Journal of Renewable Energy and Sustainable Development (RESD) Volume 10, Issue 2, December 2024 - ISSN 2356-8569
http://dx.doi.org/10.21622/RESD.2024.10.2.924
Received on, 10 July 2024 Accepted on, 23 August 2024 Published on, 23 September 2024

Do Solar Green Roofs Contribute to SDGs, Fostering Energy Efficiency and Environmental Conservation?

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ABSTRACT

The study investigates the energy efficiency of buildings by analyzing the collective advantages of numerous roof enhancement techniques, such as green roofs, solar gardens technologies, reflective paint coatings, and thermal insulation, in different climate regions. This emphasizes the significance of considering regional variances and meteorological factors when adopting energy-efficient building solutions, providing tailored recommendations that can be adjusted to specific geographical conditions. The research uses a rigorous technique to assess these roof improvements in four locations, uncovering substantial energy savings. For instance, when green roofs and solar technology are used together, there is an average reduction of 40%. Similarly, applying reflective paint results in an average decrease of 12.96%. On the other hand, thermal insulation provides the lowest percentage of savings, with an average of 2.65% across various locales. Based on economic analysis, reflective paint is the most cost-effective option, with reduction cost per kilowatt-hour from $0.12 to $0.17. However, green roofs and solar gardens have proven economically viable since they have considerable reduction cost per kilowatt-hour, ranging from $3.53 to $2.16. The study highlights the significance of customized strategies to optimize energy efficiency outcomes, offering essential knowledge for urban planners and policymakers. Applying these findings ensures a quantifiable decrease in energy use and establishes the foundation for sustainable and eco-friendly cities for future generations.

Index-words: *Energy-efficiency, Sustainable energy, Climate change, Building simulation, Net zero energy building, Environmental impact, Green- roof.*

Abbreviations	
BPS	Building Performance Simulation
EPBD	Energy Performance of Buildings Directive
GHG	Greenhouse Gas
NZEB	Nearly Zero Energy Buildings
RE	Renewable Energy
SDGs	Sustainable Development Goals

I. INTRODUCTION

Climate change, energy, the economy, and buildings are all intricately intertwined. The building sector is responsible for a significant portion of world energy consumption and greenhouse gas emissions. Building energy usage is expected to rise dramatically as the world's population continues to expand and urbanize. The building sector energy usage and greenhouse gas emissions contribute considerably to climate change. Energy consumption in buildings is predicted to rise as the world population grows and urbanizes. This increased energy consumption, coupled with the consequences of climate change, may result in rising energy bills and economic instability. To get around these challenges, energy-efficient building design, architecture, and operations must be prioritized. A switch to low-carbon energy sources and the corresponding decrease in greenhouse gas emissions are critical for addressing climate change and creating economic growth [1–6].

The current global energy challenges resulting from the conflict between Russia and Ukraine, as outlined in the latest edition of the International Energy Agency World Energy Outlook, are leading to significant and lasting changes that may accelerate the shift towards a more environmentally sustainable and secure energy system [7]. Moreover, the substantial increase in the global population since 1950 can be attributed to two distinct factors. Firstly, there has been a gradual increase in the average human lifespan as a consequence of significant advancements in public health, food production, personal hygiene, and medical innovations. Secondly, numerous nations have continued to experience elevated levels of fertility, contributing to population growth. Consequently, the global population has experienced a growth of almost fourfold since the mid-twentieth century, culminating in an estimated count of over eight billion individuals in the year 2022. Based on projections by the United Nations, it is anticipated that the global population might potentially reach approximately 11 billion individuals by the year 2100 [8,9]. It is projected that the global building floor area will experience a fourfold increase by the year 2060. In order to address the unprecedented growth of metropolitan areas, a strategic initiative has been devised to augment the worldwide building stock by an estimated 2.4 trillion square feet (230 billion square meters) of additional floor space per month over the course of the next four decades. This expansion is equivalent to the addition of an entire city comparable in size to New York city to the global landscape [10].

