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Multi-pronged strategies for enhancing building envelopes toward nearly-zero energy in hot climatic regions

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Abstract

Growing concerns about climate change and rising energy demands necessitate advancements in building energy efficiency. This study investigates the effectiveness of radiative coatings and thermal insulation, both individually and combined, in reducing energy consumption and carbon footprint for buildings in hot and humid climates. This research contributes to a growing body of knowledge by comprehensively evaluating the combined effects of these strategies. A comparative analysis was conducted using data on energy usage and carbon emissions. The research highlights the effectiveness of envelope-enhancing techniques in reducing energy consumption and carbon emissions. The application of radiative coating led to a significant 13.1% decrease in energy usage, totaling 681.95 MWh, and corresponding emissions of 482.14 tons of CO_2. Radiative coating offers the most cost-effective solution with an LCOS of \$0.045 kWh^{-1}. When integrating thermal insulation with radiative coating, there was a substantial 12.0% reduction in energy consumption, amounting to 690.39 MWh, and emissions of 488.11 tons of CO_2. The integrated model provides significant energy savings at a slightly higher LCOS of \$0.052 kWh^{-1}, making it a balanced choice between efficiency and cost-effectiveness compared to using thermal insulation alone. Moreover, the study emphasizes that the combination of Glazing Integrated Photovoltaic (GIPV) with radiative coating can lead to the creation of nearly zero-energy buildings, resulting in a significant energy savings of 34.9%. These results underscore the efficacy of these technologies in achieving significant energy savings and environmental benefits. This study demonstrates that radiative coatings significantly reduce energy consumption and carbon footprints. The combined method with thermal insulation reduces energy, suggesting further optimization strategies in hot and humid conditions. The results of this investigation recommend utilizing Glazing Integrated Photovoltaic (GIPV) to achieve nearly zero-energy buildings. Such integrated solutions not only improve energy efficiency but also make a substantial contribution to environmental sustainability in the building sector.

Abbreviations

BPS	Building Performance Simulation
GHG	Greenhouse Gas
GIPV	Glazing Integrated Photovoltaic
Ins	Insulation

NZEB	Nearly Zero Energy Buildings
RC	Radiative Coating
RE	Renewable Energy

1. Introduction

The ongoing global energy crisis, caused by several external factors, is having a tremendous impact on individuals, organizations, and entire economies all over the world. Consequently, governments have promptly taken measures, and there is a continuing debate on mitigating future disruptions. The aggression was triggered by a sequence of financial difficulties already causing instability in the region. However, these activities have resulted in substantial disruption to the worldwide economy, especially in the energy markets, and have impeded efforts to recover from the epidemic [1].

The tremendous surge in worldwide energy use in recent years has given rise to a range of worries regarding the availability of energy resources, their scarcity, and the consequential environmental impacts, including the depletion of the ozone layer, global warming, and climate change [2]. According to the Energy Information Administration (EIA), primary energy consumption has grown by 49% in the past two decades, while CO_2 emissions have risen by 43% [3].

Over the past 65 years, there have been substantial changes in global climate patterns and predictions for the twenty-first century, including global warming. Driven by climate change, rising global temperatures present a multifaceted challenge with interconnected ecological, environmental, sociopolitical, and economic consequences on a global scale [4, 5]. The global climate catastrophe has greatly intensified since the beginning of the modern era [6]. Reports suggest that promptly addressing the issue and implementing suitable protocols might increase the chances of successfully mitigating its devastating consequences. It is not possible to accurately forecast the specific effects of climate change on a sector-by-sector basis [7]. This is evidenced by the increasing consciousness and the incorporation of climate uncertainty policies at both the municipal and national levels [8].

Although there is a growing recognition among individuals about climate change, a substantial segment of the public lacks knowledge about how this issue affects energy use in buildings. The building sector is responsible for 28% of total emissions, and an additional 11% may be attributed to the carbon embedded in construction and building items [9]. This phenomenon is responsible for around 40% of carbon dioxide (CO_2) emissions produced by the construction and building sector, as well as over 33% of global energy consumption [10].

The interdependence and complexity of the interactions among climate change, energy, the economy, and buildings are immense. The building sector is responsible for a significant share of worldwide energy usage and the generation of greenhouse gases. The projected increase in building energy consumption stems directly from the concurrent phenomena of global population expansion and accelerating urbanization. This trend, coupled with the construction sector's significant energy consumption and greenhouse gas emissions, contributes substantially to climate change. The expected rise in the global population and urbanization is predicted to lead to a proportional increase in the demand for energy in buildings. The increased energy usage, along with the consequences of climate change, has the potential to result in a rise in energy prices and economic instability. To tackle these challenges, it is crucial to give priority to energy-efficient building design, architecture, and operations. Utilizing low-carbon energy sources and therefore decreasing greenhouse gas emissions is crucial in addressing climate change and promoting economic growth [11–16].

As environmental and economic concerns rise in prominence, green buildings are gaining increasing recognition as a scientifically validated approach to achieving sustainability. Their design and construction principles prioritize the minimization of negative ecological impacts while simultaneously promoting positive ones. Green buildings effectively tackle interrelated issues such as climate change and energy inefficiency by employing evidence-based techniques. According to the International Green Building Council, these buildings are designed, constructed, and operated in a way that minimizes their impact on the environment and produces beneficial ecological consequences [17, 18].

Nearly Zero Energy Buildings (NZEB) are regarded as practical alternatives for delivering energy-efficient and ecologically advantageous buildings. The development plan provides us with the essential means to analyze the relationship between current environmental challenges and the likelihood of their future advancement [19]. Toward achieving NZEB, optimizing the building envelope, consisting of the walls, roof, and windows, would decrease the heat transfer into the building's interior [20].

In recognition of the well-established influence of building envelopes on thermal performance, integrating heat and moisture transfer control strategies becomes particularly crucial in hot-climatic regions [21]. The deterioration of a building envelope's insulating efficacy directly correlates with an increase in energy

Table 1. Review summary.

