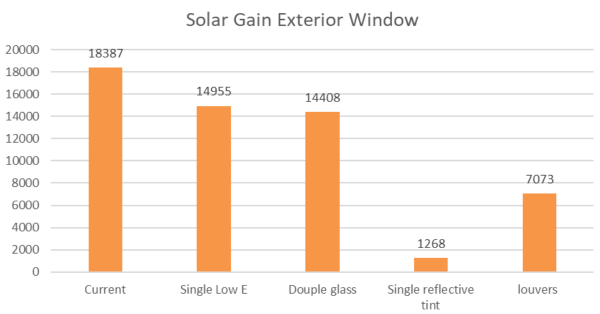


Fig.16: Simulation results of Solar heat gain, for the proposed glass alternatives Source: Author

For Air leakage, filling the openings around the air conditioner outlets, sealing the joints around the window frames with silicone glue or adhesive rubber, and replacing the damaged frames with others more efficient and sealed to prevent thermal leakage.

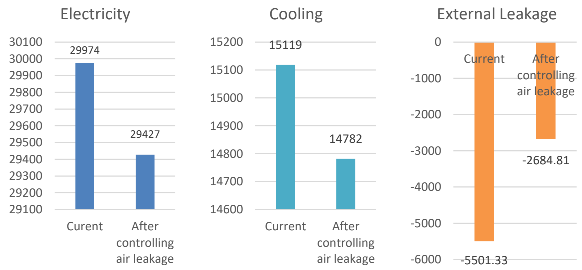


Fig.17: simulation results of energy consumption, annual cooling loads, and air leakage before and after treating air leakage Source: Author

2. Technologies involve energy production

The scope of the study will cover one type of renewable energy, which is photovoltaic panels, because they are the easiest type to use in medium-income residential buildings and implemented by individuals without the need for giant government projects. It will also provide external shading for roofs that helps control heat transfer. The panels will be installed at an angle of inclination of 30° towards the south and are of the polycrystalline type because they generate the greatest amount of energy in Egyptian conditions. The spacing between the panels has been calculated to avoid the panels overshadowing each other, and there will be 60cm between each row and the row before it.

II. RESULTS

The chosen alternative technologies for improving the efficiency of the envelope elements, including energy-conserving technologies and technologies that include energy production, were reviewed in *Fig 18*. *Table III* reviewed the simulation results for each of the best-chosen alternative techniques, including reduction ratios for cooling loads, energy consumption and CO_2 emission. The best proposed alternatives are combined to achieve the best energy consumption, provide thermal comfort, and improve the quality of the indoor environment.

TABLE III: Savings Ratios for Each Technique Source: Author

Proposed techniques to increase the efficiency of the building envelope	Savings ratios for each Technique		
	Energy consumption	Cooling loads	CO2 emission
Air leakage control	1.8%	2.3%	1.2%
Increase Roof efficiency (XPS insulation - cool roof)	20%	37%	19.4%
Increasing walls efficiency (EPS insulation - cool finish)	2.1%	1.8%	1.9%
Window (reflective single glazing + shading)	4%	12%	3.5%

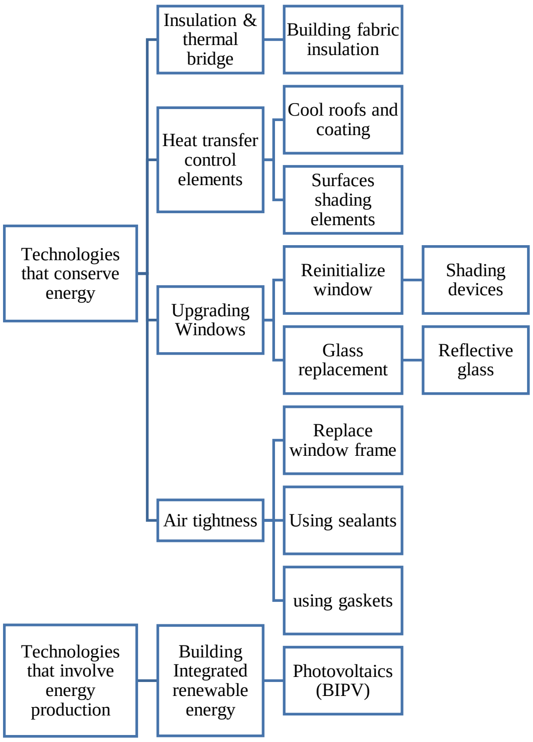


Fig.18: The Chosen technologies to increase the efficiency of the building envelope
Source: Author

The Design Builder simulation shows that the total energy annual consumption decreased by 33%, the cooling decreased by 62.7%, the CO_2 emissions decreased by 33%, the radiant temperature decreased by 3°C and the solar heat gain from the window decreased by 93.7%.