Urban regions are vital centers for economic growth and social advancement. However, the negative impacts of growing urbanization, depletion of nonrenewable resources, and pollution have resulted in severe environmental concerns worldwide [11]. As cities continue to grow in population and geographic extent, they have become the dominant impact on local, regional, and global environmental conditions[12]. According to the United Nations Department of Economic and Social Affairs, the global urban population reached 3.5 billion in 2010 and is expected to double by 2050 [13].

Recently, the globe has experienced increased urbanization, particularly in developing nations, which has resulted in a scarcity of green areas in urban neighborhoods [14]. Leading to significant environmental concerns such as the phenomenon of urban heat islands, which is seen in the increase in temperatures of capitals and cities relative to neighboring areas. Because of the increasing demand for indoor environmental comfort, this phenomenon puts pressure on the cooling load, resulting in an increase in energy consumption[15]. Moreover, by 2030, the number of megacities with populations surpassing ten million is expected to rise to 43, indicating the rapid pace of urban growth that is directly tied to economic enhancements [16].

Egypt, like many nations worldwide, is under ongoing strain from rising urbanization rates. There are essentially no green areas in the central Egyptian cities, in addition to the congestion of buildings close to each other and the short width of roadways [17,18].

A majority of impoverished Egyptians' climate-related problems can be traced to greenhouse gas (GHG) emissions. Egypt ranked 28th out of 193 countries in 2018, providing 0.67% of yearly CO_2 emissions of 329.4 million metric tons. The country energy environment is still dominated by fossil fuels, which account for 91% of its power generation [19]. Despite ongoing government attempts, a more substantial commitment to decreasing carbon emissions is required to meet the targets set out in the 2015 Paris Climate Agreement [20]. These challenges have resulted in extensive ecological problems, such as air pollution and the heat island phenomenon, which raise the energy demand for energy production, particularly in the building sector [21].

Although people are becoming more conscious of climate change, many still need to learn how it affects energy consumption in buildings. Building activities are responsible for 28% of total emissions, whereas embodied carbon from construction and building materials is responsible for 11%. This accounts for nearly 40% of CO_2 emissions from the construction and building industry and more than 33% of global energy consumption [22].

With a strong commitment to sustainability, the Egyptian Green Building Council (GBC-Egypt) promotes sustainable construction practices through the Green Pyramid Rating System (GPRS), introduced in 2011. The system aligns with Egypt's Vision 2030 and is tailored to the country unique conditions. However, challenges persist, with some buildings not earning enough points for certification and the national building code not explicitly referencing the GPRS. Recommendations include improving GPRS criteria and incorporating international standards [23–25].

Green buildings have been recognized as one of the most effective answers to contemporary issues. Green buildings, according to the International Green Building Council, are those that, by their design, construction, or operations, limit or eliminate the negative impacts on the climate and natural environment while also having the ability to bring about positive outcomes [26,27]. According to the energy performance of buildings directive (EPBD), NZEB is one of the top sustainable building methods utilized today in green building practices, and energy demands are generated on-site utilizing renewable energy [28].

Nearly Zero Energy Buildings (NZEB) are reliable alternatives for supplying energy-producing, sustainable buildings. The development strategy provides researchers with the resources to investigate the link between today's environmental challenges and the likelihood of their future evolution [29]. Concerns about the practicality of energy management measures have developed due to better awareness of global population growth and the severe environmental consequences of present resource depletion practices. The construction sector is increasingly interested in adopting strict energy-saving objectives [30].

The literature on zero energy is becoming more popular due to the NZEB definition. Most of the study articles focus on the demonstrations of various zero-energy buildings; nonetheless, there is a diverse variety of established documents. It assisted in the investigation of the NZEB's interpretation and definition. Figure 1 depicts the main concepts for NZEB: the complete energy needs of the building can be supplied by on-site energy provided by renewable energy sources. If insufficient, electricity from the local electrical grid can be used. When the energy generated by the on-site renewable energy sources exceeds the building requirements, the extra energy may be fed back into the local grid [31–34].

