

Techno-economic Assessment of Sustainable Energy Saving Measures in Multi-residential Building in Middle East Climate

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Abstract- The goal of the current study is to evaluate potential energy efficiency measures in a multi residential building located in New Borg Al Arab city, Alexandria governorate, Egypt. The studied configuration contains 32 villas that are going to be constructed in the coming few years. Renewable-energy and Energy-efficiency Technology Screening (RETScreen) software is used to simulate multi residential buildings. The model identified several retrofits that can lower greenhouse gas (GHG) emissions and energy consumption as well as the cost analysis. These retrofits include the thickness of insulation of expanded polystyrene (EPS), the Window-to-wall (WWR) ratio, different glazing materials, different roof configuration, fuel used for heating, orientation of the building and the aspect ratio of the building. Switching from electricity to natural gas for water heating systems has a massive reduction potential of GHG emissions by approximately 19%, resulting in a saving of 189 tons of Carbon Dioxide (tCO₂) per year. Replacing the traditional glazing with ASHRAE 90.1 glass has reduced the energy consumption in cooling by about 46% when 30% WWR ratio is considered. It shows a reasonable payback period of about 0.77 years. It also reduced GHG emissions by about 20.5%. Results indicate that employing a 3-inch thickness of EPS to the building envelope leads to a reduction in cooling energy consumption in summer by 12.3%. The most significant GHG reduction that was obtained by the combination of all retrofits was 66% (654 tCO₂).

Keywords Energy saving, Greenhouse gas emissions, Retrofitting techniques, Building energy regulations, Financial cost.

1. Introduction

Energy saving techniques have become a crucial topic of study in the effort to mitigate Greenhouse gas (GHG) emissions. Energy saving can be applied to two main categories: existing and new buildings. In both categories different buildings parameters can be altered to reduce energy consumption and make the building more sustainable. This is going to depend also on the type of the building residential or commercial etc. [1]

The first category of retrofitting existing buildings has limited room for building parameters change. It won't enable the change of building orientation or the building skeleton. Possible changes include adding a layer of insulation, adding Photovoltaic (PV) panels on the roof or the window or changing the building management system to reach smart buildings and cities [2]. Colak et al. [3] explored the key obstacles and technological limitations that must be addressed to fully realize the potential of modernized power grids. Overcoming such limitations and addressing them will be promising for smart grid future. Moreover, Yesilbudak and

Colak [4] reviewed over hundred research papers spanning from 2006 to 2017. They reported various approaches to integrating renewable energy sources and innovative technologies to enhance grid performance.

On the other hand, the second category applied to new buildings can modify what can altered in existing buildings in addition to the ability to change the orientation and the building skeleton. The results of this study can improve the code of buildings in the country to decrease building energy consumption and its share in increasing global warming.

1.1. Existing Buildings Retrofits

Building envelope main portions are the walls and the roof. When the building footprint increases, heat transfer from the roof constitutes a major share in the building loads. Hamza et al. [5] have studied different office building designs. They included the addition of 70mm of concrete tiles and 40mm of polystyrene to the roof material. This modification has reduced the overall heat transfer coefficient to $0.57\text{W/m}^2\text{K}$ from a base case of $1.8\text{W/m}^2\text{K}$. This reduced the energy loss of the building from the roof by 68.3%. Bughio et al. [6] investigated the effect of adding different kinds of insulation to the roof, the most significant one that decreased the energy consumption by a considerable amount is the standard Expanded Polystyrene (EPS). The addition of 10cm of standard EPS to the roof has decreased the overall heat transfer coefficient from $2.5\text{W/m}^2\text{K}$ to $0.214\text{W/m}^2\text{K}$. This has reduced the energy consumption from 20975kWh to 19129kWh, which is a reduction of about 8.8%.

Building envelope main divisions include the building wall material. It was shown to have a substantial effect on energy consumption. Radwan. et al. [7] discussed the addition of RSI-1.9 batt insulation to the walls of a hospital located in Egypt which operates 24hours a day. This insulation has reduced the overall heat transfer coefficient from $1.941\text{W/m}^2\text{K}$ to $0.401\text{W/m}^2\text{K}$. This has resulted in a reduction of about 1.7% of the energy consumed per year in the hospital. As a result of the huge size of the hospital this 1.7% has saved the hospital 291920kWh per year. Danial et al. [8] studied the effect of adding a 12.25 inch of structural insulated panel (SIP) to the regular brick walls. This has resulted in the reduction of the energy use intensity (EUI) from 56.56kWh/m^2 to 51.99kWh/m^2 . This is a reduction of about 8.12%. Bughio et al. [6] investigated the effect of adding different kinds of insulation to the walls of an architectural campus building in Karachi, Pakistan. The most significant kinds of insulation that reduced energy consumption are the ones with loose-fill cellulose insulation and the one with EPS insulation. The addition of loose-fill cellulose insulation of 10cm thickness has reduced the overall heat transfer coefficient from $2.7\text{W/m}^2\text{K}$ to $0.344\text{W/m}^2\text{K}$. This has reduced energy consumption through the year by about 11% from 20975kWh to 18667kWh. The addition of 10cm of standard EPS has reduced the overall heat transfer coefficient to $0.32\text{W/m}^2\text{K}$. This has reduced energy consumption by about 13.5% from 20975kWh to 18130kWh. Teamah et al. [9] studied the effect of increasing the thermal resistance of the walls in cold climate. The study was done in Canada in a commercial

building. The increase in thermal resistance of the walls per unit area from about 0.9 to $3.9\text{m}^2\text{K/W}$ has reduced the energy consumption of the building from about 237MWh to about 215MWh. Elsafty et al. [10] investigated the effect of varying thickness of insulation in building walls. The study was done on two buildings located in Alexandria Egypt. The first case was a conference hall, and the second case was a shopping mall. The insulation material used in the study is Polyurethane which has a thermal conductivity of 0.024W/m K . The study reveals that a minimum total cost is obtained at a thickness of insulation of about 0.15m, and it has a reduction of about 10.7% in the cooling load in case of the conference hall. While in the case of the shopping mall the cooling load has decreased by about 24.3%.