Author	Study key points
Aditya *et al* [24]	•Explores the equilibrium between thermal conductivity and insulation expenses. •Enhancing the thickness of insulation reduces thermal conductivity, but once a specific threshold is surpassed, the reduction in costs becomes less significant. •The ideal thickness of insulation maximizes cost savings while limiting energy use.
El-Sherif *et al* [25]	•Conducts a study on an administrative building in Cairo to assess the economic viability of transforming it into a net-zero energy building. •By incorporating three layers of insulation, the U-value of the building was dramatically reduced. •The biggest energy savings were realized with the lowest U-value.
Bolatturk [26]	•Insulating materials exhibit a high level of efficacy in the preservation of energy. •Engineering studies should be conducted to ascertain the most suitable insulation thickness, which is contingent upon the specific climatic conditions. •Thin layers of plaster are commonly applied over bricks in warm areas, while sandwich walls are frequently utilized in cold climates. •The recommended thickness range for polystyrene boards is 3.2 to 3.8 cm.
Pargana *et al*[27]	•This study investigates the environmental ramifications and energy consumption associated with conventional thermal insulating materials. •The findings indicate that insulation is a highly promising strategy for decreasing energy usage and encouraging the adoption of sustainable building methods.
Al-Homoud [28]	•Buildings globally consume a huge amount of energy, particularly in extreme weather conditions. •Effective building design and careful selection of materials, notably thermal insulation, can greatly decrease the amount of energy needed for heating and cooling. •Thermal insulation prolongs the duration of thermal comfort without the need for mechanical air conditioning.
Evin and Ucar [29]	•Examines the efficacy of thermal insulation in various climatic regions of Turkey. •The utilization of XPS insulation on roofs leads to a substantial decrease in energy expenses in comparison to roofs without insulation. •This strategy is recommended for different types of buildings and climates.

consumption and a diminished capacity to withstand peak structural loads. Consequently, this phenomenon translates into a concurrent elevation of both energy usage and maximum electrical demands placed on the building system. The selection of appropriate insulation can effectively provide the necessary heat flow resistance throughout the building structure [22]. Moreover, thermal insulation may significantly decrease the demand for cooling in buildings located in hot regions [23].

In this context, researchers and academicians from around the world have carried out several studies using this approach. Below, as shown in table 1, are the main conclusions drawn from these studies.

The significance of thermal insulation in strengthening the building envelope-a prerequisite for meeting NZEB targets-is highlighted by these findings. Thermal insulation is crucial for improving building energy efficiency and promoting sustainable construction practices by reducing heat loss and optimizing energy usage for heating and cooling.

Alongside thermal insulation, another significant development in reducing building energy use is the application of solar-reflecting paint. Implementing Radiative Coatings (RC) on the building exterior is a potential solution to the urban heat island (UHI) problem [30–32].

Using a simulation fed with extensive climatological data, Moujaes and Brickman examined the efficacy of reflective paint applied to buildings in the hot-arid climate of the southwest United States. Their results revealed an 11% decrease in energy usage throughout the summer when reflective paint was only applied to the roof. The study conducted by Zhang *et al* showed that the use of high-reflectivity coatings on external walls is a very efficient approach to decreasing solar heat absorption and energy consumption. Their study, conducted in urban areas of southern China, demonstrated that the application of reflective coatings could reduce summer energy consumption by around 15%. The economic analysis demonstrated that these coatings provide notable advantages, including a shorter payback period owing to a considerable reduction in cooling energy consumption during periods of high temperatures. The aforementioned research highlights the efficacy of reflective materials in improving the energy efficiency of buildings in various local climates [33, 34].

In addition, by aligning with Net Zero Energy Building concepts and classifications, the use of renewable power sources can reduce the need for fossil fuel energy usage. One possible strategy entails exporting excess photovoltaic (PV) or wind energy to the power grid, which can effectively reduce natural gas usage [35]. As defined in the European Performance of Buildings Directive (EPBD) reprint, the following criteria are assigned to Net Zero Energy buildings: A major shift toward using renewable energy sources and a sharp decline in overall energy use should be the goal [36]. To achieve Net Zero Energy, photovoltaic (PV) systems that can supply at least 30% of the overall energy needs must be integrated [37]. To achieve the goal of net zero energy, solar panels should be used for more than just powering buildings. The shade effect created by solar panels has an added importance as it helps to lower surface temperature and, as a result, decrease the overall energy usage of the building [38].

The growing interest in on-site energy production has led to the development of numerous research papers focusing on photovoltaic (PV) technology [39–41]. Several investigations have examined the enhancement of photovoltaic (PV) systems through the analysis of factors like as panel orientation, number of panels, tilt, and azimuth. The suggested framework aims to optimize energy generation in different climate zones by taking into account horizontal irradiation levels. Research has also investigated methods to minimize the discrepancy between electricity generation and demand, hence enhancing the efficiency of photovoltaic systems. These collective endeavors contribute to enhancing the understanding and implementation of ideal photovoltaic (PV) systems under various environmental conditions [42, 43].

Furthermore, building integrated photovoltaics (BIPV) has surfaced as a highly promising technology. BIPV refers to photovoltaic cells incorporated into the building envelope, such as the roof or facade. This approach harnesses the incoming solar radiation on the building's surface to generate electrical energy. Solar cells in BIPV systems serve as building envelope materials, such as tiles, foils, modules, or windows. The technology preserves the characteristics of existing building envelope materials, such as weather resistance, privacy, noise reduction, and thermal insulation, while also producing electricity for the building. BIPV systems combine photovoltaic (PV) technology with the building's structure, providing both energy generation and the practical advantages of conventional building materials. This integration greatly enhances sustainable and energy-efficient building design [44, 45].

One potential way to incorporate renewable energy sources into building designs worldwide is through building integrated photovoltaics, or BIPV. Research has been undertaken in many parts of the world to investigate the technical, economic, and environmental aspects of BIPV systems. Alnaser [46] assessed Bahrain's 8.6 kW polycrystalline photovoltaic (PV) building-integrated photovoltaic (BIPV) system. The evaluation revealed that the system would take 624 years to recoup its cost, primarily because of the subsidized power pricing. However, if the feed-in tariffs were increased, the payback period could potentially be reduced to five years. Researchers in Shanghai, led by Wang *et al* [47], analyzed a Building-Integrated Photovoltaic (BIPV) system. it was found that the system had a payback period of 6.52 years under the current feed-in tariffs. The study emphasized the potential for better economic results by taking into account wider societal and environmental advantages. Aste *et al* [48] found that Italy's first BIPV project showed negligible performance deterioration, with a rate of 0.37% per year, over 13 years. This suggests that the durability of the BIPV project is equivalent to that of traditional systems. Meanwhile, Sorgato *et al* [49] demonstrated in Brazil that thin-film CdTe BIPV systems may efficiently fulfill the energy requirements of buildings, highlighting the crucial influence of climate on energy production and consumption concerns.