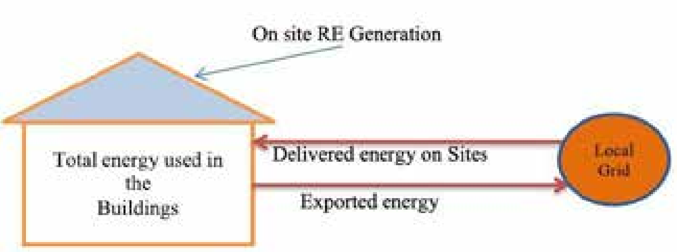


Fig. 1. NZEB's Concept [31]

Improving the thermal performance of the building envelope, which encompasses the walls, roof, and windows and serves as a partition between the inside and outside of the building, would result in a decrease in the transfer of heat to the indoor space [35,36].

The impact of building envelopes on building thermal endurance is well acknowledged. Therefore, it is essential to include measures for managing moisture and heat transmission in hot-climatic regions [37]. Moreover, the building envelope impacts energy consumption and the magnitude of loads. The decline in the insulating characteristics of the building envelope leads to an increase in energy consumption and peak loads. The thermal layer must possess sufficient heat flow resistance throughout the building structure, a goal that may be achieved by appropriately choosing the insulation material [38].

In the context of energy-efficient building practices, implementing efficient building and remodeling techniques is of the utmost significance. In order to mitigate the environmental impact of the construction sector, the revised Energy Performance of Buildings Directive (EPBD) has prompted EU member states to enact stricter regulations for thermal insulation in buildings. Thermal insulation is a very efficient approach to reducing the heating energy consumption of a building and enhancing interior thermal comfort. The optimal thickness of insulation increases in correlation with the rise in heating days. However, the impact of this phenomenon on the cooling process remains a subject of debate within academic circles. The outcome, whether it mitigates or exacerbates the occurrence of overheating, is contingent upon several criteria [39,40].

According to the literature, overheating risk in lightweight, highly insulated building shells can be reduced by adding internal mass and adequate ventilation. However, in hot-arid climates, high thermal resistance envelopes may increase the likelihood of overheating due to continuous heat transfer. The presence of a substantial insulating layer can act as a barrier against heat infiltration, posing a risk that requires attention [41–43]. However, it is necessary to assess the impact of insulation on a building comprehensively, considering both cooling and heating requirements on an annual basis. This is particularly important in countries with moderate climates since the benefits of improved heating efficiency often outweigh any potential cooling-related problems [44].

Several researchers [45–50] highlighted the importance of thermal insulation in architectural structures as an approach to reducing energy consumption and augmenting energy efficiency.

The compilation of research papers emphasizes the fundamental significance of constructing envelope design and material selection in energy-efficient construction. Al-Homoud [45] emphasizes the significant reduction in reliance on mechanical heating and cooling systems that may be achieved via these approaches. Bolatturk [46] places significant emphasis on using insulation materials, namely extruded polystyrene, to effectively enhance thermal insulation under various climatic conditions. Pargana et al. [47] underscore the ecological advantages of insulating materials, namely extruded and expanded polystyrene, in promoting the progress of sustainable building practices. Aditya et al. [48] emphasize the importance of ecological sustainability in the context of thermal insulation, specifically highlighting the need to strike a balance between insulation thickness and its associated budgetary consequences. The multi-climate research conducted by Evin and Ucar [49] provides validation for the potential energy cost savings that may be achieved by using materials such as extruded polystyrene. The study conducted by El-Sherif et al. [50] in Cairo examines the economic viability of improving insulation in pre-existing buildings, uncovering possible energy savings. In aggregate, the above mentioned papers jointly illustrates the crucial significance of insulation in sustainable and energy-efficient construction methodologies.