Windows influence cooling loads to a great extent as it allows solar energy into the building. Radwan. et al. [7] suggested adding thermal breaks to the windows. In addition to that they replaced the 3mm clear glass with double 6mm low emissivity clear glass with an air gap of 6mm. This change has reduced the overall heat transfer coefficient from $6.975\text{W/m}^2\text{K}$ to $3.138\text{W/m}^2\text{K}$. This has saved around 6.37% of the total energy consumed which is about 1092510kWh per year. Garcia-Fernandez and Omar [11] added Kalwall which is a glass that fills spaces with natural, balanced daylight. This is done with the help of a large number of prismatic glass fibers which are embedded in their panel's translucent face sheets [12]. This type of glass doesn't need a continuous supply of electric current like electro-chromic glass. Danial et al. [8] studied the effect of replacing the glass windows from a single 3mm to triple low emissive glass. This has reduced the EUI from 56.59kWh/m^2 to 45.29kWh/m^2 which is a reduction of about 20%. Al Rashdi et al. [13] studied the effect of adding two types of solar film layer to the window. One of them is of Neutral 50 type with visible light transmission (VLT) of 52% and solar heat gain coefficient (SHGC) of 0.56. The other one is of ceramic which has a VLT of 28% and a SHGC of 0.44. This has resulted in reducing energy consumption by about 7.6% and a payback period of less than 2.5 years. Doukas and Bruce [14] investigated the addition of a secondary glazing window without affecting the exterior appearance of the building. This extra layer is installed in the interior side of glazing. The effect of this secondary glazing decreased the overall heat transfer coefficient from $5\text{W/m}^2\text{K}$ to only $2\text{W/m}^2\text{K}$. This has reduced the energy lost by the wall by over 50%. Azemati et al. [15] studied the effect of adding coating containing nano-composite particles using numerical simulation. They studied two different kinds of coated polyurethane. The first type contains nano Aluminum Oxide (Al_2O_3) and the second one contains nano Zirconium dioxide (ZrO_2) The results showed that the energy consumption has reduced by 4% in case of Al_2O_3 and 13% in case of ZrO_2 compared to the one coated with pure polyurethane and acrylic paints. Ruggiero et al. [16] investigated the effect of adding smart windows to buildings in order to reduce energy consumption. The study was done in four different cities (Athens, Benevento, Cairo and London). The smart glass used in this study is composed of a float uncoated glass of 4 mm thickness, an Argon gap of 16 mm thickness and a laminated glass with Electro-tropic technology with 9 mm thickness. The

overall thickness of the glass is 29 mm. The smart window has two states: the clear state which happens when a voltage is applied to the glass and a milky state which happens when no voltage is applied. The glass needs a 115volt in order to transform into the clear state and it will have a transmissivity of 0.725 in clear state instead of 0.607 in the milky state. The results revealed an energy saving of up to 17%.

Shades can reduce the cooling loads inside the building. This is due to the reduction in solar radiation that enters through glass. Alhuwayil et al. [17] studied the effect of adding different types of shading. They studied the addition of fins in the north facades with different projection factor in 8 different cities and found a reduction of about 4.13% in the energy consumption has been accomplished by using a fin with projection factor of 0.45 in Jeddah city. They also studied the addition of horizontal overhang shades in the same six cities. The results revealed that a reduction of 18.07% in energy consumption is achieved through placing horizontal overhangs with a projection factor of 1 and in Khamis Mushait city.

Lighting is one of the most important contributors to energy consumption. Bonnema et al. [18] has retrofitted a few things that allow daylight to enter and this reduced the lighting power density (LPD) by 37.5%. Radwan et al. [7] has applied the same technique to the hospital that they studied. This has reduced power consumption by 2.6%. This reduced the power consumption by 446021kWh each year. Garcia-Fernandez and Omar [11] studied the effect of replacing halogen and fluorescent and metal halide lamps with light-emitting diodes (LEDs) in Alexandria library. These LEDs not only have higher efficiency but also a longer lifetime. This effect has saved up to 89% of the energy consumed by the lighting sector which accounts for 58% of the total library energy consumption. Bosu et al. [19] replaced the incandescent bulbs with LED bulbs in a college residential building. In addition to that, they upgraded the security lights to one that has a motion sensor. Another minor modification they did is that they put signs to remind people to turn off the lights when they are out. Omar et al. [20] studied the effect of replacing fluorescent tube lamps of (25W and 40W) by LED lighting. This study was done on an educational building in Elshorouk city. This has resulted in a saving of about 1270\$ per month. This is about 68% saving. Kumar et al. [21] concluded that heavy dust over the surface of the old lamp can block around 50% of the light. This will lead to an increase in the wattage of the lighting needed to illuminate the place. In addition to that, the light will not be adequate to illuminate the place by the proper amount. Alajmi [22] investigated the effect of changing the lighting system in an educational building from T-8 lamps type to more efficient T-5 lamps type. This has reduced energy consumption by about 2.3%.

1.2. New Buildings Retrofits

On the other hand, numerous energies saving techniques were applied to new buildings. Emil and Diab [23] investigated the effect of adding 50mm roof insulation of 0.049W/mK thermal conductivity in addition to roof vegetation. This study was done in the mechanical engineering

building of Ain Shams University. This results in a roof of overall heat transfer coefficient of 0.424W/m²K instead of 1.743W/m²K. Zhang et al. [24] studied a building located in Dubai in the middle east. They studied the effect of changing the thermal resistance of the roof of the building from 1 to 7m²K/W and the study revealed that the annual load caused by the roof is reduced by 24.9%. Aboelata [25] investigated the effect of using green roof over building in Cairo. Two green roofs are proposed intensive and extensive ones. The study reveals that using a green roof reduced the outside average temperature that surrounds the building. And this resulted in reducing the cooling daily load by 3.2% in case of extensive green roof while a reduction of 4% in case of intensive green roof.

There is also high potential energy saving by changing wall materials in new buildings. Hamza et al. [5] discussed the change of building brick thickness from 12.5 to 25cm in addition to that they added a layer of 2cm of polystyrene. This has resulted in the change in the overall heat transfer coefficient to 0.7W/m²K instead of 1.44W/m²K. This has resulted in the reduction of the energy lost from the wall by 51.4%. Emil and Diab [23] investigated the effect of replacing the base walls of mechanical engineering building of Ain shams university which consists of 12.7mm Gypsum Board, 101.6mm heavyweight concrete and 9.5mm stucco with ASHRAE 90.1 wall [26]. AnteBoard, [27] investigated the effect of the addition of phase change material (PCM) to the walls of a building. The study was done on a building located in Aswan Egypt which can be considered as a hot and dry weather. This PCM will play a role of energy storage due to the large latent heat that it possesses which helps in reducing the range of temperature change through the day. The study was done to different types of PCMs including (RT-27, RT-31, RT-35HC, RT-42, RT-44HC and lauric acid) and for different thicknesses ranging from 1cm to 8 cm. The study reveals that the best type of PCM is RT-35HC. While the best location of the PCM is 1.5 cm from the inside and the outside of the wall. The average inner wall surface temperature has reduced from 31.1oC to 27.7 °C. This has reduced the overall energy gain during summer by about 66%.