Given this consideration, a proposal is made for the integration of photovoltaics into the building facade following an enviro-economic assessment. This solution aims to improve building efficiency by reducing energy usage and generating clean energy without compromising interior thermal comfort. This prototype explores the use of glazing-integrated photovoltaics (GIPV) systems within building envelopes to enhance energy efficiency and offer a viable solution for sustainable energy integration, considering the limited roof area available for solar panels[50]. Based on the transparency of BIPV systems, sunlight can permeate through them, therefore modifying their interior environment [51]. The versatility and lightweight nature of GIPV have made it easier to integrate PV into building components. [52].

In conclusion, the analysis of the literature emphasizes the crucial importance of building envelopes in thermal performance, especially in hot areas where it is vital to have effective measures for controlling heat and moisture [53]. Moreover, thermal insulation, which has been emphasized in several research, has a crucial role in decreasing energy usage for heating and cooling, thereby encouraging sustainable building methods. Incorporating renewable energy sources such as photovoltaic (PV) systems into building designs, namely through building integrated photovoltaics (BIPV), presents favorable opportunities for attaining Net Zero Energy Building objectives.

These technologies have the dual duty of generating electricity and improving building functionality. This highlights the importance of conducting thorough studies to maximize their economic, environmental, and societal advantages.

1.1. Scope, objectives and novelty

Aligning with the global trend towards NZEBs and Egypt's Vision 2030 for sustainable communities [53], this research investigates strategies to reduce building energy consumption and its environmental implications. This study explores methods to improve the energy efficiency of buildings by implementing different strategies for improving walls' thermal performance, particularly through thermal insulation, radiative coating, and their combined application. The scope involves doing a thorough examination of various strategies, considering their individual and collective effects on energy efficiency.

This study's overarching goal is to evaluate, in detail, how various wall enhancement techniques contribute to enhanced building energy efficiency. This involves assessing the initial energy usage, comparing the performance to ASHRAE requirements, and analyzing the unique advantages of thermal insulation and radiative coatings in decreasing heat transfer and solar heat gain, respectively.

By using a comprehensive and systematic method to evaluate the combined effects of several wall enhancement techniques, this work represents a substantial advancement in the field of building energy efficiency. In contrast with conventional studies that primarily concentrate on individual technologies like thermal insulation or radiative coatings, this research combines these traditional improvements with Glazing Integrated Photovoltaic (GIPV) technology. Through a meticulous analysis of the interplay between energy consumption, economic viability, and renewable energy-generating capability, the research pioneers a complete method that aspires to develop nearly zero-energy buildings.

The study's novel approach arises from its assessment of the combined effects of different energy-saving and energy-generating technologies, providing a detailed understanding of how these interventions collectively influence the overall performance of buildings. This multifaceted research provides actionable insights into how to optimize construction processes to meet future energy demands while also advancing the scientific debate on sustainable building design. The paper introduces a framework that takes into account technological interactions and their combined advantages. This methodology establishes a fresh standard for integrating various energy solutions in the built environment. It emphasizes the possibility of changing existing construction paradigms to achieve more sustainable and energy-efficient outcomes.

2. Materials and methods

The study examines a comprehensive three-step methodology specifically developed to improve the energy efficiency of a building, with a particular emphasis on evaluating various techniques for enhancing walls. The comprehensive strategy is illustrated in figure 1.

The initial phase involves developing a baseline model of the building, which serves as a vital reference point for evaluating the existing energy efficiency levels without any modifications. The initial model undergoes thorough quantitative evaluations to assess many variables such as energy consumption, thermal properties, and overall efficiency. This step is crucial for identifying the primary areas that possess the highest potential for improvement. To ensure accuracy and consistency in the evaluation process, this study employs DesignBuilder version 7 software to create and validate the baseline model. It is important to emphasize that the model has been extensively validated using on-site energy consumption data, ensuring its reliability and appropriateness for real-world scenarios.

The second phase, the focus is on improving the baseline (as-built) model to meet the requirements set by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). This involves incorporating universally recognized standards and recommendations for constructing energy efficiency and performance into the model. The ASHRAE-compliant model ensures a more precise depiction of a building that complies with current energy efficiency standards by following these criteria. This process guarantees that the performance of the building is evaluated in relation to current and up-to-date industry standards, enabling a thorough comparison with the reference model. Guaranteed to be in line with current standards, making a thorough comparison with the reference model possible.

The third stage of the approach centers on the utilization of energy-conserving technologies, such as thermal insulation, radiative coating, and their integrated implementation. This comprehensive methodology takes into account the precise orientations of the building walls to achieve maximum energy efficiency. The thermal insulation model employs a 25-mm layer of polyurethane, a widely used insulating material known for its thermal conductivity of 0.026 w $(m\,k)^{-1}$. Polyurethane has a specific heat capacity of 1590 J kg^{-1}-k^{-1}, which helps to reduce heat transmittance and improve the thermal efficiency of building envelopes. Additionally, with a solar absorption rate of 0.6 on all building walls to decrease heat transfer, hence improving the building's ability to retain warmth during winter and sustain cool temperatures during summer [54–56]. The radiative coating model involves the application of a particular radiative coating to all the walls of the building. The coating possesses a thermal conductivity of 0.0913 w $(m\,k)^{-1}$, specific heat of 1423 J kg^{-1}-k^{-1}, specific gravity of 1.1, and a solar absorption coefficient of 0.148. These properties are designed to enhance the reflection of solar radiation, thereby reducing the absorption of thermal energy and minimizing the requirement for cooling during hotter seasons [57, 58].