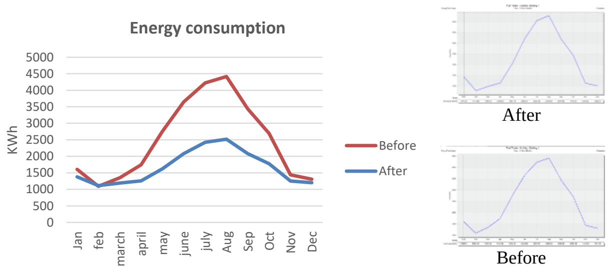


Fig.19: Total energy consumption through the year
Source: Author

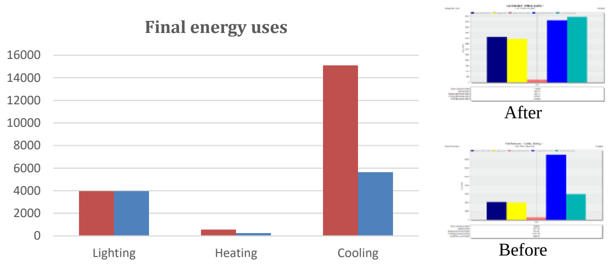


Fig.20: Annual Electrical Usage
Source: Author

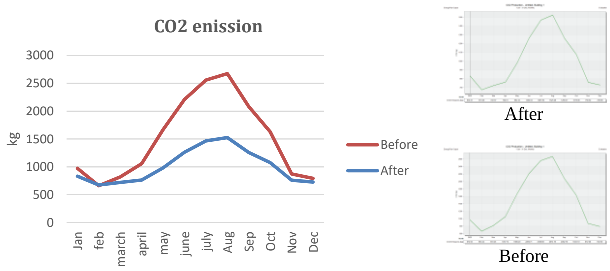


Fig.21: CO2 Production throughout the year
Source: Author

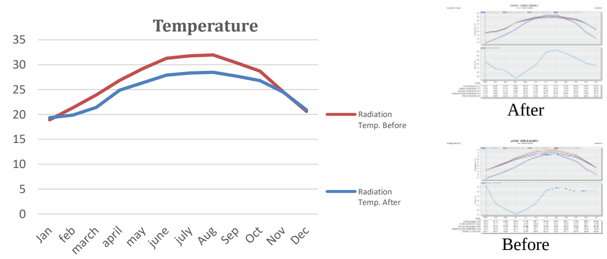


Fig.22: Radiant Temperature through the year
Source: Author

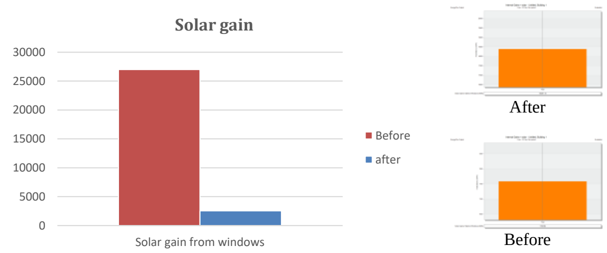


Fig.23: Annual Solar Gain
Source: Author

To calculate the photovoltaic system, the amount of electricity related only to lighting and electrical appliances resulting from the simulation of energy-conserving technologies will be used, which was estimated at approximately 8092.19 kilowatt-hours. Assuming that there are 300 sunny days per year and an average of 6 hours of sunlight per day, this means that the building will need at least 8092.19/6 x 300 = 4 kilowatts every hour. Regarding the number of photovoltaic panels, each power station with a capacity of 1 kilowatt has 4 panels and an area of 10 m^2, and by making calculations, you will need 40 m^2 of surface area with 16 photovoltaic panels.

Based on the combination of energy conservation technologies and technologies that include energy production, these technologies will provide the building with about 60% of the energy consumed in the building, bringing the total consumption of the building to 11803 kilowatt hours / year.

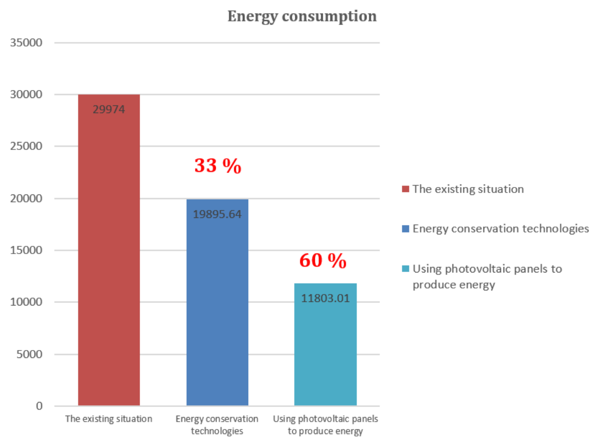


Fig.24: Energy consumption simulation results for using PV panels
Source: Author

CONCLUSIONS

Improving the efficiency of building envelopes is essential for modernizing existing structures to reduce energy consumption. Enhancing envelope efficiency achieves several goals, including energy savings, improved energy efficiency, reduced carbon emissions, lower operating costs, better indoor environmental quality, and extended building lifespan. These improvements benefit tenants, owners, and investors by providing financial savings and a healthier living environment., In Egypt, knowledge of environmental treatments and techniques to improve building envelope efficiency exists but is not widely known or commercially accessible. The research categorizes these techniques into two types: energy-conserving methods and energy-producing technologies integrated into the envelope. This classification serves as a reference for reducing energy consumption and carbon emissions.

The study also presents methodologies to optimize building envelope performance for better environmental efficiency in residential buildings. A case study demonstrated that combining optimal technologies available in the market significantly reduces cooling loads and energy use. The findings highlight that integrating energy-conserving techniques and energy production technologies into existing residential building envelopes can achieve energy savings of up to 60%.

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