Windows are also effective in reducing new buildings energy consumption. Hamza et al. [5] discussed the replacement of the old single glass window by a double glass one. The new glass has a SHGC of about 0.67. Another important aspect in choosing glass is VLT. This double glass chosen has a 76% VLT. They also added a semi-transparent mono-crystalline silicon PV. The PV had 0.36 SHGC and 40% VLT. This PV was able to generate about 115W/m². Radwan et al. [7] studied the effect of reducing the window-to-wall ratio (WWR) from 40% to 30%. They concluded that about 4.3% of the energy has been saved, which is about 737650kWh each year. They also studied the effects of decreasing glass in west and east directions by 20%. This has resulted in 11.6% energy savings. Adly and El-Khouly [28] studied the effect of changing the glass type from single glazing of 0.58 SHGC to a double glazing with air gap of 6mm and 0.27 SHGC. The result shows a decrease in the energy consumed from 15624.286kWh to 12926.05kWh per year. This reduction is about 21% of the original consumption.

Aldali and Moustafa [29] studied the effect of WWR in buildings. The study was done in Madenaty City in Egypt. The study revealed that the effect of reducing the WWR from 90% to 30% has reduced the cooling load by 4.28kW which is about 14.26% reduction from the initial case. On the other hand, the effect of WWR in this location had minimal effect below 30%.

Abdul Mujeebu et al. [30] studied the effect of using Nano-gel glazing. The study was done on an office building located in Dhahran city in Saudi Arabia. The base case used a double-glazing window, while the proposed case used Nano-gel glazing. It has an overall heat transfer coefficient of $0.45\text{W/m}^2\text{K}$ and a SHGC of 0.35 which is much less compared to the double glazing that has an overall heat transfer coefficient of $2.71\text{W/m}^2\text{K}$ and a SHGC of 0.75. The study reveals a reduction in energy consumption by about 16.13%.

Adly and El-Khouly [28] studied the effect of adding shading device to a building in El-Shorouk City. This has reduced the energy consumed by the building from 15624.286kWh to 12392.01kWh per year. This reduction is about 20% of the original energy consumed by the building. Cho et al. [31] investigated the effect of using shading devices in high-rise residential building Located in Korea. The study found that when using a horizontal shade that has an overhang depth of 600mm and placed in the south façade, the cooling load of the building has reduced by about 19.7%. On the other hand, when using a vertical shade of depth 600mm in the south façade, the cooling load of the building has reduced by about 17.3%.

Lighting system upgrade in new buildings is crucial. According to Dr. George B. Hanna [32] lighting consumes around 36% of the consumed electricity in commercial sector in Egypt. This makes it an important sector for study. Hamza et al. [5] has replaced the lighting fixtures with LED. According to Khan and Abas [33] LEDs can produce about 90lumens/W. This is about 5 times the capacity of the incandescent bulbs. Adly and El-Khouly [28] studied the effect of replacing incandescent 40W lamps and spotlight 60W lamps with LED lamps of 9 and 13W. This has decreased the internal loads of a residential building from 11606.85kWh per year to 10456.28kWh per year. This reduction is about 1% of the original energy consumed by the building.

Heating ventilation and air conditioning (HVAC) system is usually the highest energy consuming device in most of the buildings. As a result, it should be considered to lower this consumption. This is done through increasing its efficiency. Hamza et al. [5] used a mixed-mode HVAC system which allows both natural and mechanical ventilation. Which have a rule in achieving nearly zero energy building in some of the configurations they studied. Radwan et al. [7] investigated the change in the HVAC system from constant air volume flowrate (CAV) to demand control ventilation (DCV) and this has a huge saving of about 34.28% on the total energy consumed by the HVAC system. Ho et al. [34] increased the performance effectiveness of the HVAC system by placing the grilles which supplies air at the vertical center line. On the other hand, they found that the place of the air exhaust grilles is not very important.

Orientation can be studied before the building is built to reduce energy consumption. As the energy consumption will increase if the largest wall area of the building faces the direction which is subjected to the sun most of the time. Radwan et al. [7] has studied the effect of changing the orientation of the building. The result shows a difference between the worst case (East) and the best case (south) 280703kWh.

Adly and El-Khouly [28] studied the effect of changing the orientation of residential building. They concluded that the highest energy consumption is in the building which faces south. It consumes about 33980.136kWh per year. On the other hand, the lowest energy consumption is the building which faces north. It consumes about 32622.996kWh. About 4% of the energy has been saved because of changing the design orientation of the building.

Bellah et al. [35] showed that a novel hybrid Maximum Power Point Tracking (MPPT) strategy, combining Perturb and Observe, Incremental Conductance, and Artificial Neural Networks, significantly outperforms traditional methods. The hybrid approach enhances power extraction, adapts quickly to changing solar conditions, and improves power quality and tracking accuracy, demonstrating superior performance in real-time simulations. Al Abri et al. [36] introduced a global Maximum Power Point (GMPP) searching method based on the Bald Eagle Searching (BES) algorithm, significantly enhancing the efficiency of photovoltaic systems under partial shading conditions. The proposed method outperforms Cuckoo Search and Particle Swarm Optimization by reducing search time by over 36% and consistently locating the GMPP, making it both highly effective and easy to implement.

Periola and Davidson [37] proposed a bio-inspired orientation diversity approach for future solar-photovoltaic systems, demonstrating that using multiple mini-solar panels at varying altitudes and orientations significantly enhances power output and reduces tracker acquisition costs by an average of 35.6% and 65%, respectively. Oufettoul et al. [38] introduced a novel hybrid scanning technique combined with the Perturb and Observe algorithm to accurately track the global maximum power point in partially shaded photovoltaic systems. Extensive simulations and validation with an Arduino board demonstrate that this method significantly enhances power extraction accuracy and stability under varying shading conditions. Ishiyama et al. [39] demonstrated the feasibility of using thermoelectric power generation to recover low-temperature waste heat from sources like liquid nitrogen and liquefied natural gas. Experimental results showed that power output increases with temperature difference, validating that low-temperature waste heat can be effectively harnessed for power generation, similar to high-temperature sources.