The integration model utilizes a hybrid method, wherein thermal insulation is implemented on the north wall to reduce heat transfer, while radiative coatings are applied on the east, west, and south sides to deflect solar

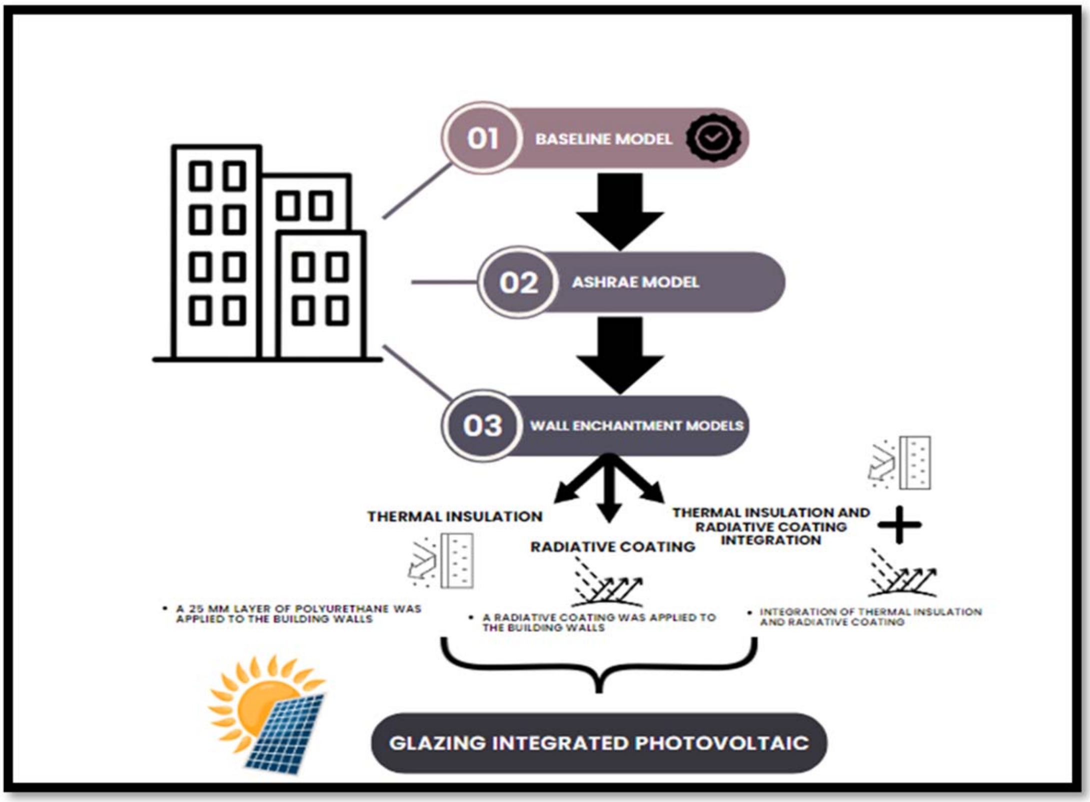

Figure 1. Modeling methodology.

radiation. The purpose of this strategic orientation is to optimize energy efficiency by effectively decreasing both heating and cooling requirements through synergy. The study aims to give a comprehensive approach to building energy optimization by evaluating the individual and collective impact of these enhancements on energy efficiency and CO_2 emissions.

After assessing various approaches for enhancing walls based on their energy usage patterns, the most effective choice was chosen to be combined with Glazing Integrated Photovoltaic (GIPV) technology. The selection was made based on a thorough evaluation of the energy performance parameters of each improvement, with a specific focus on aspects like the annualized capital expenses and levelized costs of savings. The study seeks to integrate the selected technique with GIPV in order to combine energy efficiency enhancements with renewable energy generation.

2.1. Model description

This investigation was conducted within an educational building and focused on a specific architectural entity, shown in figure 2. With a total area of approximately 6,020 m^2 and organized across five floors, the building presents a well-considered functional layout that caters to a diverse range of functional requirements. The facilities include classrooms, labs, storage areas, faculty offices, a designated meeting room, a prayer area, and a cafeteria. Each of these spaces is carefully arranged according to the detailed floor plan. One notable element of this building is the use of a centrally deployed Fan Coil Unit (FCU) air conditioning system. This system serves the targeted zones outlined in table 2.

Employing DesignBuilder V7, this investigation leverages high-resolution, hourly dynamic simulations to conduct a granular analysis of the building's energy consumption patterns within a specific climatic region. Recognizing that climatic factors influence the complex interplay of a building's energy dynamics, this approach aims to definitively characterize its complex energy requirements and foster a profound understanding of its energetic behaviour [59].

By accounting for the specific climatic context, this investigation strives to provide a more comprehensive and insightful picture of the building's energy performance.

Table 3 presents a comprehensive compilation of the building's detailed specifications, serving as a database that documents its dimensions, configurations, and operational elements. Incorporating the building's specifications into table 1 with great care not only provides a unified point of reference, but also lays the framework for a more comprehensive analysis of its features.

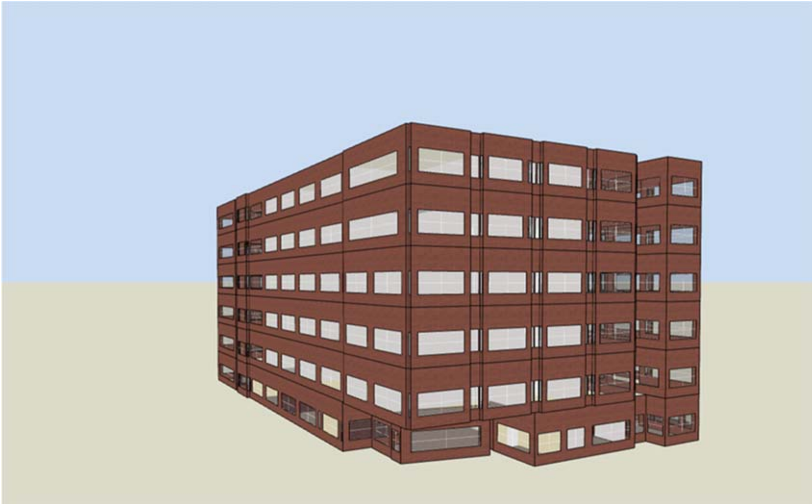

Figure 2. Building external overview.

Table 2. Conditioned zones area.