The previous studies discussed in this section highlight the novelty of the current work. The majority of studies in Middle East climate were oriented towards single residential and commercial buildings. In addition, the superposition of numerous proposed retrofits was not reported before for the considered configuration. The current study outcome aims to

provide guidelines for new and existing multi residential buildings in Middle East climate.

2. Methodology

Renewable-energy and Energy-efficiency Technology Screening (RETScreen) is the modeling tool used in the current study. Modeling energy consumption with RETScreen experts has shown to be a reliable tool. Natural Resources Canada is the company that created the program. NASA has contributed weather data to RETScreen.

A thorough feasibility analysis for a new project or for retrofitting an existing one can be obtained from RETScreen. It models using the conventional five-stage analysis procedure. This covers facility location specifications, energy and benchmarking analyses, financial analyses, risk assessments, and potential reductions in GHG emissions. This thorough study aids in directing decision-makers as they move forward with various projects.

The benchmark analysis, feasibility, and performance assessment are the three primary phases that require the modeller's attentive contribution. A reference consumption for the location under consideration is established in the benchmark study. To help the modeler make sure that the consumption is within the range, the program includes a database that suggests the average consumption of nearby facilities.

The feasibility study comes after the benchmark analysis. It contains the energy system's specification that is being considered. Cost analysis can also be done, taking into account the initial cost as well as the costs associated with operation and maintenance. GHG reduction can be examined once energy has been measured. Furthermore, risk analysis can point out the key elements that guarantee the project under consideration is feasible.

The performance assessment is the final major phase. A method of examining feasibility conditions is performance assessment, which comes after the energy system description. It provides a worksheet for analysing and reporting important performance indicators that are required for making decisions. It has sophisticated regression analysis that can be used to forecast the facility under consideration's future energy performance.

The following are the major sub-goals of the current study:

- Investigating the financial viability of a project.
- Comparing the payback time.
- Investigating the reduction in GHG emissions.

The literature assessment that is being presented indicates that those subobjectives have not been taken into account in the Egyptian context. Providing readers with credible results is the primary objective of the suggested methodology. The following equations are used in the current model.

2.1. Financial Model Parameters

Project cash outflow: It considers the criteria connected to debits, the annual cost of fuel or energy, and the necessary operation and maintenance. It is provided by equation (1).

$$C_{out,n} = C_{fuel}(1+r_e)^n + C_{O\&M}(1+r_i)^n + D + C_{per}(1+r_i)^n \quad (1)$$

$C_{out,n}$ is the cash outflow in the year n , C_{fuel} is the yearly cost of fuel or electricity, r_e is escalation rate of energy cost, $C_{O\&M}$ yearly cost of operation and maintenance, r_i is the inflation rate. D is the annual debt payment and C_{per} is the periodic cost and credits.

Project cash inflow: It considers credits for renewable energy and the reduction of GHG emissions, as well as annual energy and capital savings. It is provided by equation (2).

$$C_{in,n} = C_{ener}(1+r_e)^n + C_{RE}(1+r_{RE})^n + C_{capa}(1+r_i)^n + C_{GHG}(1+r_{GHG})^n \quad (2)$$

$C_{in,n}$ is the cash inflow in the year n , C_{ener} is the cost of the annual energy savings, C_{RE} is the annual renewable energy production credit income, r_{RE} is the renewable energy credit escalation rate, C_{capa} is the annual capacity savings, C_{GHG} is the cost of GHG reduction and r_{GHG} is the GHG escalation rate.

After tax cash flow ($\widetilde{C}_n$): It is computed by deducting taxes from pre-tax cash flow in accordance with the various provinces' and territories' tax laws. It is provided by equation (3).

$$\widetilde{C}_n = C_n - T_n \quad (3)$$

C_n is the net cash flow, and T_n is the taxes per year.

The project's simple payback period is the amount of time it takes to turn a profit. It is provided by equation (4).

$$Simple\ Payback = \frac{C - IG}{(C_{ener} + C_{RE} + C_{capa} + C_{GHG}) - (C_{O\&M} + C_{fuel})} \quad (4)$$

Where C is the initial cost required and IG is the Incentives and Grants.

The project's investment return is computed using the internal rate of return (IRR). It is provided by equation (5).

$$0 = \sum_{n=0}^N \frac{C_n}{(1 + IRR)^n} \quad (5)$$

Net present value (NPV) is the value of all future cash flows reduced at the discount rate and expressed in current currency. It can be computed by equation (6):

$$NPV = \sum_{n=0}^N \frac{\widetilde{C}_n}{(1 + r)^n} \quad (6)$$

The model of the present includes 32 identical villas that is going to be built in Borg El Arab city. These buildings cover a total area of 4150 square meters, and each has three floors. They're all the same in layout and design.

The model is looking into ways to make them use less energy and be more eco-friendly. The aim of this work is to cut down on GHG emissions. Figure 1. shows the villas layout.

The differences between the base case design and the proposed case design are shown in Table 1. While The expenses linked to these retrofits are detailed in Table 2. And

the financial parameters related to these retrofits are displayed in Table 3.

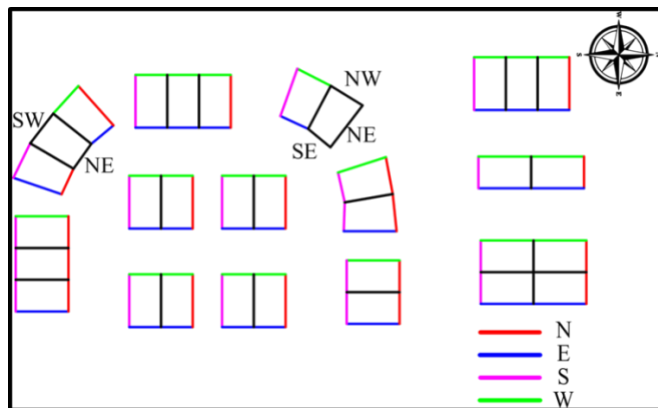


Figure 1. the 32 identical villas layout

Table 1. Differences between base case and proposed case

	Base Case	Proposed Case
Walls	Two cement plaster layers of 2cm thick. In addition to a red clay brick of 10cm width	-Base Case Wall + different thicknesses of insulating materials (EPS)
Roofs	Base Roof composed of: -9.5mm Roof Membrane -203.2mm Heavyweight Concrete -180mm Ceiling Space -12.7mm Gypsum Board	ASHRAE Roof composed of: -9.5mm Roof Membrane -170mm Roof Insulation -1.5mm Gypsum Board
Glazing	Single clear glazing	-ASHRAE 90.1 glazing -Double clear glazing -Triple clear glazing
WWR	30%	Ranges from 10% to 35%
Aspect ratio of the building	1.3	Ranges from 1 to 2.5
Lighting System	Incandescent	LED
Water heating system	Uses electricity	Uses natural gas
Orientation	North	East, South and West

Table 2. Cost of different retrofits

Retrofit	Price
EPS	160 \$/m ³ [40]
Incremental ASHRAE Roof	8.318 \$/m ² [23]
Single clear glazing	1.04 \$/m ² [23]
Double clear glazing	3.61 \$/m ² [23]
Triple clear glazing	8.28 \$/m ² [23]
ASHRAE 90.1 glazing	13.19 \$/m ² [23]
Incandescent lamps (60W)	2.7 \$/lamp [41]
LED (12W)	6.25 \$/lamp [41]

Natural gas	0.3 \$/m ³
Electricity	0.1 \$/kWh

Table 3. Financial parameters

Financial Parameters	Values
Fuel cost escalation rate	2%
Inflation rate	2%
Discount rate	9%
Reinvestment rate	9%
Project life	20 years
Debt ratio	70%
Debt term	15 years

3. Results and Discussions

3.1. Upgrading Water Heating System

When transitioning the water heating system from electric to natural gas, a notable annual fuel cost reduction of approximately \$43,400 was achieved. As illustrated in Figure 2. The implementation of this retrofit resulted in a decrease in GHG emissions by 189 metric tons of CO₂ per year, constituting a reduction of roughly 19%. The observed reduction in GHG emissions can be attributed to the enhanced efficiency inherent in the conversion of fossil fuels to electricity in power plants. This phenomenon underscores the significance of optimizing energy conversion processes to mitigate environmental impact.

3.2. Upgrading Lighting System

In the transition from incandescent lamps to LED within the lighting system, a reduction in annual electricity consumption by approximately 10.8% was realized, as depicted in Figure 3. This efficiency enhancement led to an annual fuel cost saving of approximately \$4009. Concurrently, an incremental initial cost of approximately \$2726 was incurred. The payback period for this retrofit is estimated to be approximately 0.68 years.

Figure 4. illustrates the resultant reduction in GHG emissions following the implementation of this retrofit. The adoption of LED lighting technology facilitated a noteworthy decrease in GHG emissions by 19.71 metric tons of CO₂ per year, representing a reduction of approximately 2%.

3.3. Upgrading Building Envelope

3.3.1. Upgrading Building Roof

In the substitution of the base roof with an ASHRAE roof system, as in Figure 5., a reduction in annual cooling load by approximately 4% was achieved. This efficiency improvement yielded an annual fuel cost saving of approximately \$8295. Concurrently, an incremental initial cost of approximately \$34522 was incurred. The payback

period for this retrofit is estimated to be approximately 4.16 years.

Figure 6. illustrates the resultant reduction in GHG emissions subsequent to the implementation of this retrofit. The adoption of the ASHRAE roof system facilitated a notable decrease in GHG emissions by 40.7 metric tons of CO₂ per year, representing a reduction of approximately 4%.

3.3.2. Upgrading Building Wall Material

The thickness of the wall thermal insulation was increased to mitigate heat loss from the structure. This, in turn, leads to a reduction in building energy usage. Figure 7. depicts the influence of thermal insulation thickness of EPS on cooling energy demand in kWh per year. The graph shows that as the thickness of the wall thermal insulation increases, the total consumption drops. It lowered the cooling load from 3627683kWh per year to 3180433kWh per year, a reduction of approximately 12.33%. Figure 8. additionally presents the annual energy cost savings associated with varying insulation thicknesses. The 3-inch insulation thickness demonstrates significant energy savings, amounting to approximately \$23,748 per year. This improvement, however, entails an incremental initial cost of \$73,441. The overall payback period for this investment is estimated to be 3.1 years.

Figure 9. illustrates the impact of altering insulation thickness on the reduction of GHG emissions. Increasing insulation thickness to 3 inches resulted in a decrease in GHG emissions from 991 to 874 metric tons of CO₂ per year, signifying a reduction of 116 metric tons of CO₂ per year (11.78% relative reduction).

3.3.3. Upgrading Building Glazing

In evaluating the impact of replacing the base single clear glazing with ASHRAE 90.1 glazing, double glazing, and triple glazing, notable reductions in annual cooling load were observed. The ASHRAE 90.1 glazing demonstrated the most significant reduction, with a decrease of approximately 46%, followed by a 22% reduction with triple glazing, and a 14% reduction with double glazing, as illustrated in Figure 10. This translated to considerable annual fuel cost savings of \$41,306, \$31,311, and \$21,234 for ASHRAE 90.1 glazing, triple glazing, and double glazing respectively.

However, the incremental initial costs varied, with ASHRAE 90.1 glazing incurring approximately \$31,816, triple glazing approximately \$18,952, and double glazing approximately \$6,721. Consequently, the payback period for each retrofit was calculated to be approximately 0.77 years, 0.605 years and 0.3166 years for ASHRAE 90.1 glazing, triple glazing, and double glazing respectively.

Furthermore, Figure 11. depicts the resultant reduction in GHG emissions following the implementation of these retrofits. The adoption of ASHRAE 90.1 glazing led to a significant decrease in GHG emissions by approximately 203.13 metric tons of CO₂ per year, representing a reduction of about 20%. Similarly, triple glazing contributed to a

reduction of about 154 metric tons of CO₂ per year (16% relative reduction). Additionally, double glazing resulted in a reduction of approximately 104.4 metric tons of CO₂ per year (11% relative reduction).

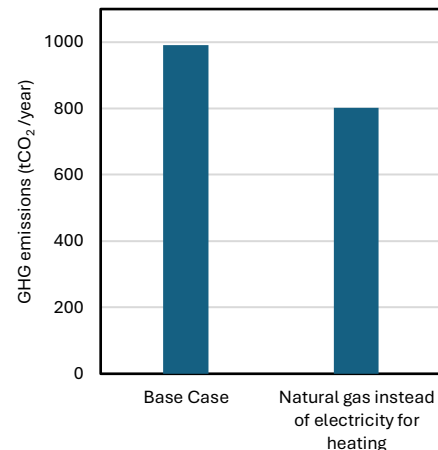


Figure 2. GHG emissions by using Natural gas instead of electricity.