Zone	Area [m^2]	Area [%]
Lecture Hall	198.27	5.15
Rest Room	10.51	0.27
Staff Offices	702.97	18.27
Students Union Room	21.17	0.55
Labs	797.89	20.73
Copy Centre	14.34	0.37
Servers Room	36.84	0.96
Computer Labs	496.31	12.90
Researcher Rooms	65.31	1.70
Classrooms	849.76	22.08
Drawing Hall	599.99	15.59
Mechanical Lab	54.88	1.43
Conditioned Total Area	**3848.24**	**100.00**

Table 3. Building technical data (Baseline Model).

Item	Parameter	Value
	Building location	Alexandria, Egypt
	Building type	Educational Building
Building	Floor area	6020 m^2
	Number of floors	5
	Walls U-value	1.924 W m^{-2}.K
	Window type	6 mm Single Clear
Envelope	Window-to-wall ratio	30%
	Roof U-value	0.708 W m^{-2}.K
	HVAC system	FCU
HVAC	Ventilation rate	No Fresh Air
	Average Thermostat set point (cooling)	24 °C
Lighting	Lighting power density	15 W m^{-2}

Based on typical values found in Egyptian buildings that are currently in use, the thermal properties of the building envelope were simulated. The existing thermal performance of the building under consideration was represented by a wall U-value of 1.924 W m^{-2}. K and a roof U-value of 0.708 W m^{-2}. K, which established the baseline model. The values provided represent the typical non-insulated walls and insulated roofs that are commonly found in traditionally constructed buildings [60]. These U-values suggest a considerable opportunity

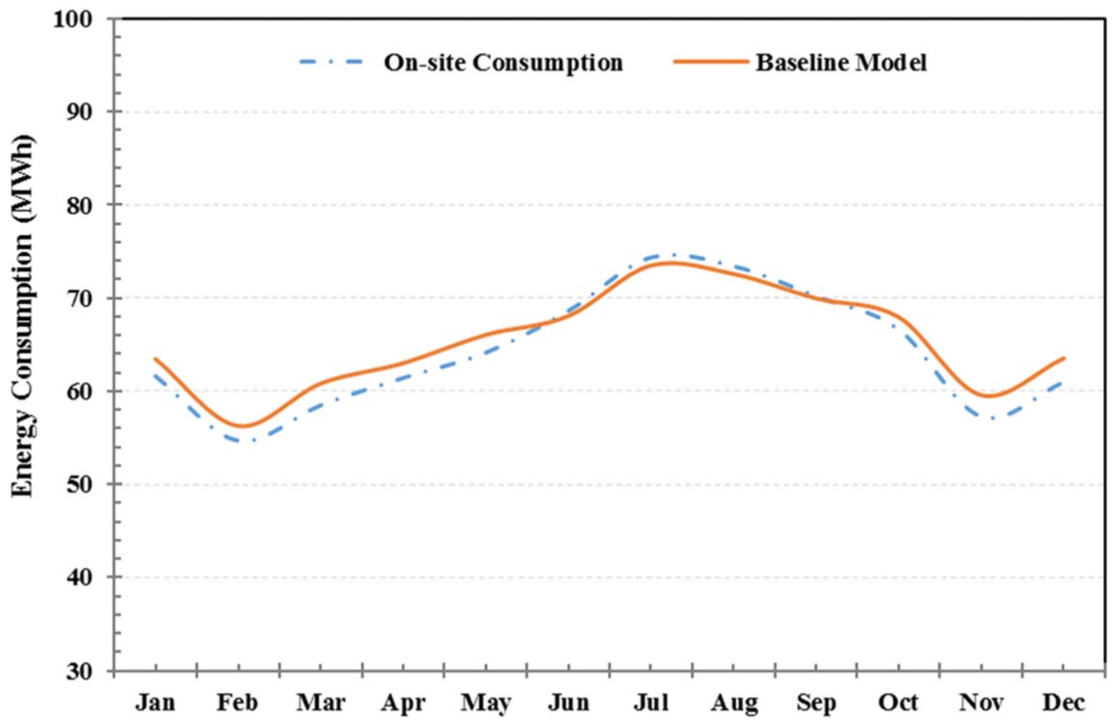

Figure 3. Model validation.

for retrofitting, since the use of improved insulation materials might greatly decrease heat transmission and diminish energy usage, especially in Alexandria's hot environment. The present study examines retrofitting options that specifically target energy efficiency optimization and overall building performance enhancement.

2.2. Model validation

The developed baseline model's accuracy was verified by comparing predicted consumption with actual electricity usage data obtained from the metering system over a one-year period. To evaluate the model's accuracy as a starting point, its alignment with actual energy consumption patterns was examined. To assess the model's accuracy and reliability, the validation concentrated on its ability to capture the intricate variations in on-site consumption that occur within a building environment.

To evaluate the prediction accuracy of the built-up baseline model, the Root Mean Square Error (RMSE) was employed as the primary metric. Figure 3 depicts the monthly variation between the model's forecasts and actual on-site consumption data, visually highlighting the extent of prediction errors. This analysis yielded an RMSE value of approximately 1.63, indicating the average magnitude of errors across all months. Additionally, the coefficient of variation root mean square error (CVRMSE) was calculated to be 2.54%. Notably, both the RMSE and CVRMSE values fall within the acceptable range suggested by ASHRAE Guideline 14 [61, 62], demonstrating the model's satisfactory performance in capturing the building's energy consumption patterns.

The initial model was modified to adhere to ASHRAE standards 62.1 and 90.1, in accordance with ASHRAE guidelines, to ensure compliance [63, 64]. The improvements involved alterations in lighting and ventilation rates, with the goal of maximizing energy efficiency and improving indoor air quality. In addition, the central air conditioning system changed from a Fan Coil Unit (FCU) to a Variable Air Volume (VAV) system providing the recommended fresh air rates as recommended for educational facilities [63, 65]. The purpose of this change was to strengthen the provision of fresh air and improve the air quality in educational buildings. These adjustments are crucial in fighting infections, especially in the time post-COVID-19, following the recommendations of ASHRAE and NREL to enhance the quality of indoor environment [66].