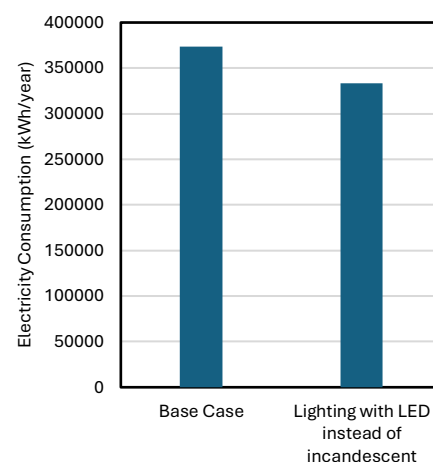


Figure 3. Electricity consumption in case of switching the lighting system to LED instead of incandescent.

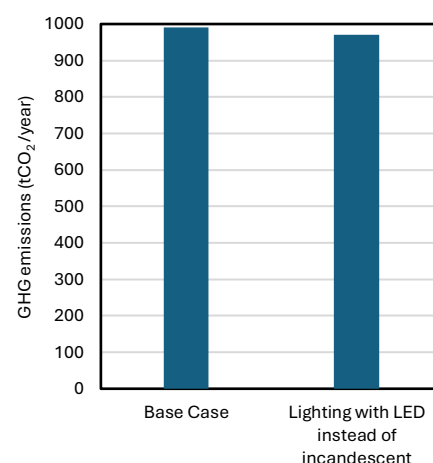


Figure 4. GHG emissions when using LED instead of incandescent lamps.

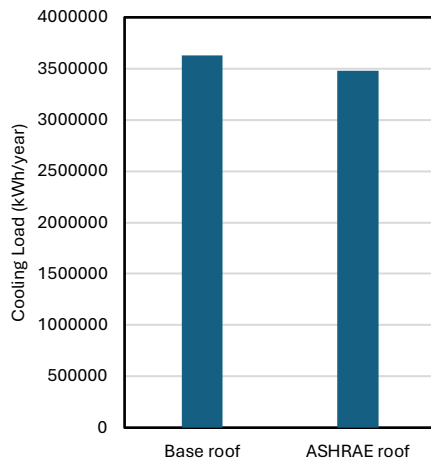


Figure 5. Cooling Load in case of Base roof and ASHRAE roof.

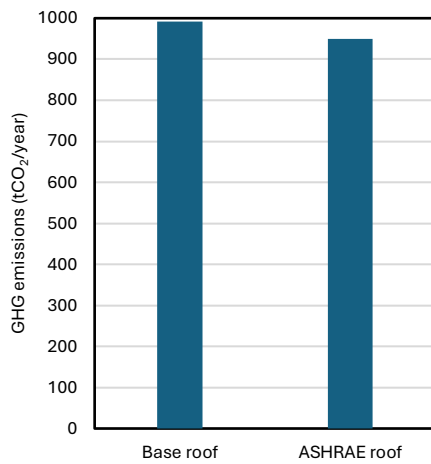


Figure 6. GHG emissions in case of Base roof and ASHRAE roof.

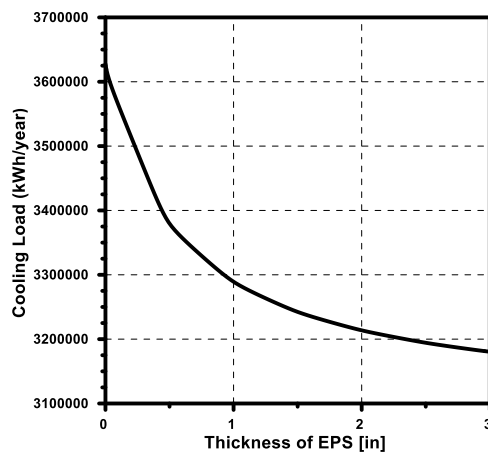


Figure 7. effect of changing the thickness of insulation of EPS on cooling load.

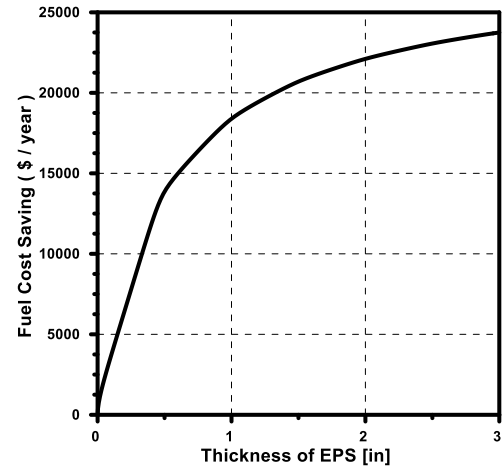


Figure 8. effect of changing the thickness of insulation of EPS on the fuel cost saving.

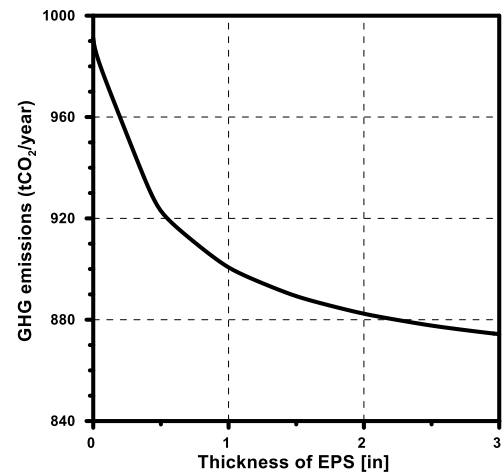


Figure 9. effect of changing the thickness of insulation of EPS on GHG emissions.

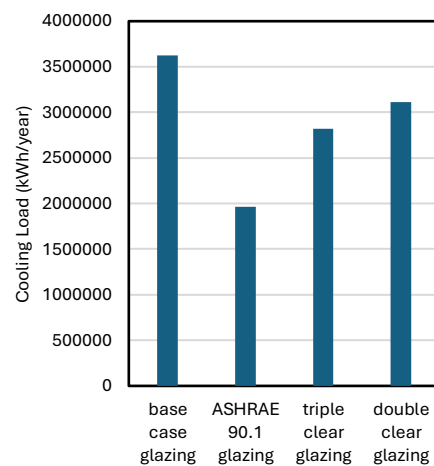


Figure 10. Cooling Load for different glazing types.