3. Results

3.1. ASHRAE model

As shown in figure 4, The comparative analysis of energy consumption between the Baseline Model and the ASHRAE Model reveals noteworthy findings. Over the observed period, the Baseline Model exhibited a total

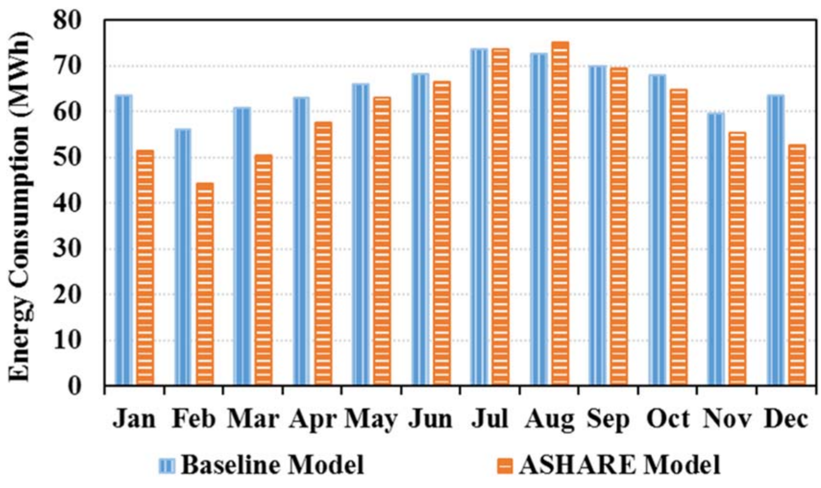

Figure 4. Monthly energy consumption comparison between baseline and ASHRAE model.

energy consumption of 784.70 MWh, while the ASHRAE Model demonstrated a lower consumption of 723.54 MWh, with a reduction of approximately 8% in energy usage.

Month-to-month analysis underscores the ASHRAE Model's more prominent advantage in energy savings compared to the baseline model across most months, particularly evident in January, February, March, April, May, and June, where reductions ranged from approximately 18% to 14%. However, deviations from this trend are observed in July and August, wherein the Baseline Model's energy consumption slightly surpassed that of the ASHRAE Model by approximately 0.04% and 3%, respectively.

3.2. Wall enchantments techniques

Having established the baseline model of the building, this section explores the potential for improvement through the implementation of wall enchantment techniques. These techniques encompass thermal insulation materials and radiative coatings, both of which aim to optimize the building envelope's performance and reduce energy demands.

3.2.1. Thermal insulation

The INS Model achieves a 9.6% drop in annual consumption compared to the Baseline Model by adding a 25 mm polyurethane, resulting in a lowered consumption of 709.43 MWh. The INS Model achieves a 2% greater reduction in energy consumption compared to the ASHRAE Model. The efficacy of the INS Model is particularly remarkable during periods of high energy demand. In July, the Baseline Model's consumption reaches its highest point at 73.55 MWh. The ASHRAE Model reduces the value to 73.58109 MWh, whilst the INS Model drastically decreases it to 70.94 MWh. This signifies a decrease of around 3.5% from the highest point reached by the Baseline Model in July. In general, the INS Model consistently shows the high level of energy savings, with a yearly reduction in consumption of up to 9.6% compared to the Baseline Model and an additional 2% compared to the ASHRAE Model.

3.2.2. Radiative coating

By implementing a radiative coating on the building, the RC walls model achieves a further decrease, resulting in a total annual consumption of 681.95 MWh. This represents a 13.1% reduction compared to the Baseline Model. This signifies a further reduction of 5.8% in comparison to the ASHRAE Model.

Upon analyzing the monthly data, it is evident that the RC walls model continuously exhibits lower energy use throughout all months in comparison to both the Baseline and ASHRAE models. The results show that adding a radiative coating layer significantly improves the building's energy efficiency. The RC walls model surpasses the ASHRAE Model in terms of energy consumption reduction and consistently produces substantial energy savings year-round. This makes it an exceptionally efficient choice for enhancing building energy performance.

3.2.3. Insulation and radiative coating integration

The INS and RC Integration Model, which uses radiative paint on the south, west, and east walls and thermal insulation on the north wall, as well as the Baseline Model and the ASHRAE Model, all display their monthly energy usage (in MWh). The results demonstrate substantial decreases in energy usage for the INS and RC

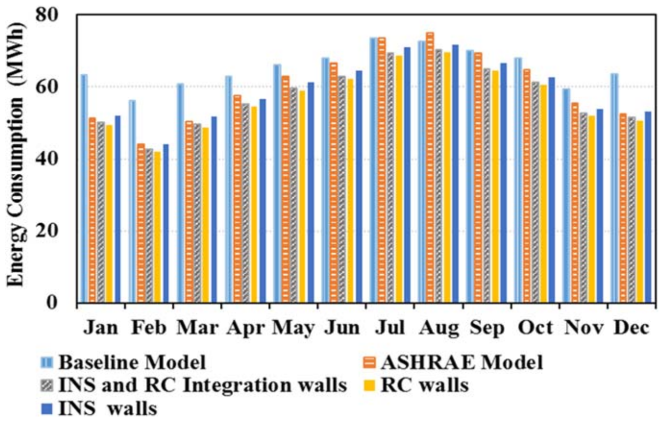

Figure 5. Comparison of energy consumption across different models.

Integration Model. In January, it achieved a 20.9% decrease compared to the Baseline Model and a 2.3% decrease compared to the ASHRAE Model. In February, there is a decrease of 24% compared to the Baseline and a decrease of 3.4% compared to the ASHRAE Model. The reductions in March are 18.1% and 1.1%, respectively. In June, there is a decrease of 7.7% compared to the Baseline and a decrease of 5.5% compared to the ASHRAE Model. In July and August, the INS and RC Integration Model delivered reductions of 5.7% and 3.7% compared to the Baseline, and 5.8% and 6.4% compared to the ASHRAE Model, respectively, during the high summer months. The reduction in November is 11.6% compared to the Baseline and 5.0% according to the ASHRAE Model. In December, there is a decrease of 18.9% compared to the Baseline and a decrease of 2.0% compared to the ASHRAE Model. The combined yearly energy usage for the INS and RC Integration Model is 690.395 MWh, which is 12% lower than the Baseline Model and 4.6% lower than the ASHRAE Model. The findings emphasize the significant effect of combining thermal insulation with radiative paint in enhancing energy efficiency.