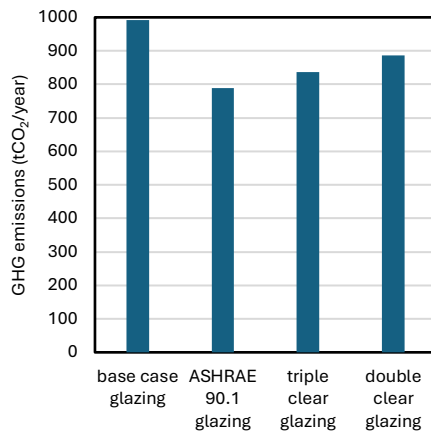


Figure 11. GHG emissions for different glazing types.

3.4. Effect of Changing WWR

The WWR plays a significant role in building's energy consumption. Figure 12. illustrates how adjusting this ratio impacts energy usage. Decreasing the WWR from a base case of 30% to a proposed case of 10%. This resulted in a notable reduction of 44.6% in cooling load.

Figure 13. provides insights into the effect of the WWR on yearly savings in fuel costs. Notably, reducing the WWR led to an annual saving of approximately \$43,700.

Figure 14. offers further clarity on the environmental implications of adjusting the WWR. Here, the influence of changing the ratio on GHG emissions is outlined. A reduction from 30% to 10% in the WWR corresponded to a significant decrease of about 21.7% in GHG emissions.

3.5. Changing Orientation of Buildings

Optimizing building orientation can lead to energy savings by altering the impact of sunlight on building load. Initially, the base orientation, denoted as North and illustrated in Figure 1., serves as the reference point. Evaluating four different orientations—North, East, South, and West—revealed that the West orientation yielded the most favorable outcomes. This orientation demonstrated a reduction in cooling load by approximately 2.62%, as indicated in Figure 15. This results in annual cost savings of approximately \$2723.

Moreover, this change in orientation had a positive environmental impact by reducing GHG emissions, as depicted in Figure 16. This adjustment led to a decrease of approximately 13.4 metric tons of CO₂ per year (1.35% relative reduction).

3.6. Effect of Changing Aspect Ratio of Buildings

The aspect ratio of a building significantly influences its energy consumption, primarily due to alterations in the exterior area exposed to sunlight. Figure 17. shows the effect of adjusting the aspect ratio on the cooling load. It reveals that the optimal aspect ratio for the building is 2, resulting in a 2%

reduction in cooling load compared to the base case of 1.3 aspect ratio.

In Figure 18., the effect of the aspect ratio on yearly fuel cost savings is plotted. As seen from the numbers, reducing the aspect ratio translates to an annual saving of approximately \$2,361.

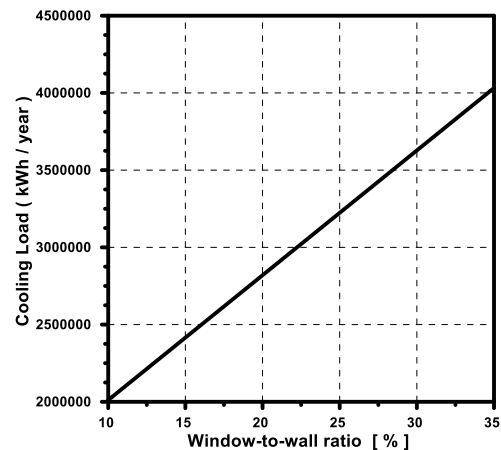


Figure 12. Effect of the WWR on the cooling load.

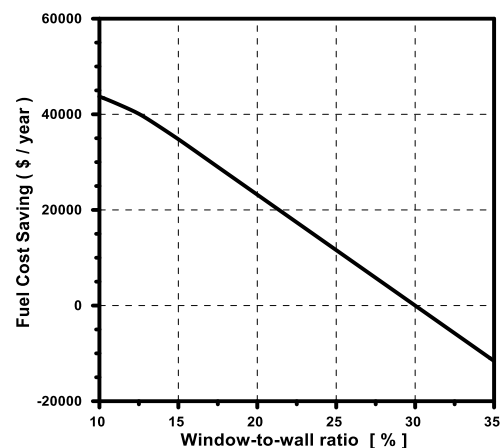


Figure 13. Effect of the WWR on the fuel cost saving.

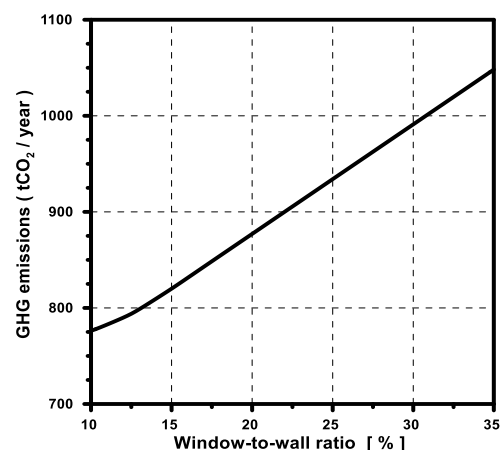


Figure 14. Effect of the WWR on the GHG emissions.

Figure 19. shows the environmental implications of varying aspect ratio. It indicates that the optimal aspect ratio of 2 leads to a reduction of approximately 1.17% in GHG emissions compared to the base case of 1.3 aspect ratio.

3.7. All Retrofits

Upon implementing all the aforementioned retrofits, the results indicate a substantial annual fuel cost saving of approximately \$136,497. Despite an incremental initial cost of about \$146,844, this culminates in a relatively short payback period of about 1.08 years.

Figure 20. provides a comprehensive impact of these retrofits on the cooling load. Notably, all retrofits have led to a remarkable reduction in cooling load by about 81.03%.

Moreover, Figure 21. sheds light on the effect of these retrofits on GHG emissions. It showcases a notable reduction in GHG emissions by about 66% as a result of implementing these retrofits.

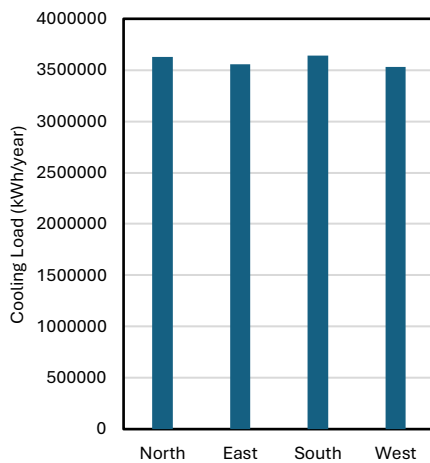


Figure 15. Cooling Load for different buildings orientation.