3.3. Comparative analysis

The presented data in figure 5 demonstrates the energy usage of several models over a year. Comparisons are conducted between the Baseline Model and ASHRAE standards.

The ASHRAE model shows an average decrease of around 8.03% compared to the Baseline model. Using RC walls leads to noticeable improvements, resulting in an average reduction of around 13.05% compared to the Baseline model. Similarly, the INS walls demonstrate an average decrease of approximately 9.52% compared to the Baseline model.

Compared to the ASHRAE model, the RC walls exhibit an average decrease of around 5.72%, whereas the INS walls demonstrate a reduction of approximately 3.39%. The combination of RC and INS approaches leads to an average decrease of around 4.57% compared to the ASHRAE model.

The results emphasize the efficacy of advanced building techniques in greatly decreasing energy usage, particularly when using RC walls and also integrating them with INS approaches.

3.4. Impact of glazing-integrated photovoltaic (GIPV)

As show in figure 6 The analysis demonstrates the effect of combining glazing-integrated photovoltaic (GIPV) systems with radiative coated walls on the energy efficiency of the building. Monthly energy use and generation data are recorded. The building's energy usage varies seasonally, with lower values in winter (e.g., 41.58 MWh in February) and higher values in summer (e.g., 68.33 MWh in August). Energy generation exhibits a seasonal pattern, with lower levels during the winter (e.g., 10.29 MWh in December) and greater levels during the summer (e.g., 14.54 MWh in July). Incorporating GIPV into the building's design substantially reduces energy consumption. For example, in May, the building consumed 57.93 MWh of energy but generated 14.48 MWh using GIPV, resulting in a significant decrease in net energy demand. The building's annual energy consumption is 671.35 MWh, while the GIPV system produces 160.84 MWh. This results in a net annual energy usage of 510.51 MWh. This integration not only reduces the amount of energy consumed by the building but also improves sustainability by decreasing its carbon impact. The results emphasize the effectiveness of glazing-integrated PV systems in greatly enhancing energy efficiency in buildings, especially in regions with abundant solar radiation.

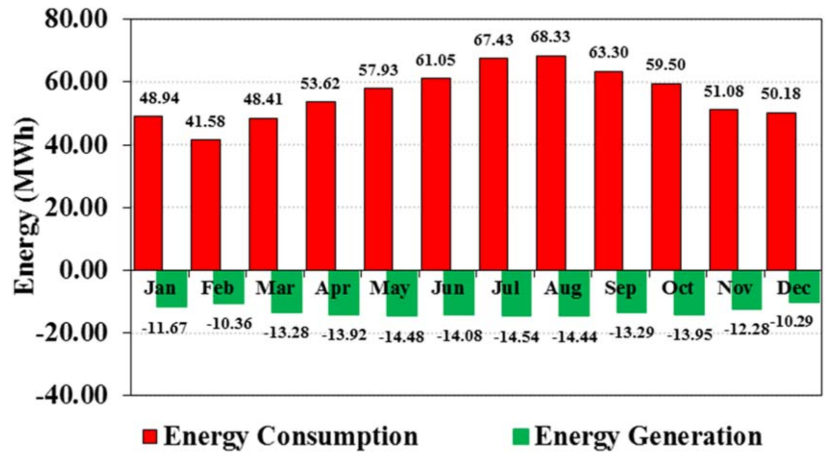

Figure 6. Energy consumption and generation of GIPV with RC walls.

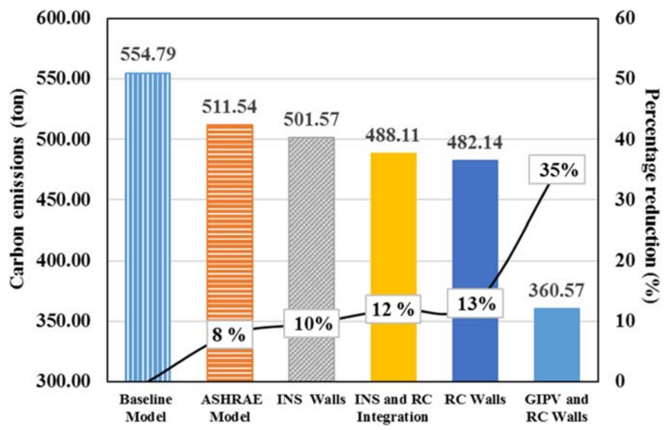

Figure 7. Carbon emissions for different models.

3.5. Carbon footprint assessment

Reducing energy consumption contributes to the mitigation of CO_2 emissions, anthropogenic climate change, and environmental pollution. As per the United States Environmental Protection Agency, the consumption of 1 kWh of energy leads to the emission of 0.707 kg of CO_2, which is equivalent to 0.000707 tons of CO_2 [67]. Figure 7 demonstrates a reduction in Carbon emissions in INS and RC model as compared to the baseline and ASHARE models.

Figure 7 displays the quantities of CO_2 emissions (measured in tons) and the corresponding percentage (%) decrease in emissions for three distinct models: The carbon footprint evaluation provides crucial insights into the environmental consequences of various building energy efficiency schemes. Through the comparison of carbon emissions attributed to each model, we can acquire a thorough comprehension of their sustainability implications.

Our starting point is the baseline model, which has carbon emissions of about 554.79 ton, which is directly proportional to its energy consumption. Transitioning to the ASHRAE model results in an 8% reduction in energy use, leading to about 511.54 ton of carbon emissions. This decrease represents a significant enhancement in environmental sustainability, by ASHRAE criteria. Additional improvements, such as the incorporation of insulated (INS) walls and the combination of INS with radiative coating (RC) methods, result in even more significant decreases in energy usage and carbon emissions. The INS walls and INS/RC integration models both demonstrate a reduction in energy usage of 10% and 12% respectively. This results in a decrease in carbon emissions of roughly 501.57 ton and 488.11 ton. The results emphasize the effectiveness of insulating techniques in enhancing energy efficiency and mitigating environmental impact.