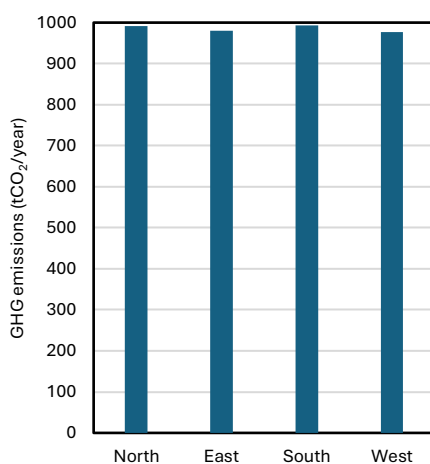


Figure 16. GHG emissions for different building orientations.

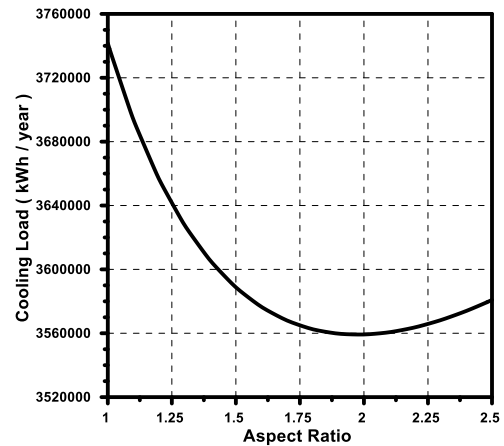


Figure 17. Effect of aspect ratio on cooling load.

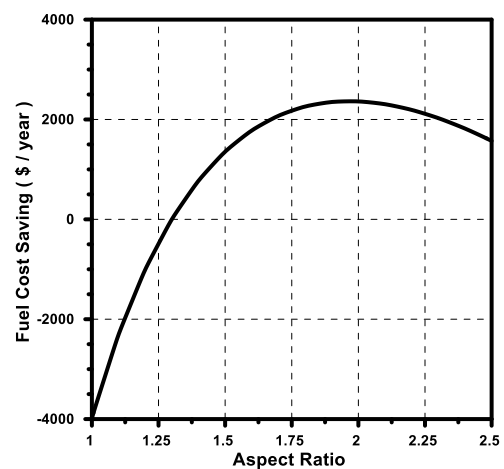


Figure 18. Effect of aspect ratio on fuel cost saving.

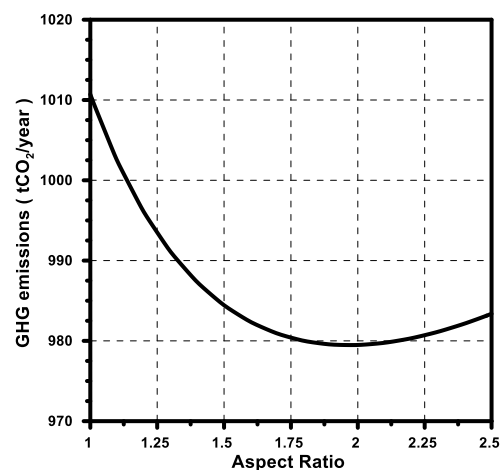


Figure 19. Effect of aspect ratio on GHG emissions.

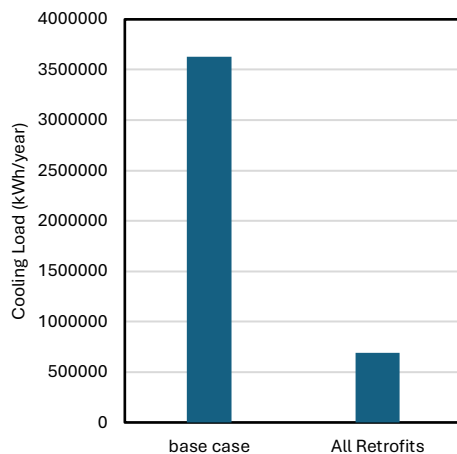


Figure 20. Effect of all retrofits on the cooling load.

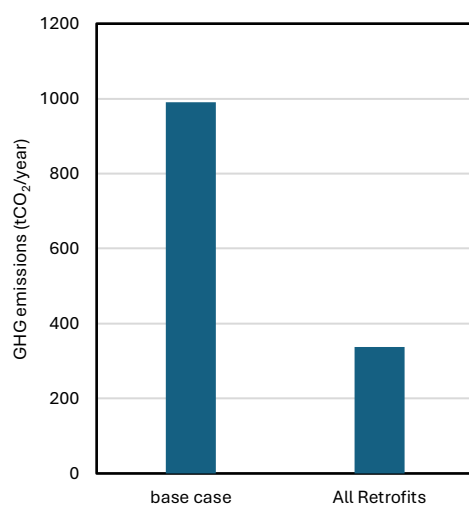


Figure 21. Effect of all retrofits on the GHG emissions.

4. Conclusion

The current paper proposed energy-saving measures for residential buildings in the Middle East climate zone, exemplified through a case study of 32 multi-residential buildings in Borg Al Arab City, Alexandria, Egypt. Using RETScreen software, simulations assessed various retrofits. Altering the WWR from 30% to 10% reduced cooling load by 44.6%, GHG emissions by 21.7%, and yielded monthly savings of \$43,700. Transitioning from electric to natural gas water heating systems decreased GHG emissions by nearly 19% and saved approximately \$43,400 annually. Replacing single clear glazing with ASHRAE 90.1 glazing cut cooling load by 46% and GHG emissions by 20%. Wall insulation reduced cooling load by 12.33% and GHG emissions by 11.78%. Minor impacts were noted for retrofits like ASHRAE roofs or LED lighting systems. Overall, combined retrofits resulted in an 81% reduction in cooling load and a 66% decrease in GHG emissions, demonstrating the effectiveness of comprehensive energy efficiency measures in residential buildings within the Middle East climate zone.

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N/A

Author Contributions

All authors were responsible for the conceptualization, validation, resources, data curation, software development, and project administration. They jointly contributed to the methodology, formal analysis, investigation, original draft preparation, review and editing, visualization, supervision, and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

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

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