The RC walls model stands out for achieving significant savings in energy consumption and carbon emissions. It shows a 13% drop compared to the baseline, resulting in emissions of roughly 482.14 ton. This

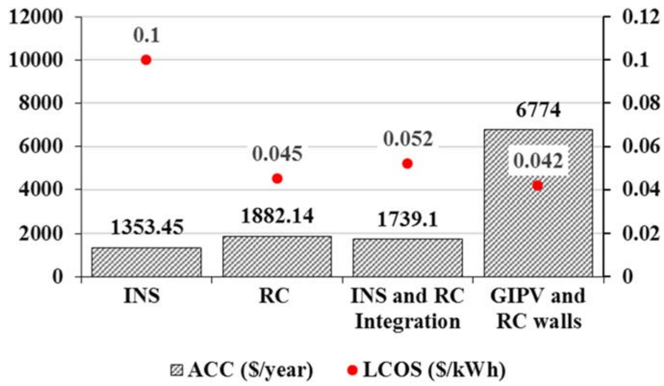

Figure 8. Annualized capital cost and levelized cost of savings for different wall enhancements techniques.

emphasizes the crucial function of radiative coatings in reducing carbon emissions and improving environmental sustainability in the construction of buildings.

Radiative coating walls combined with glazing-integrated PV represent an innovative approach to sustainable building design. This integrated system effectively delivers significant reductions in carbon emissions, with a maximum reduction of 35% compared to the baseline model. Using a technique that blends solar panels into building exteriors and maximizes solar heat management through radiative coatings, this method increases indoor comfort and energy efficiency while producing renewable energy. Collectively, these progressions indicate a thorough approach to supporting sustainable urban development, fostering environmental responsibility, and integrating renewable energy.

To summarize, the carbon footprint assessment highlights the significance of implementing energy-efficient building practices in order to reduce environmental effect. Implementing strategies such as insulation and integrating radiative coatings are crucial in achieving substantial reductions in carbon emissions, thereby making a valuable contribution to creating a more sustainable built environment.

3.6. Economic analysis

The Levelized Cost of Savings (LCOS) is a vital economic indicator employed to assess the cost efficiency of energy-saving solutions.

Expressed in the unit of currency per unit of energy, specifically dollars per kilowatt-hour ($/kWh). The metric presented offers a thorough assessment of the enduring economic advantages of energy-saving measures. It takes into account the initial expenses as well as the energy savings realized over a period of time. This study assesses the economic viability of three different ways to improve walls: thermal insulation (INS), radiative coating (RC), the combination of both (INS & RC combination), and the use of Glazing Integrated Photovoltaic (GIPV) & RC walls. Based on the study and illustrated in figure 8, thermal insulation (INS) is identified as the expensive choice for energy conservation, with an annualized capital cost (ACC) of $1353.45 and a levelized cost of savings (LCOS) of $0.1 per kilowatt-hour (kWh). Although it is effective, the high levelized cost of solar (LCOS) diminishes its economic appeal in comparison to alternative choices. The radiative coating (RC) is the most economically viable option among the available choices, with an annualized cost of $1882.14 and a levelized cost of savings of $0.045 kWh^{-1}. The integrated INS & RC model demonstrates an ACC of $1739.1 and an LCOS of $0.052 kWh^{-1}, providing significant energy efficiency while maintaining a competitive price compared to using INS alone. Nevertheless, the GIPV & RC walls model showcases superior economic efficiency, with an ACC of $6774 and an LCOS of $0.042 kWh^{-1}. This highlights its potential as the most advantageous choice for integrated energy solutions in environmentally friendly building techniques.

To sum up, the building envelope optimization is critical for achieving Net Zero Energy Buildings (NZEB) within the LEED criteria framework. Through the upgrading of insulation, the optimization of glazing performance, and the use of high-reflectance materials, buildings have the potential to substantially reduce energy requirements for heating and cooling. These approaches not only effectively reduce operational energy usage, but also conform to LEED's objectives in terms of reducing carbon emissions and promoting sustainability. An appropriately engineered building envelope reduces thermal bridging and air leakage, therefore improving overall energy efficiency, a crucial factor in achieving the demanding performance standards established by LEED Furthermore, the integration of renewable energy systems with an enhanced envelope facilitates the shift towards a genuinely sustainable constructed environment, enhancing resilience against climate effects [68, 69].

4. Conclusion and prospects

In a hot and humid climate, this study looked at how buildings' energy consumption and carbon emissions were influenced by thermal insulation (INS) walls, radiative coatings (RC) walls, and their combined application. The results indicate substantial energy conservation and associated decreases in CO_2 emissions when compared to a baseline (as built) model.

The study's primary conclusions, which emphasize the effects of utilizing ASHRAE standards in conjunction with radiative coatings and thermal insulation on energy consumption and carbon footprint in an educational building located in a hot and humid climate, can be summarized as follows:

- By reducing energy usage by 8.03% on average, the ASHRAE-compliant model was able to cut CO_2 emissions by 8%, from 554.79 ton to 511.54 ton.
- Radiative Coatings (RC Walls) showed a significant impact, resulting in an average energy savings of 13.05% and an associated reduction of 13% in CO_2 emissions. This signifies an additional 5.72% enhancement compared to the ASHRAE model.
- Implementing insulation (INS) in the walls resulted in a significant 9.52% drop in energy usage and a 10% reduction in CO_2 emissions, amounting to a total of 501.57 ton. This signifies a 3.39% enhancement in comparison to the ASHRAE model.
- The integration of both insulating and radiative coatings resulted in the most significant results. The implementation of this integrated approach led to a mutually advantageous outcome, with a notable decrease of 12.0% in both energy consumption and CO_2 emissions, culminating in a final value of 488.11 ton.
- Glazing Integrated Photovoltaic (GIPV) combined with radiative coating (RC) walls emerges as the most economically efficient solution, with 34.9% savings, offering a competitive levelized cost of savings (LCOS) of \$0.042 kWh^{-1}, significantly lower than other strategies evaluated.

Based on the findings, it has been evident that in hot and humid areas, radiative coatings are more effective than thermal insulation alone. The combination of these technologies, specifically the integration of Glazing Integrated Photovoltaic (GIPV) with radiative coating (RC) walls, demonstrates significant potential for sustainable growth. Subsequent investigations should evaluate the extended-term efficacy, expenses related to upkeep, and economic viability in various climatic conditions. The results emphasize the significant role that thermal insulation and radiative coatings can play in addressing climate change and promoting sustainable development.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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