In aggregate, the previous studies highlighted the need to use suitable thermal insulation materials and methods to mitigate energy consumption, boost energy efficiency, and advance sustainable building methodologies. Alongside thermal insulation, another significant development in reducing building energy use is the application of solar-reflecting paint. Implementing solar-reflective coatings on the building exterior is a potential solution to the urban heat island (UHI) problem [51].

The focus shifts to an alternative approach for enhancing the roof infrastructure, specifically exploring the idea of including a green roof system. The purpose of this augmentation is not only to improve visual aesthetics but also to generate a range of environmentally beneficial results that correspond with sustainable principles.

Green roofs, a popular technique worldwide, involve planting greenery on rooftops to reduce direct and diffuse radiation, conserve energy, and prevent thermal stress and heat aging on roof membranes. They are particularly popular in Europe, North America, and Asian regions due to their environmental and economic benefits [52–54]. The addition of vegetation on the rooftops of buildings has been found to have an impact on the relative humidity. The implementation of green roof technology provides numerous advantages, including improved air quality, the formation of rooftop habitats, the mitigation of heat island effects, and a decrease in the overall energy consumption of buildings [54]. Furthermore, it enhances the thermal comfort of those residing in buildings, particularly in regions with a climate of elevated temperatures and significant sun radiation levels throughout the day [55]. The energy-saving benefits of green roof technology are directly associated with the decreased expenses incurred in maintaining the indoor environment [54].

Moreover, sustainable building practices and decreased greenhouse gas emissions may be aided by using solar photovoltaic (PV) systems and green roofs. Their joint use on the top of a building may improve its cooling and shading capabilities [56]. Vegetation and soil layers significantly impact green roof performance, enhancing evapotranspiration rates and reducing heat. This can lower the temperature of the photovoltaic surface, optimizing power generation capacity, making PV-green roofs a viable sustainable energy solution for urban environments [57–59].

To address the challenges of photovoltaic (PV) panels on green roofs, dynamic solar tracking systems can optimize panel orientation, mitigating shading, and enhancing light penetration. Additionally, incorporating an evening tilt mechanism can improve heat dissipation through enhanced convective cooling by maximizing exposure to prevailing wind. These strategies, supported by both practical applications and research [60–65], demonstrate the feasibility and effectiveness of the proposed approach in fostering sustainable and energy-efficient building designs.

Table I presents a succinct summary of the primary research papers included in the literature study. It displays the names, authors, utilized methodology, main findings, and contributions to the field for each unique work.

TABLE I
BRIEF OVERVIEW OF THE KEY RESEARCH PAPERS INCLUDED IN THE LITERTURE REVIEW.

Authors	Methodology	Key Findings	Contribution
William et al. [66]	• This study utilizes dynamic simulations to examine retrofitting techniques in an institutional building situated in three ASHRAE hot climate zones in Egypt. • The constructed baseline model is verified by the utilization of real energy consumption data. • A localized sensitivity analysis is employed to identify the primary factors that have a significant impact on energy demand. The decision-making technique employed in this study adopts a multi-approach strategy, taking into account contemporary measurements. • The evaluation of results is conducted through a comprehensive analysis that combines environmental-economic evaluation and indoor thermal comfort analysis. This methodology also incorporates the input of experts, including their weighting of factors, comments, and suggestions.	• The attainment of zero-energy buildings in developing countries continues to be a formidable obstacle. • The examination of the influence of retrofitting solutions on energy efficiency and thermal comfort is conducted using dynamic models. • Reflective paint solutions have been shown to yield substantial energy conservation benefits and enhance thermal comfort. • A decision-making strategy that incorporates many approaches takes into account both environmental-economic evaluation and interior thermal comfort.	• This study provides valuable insights into energy-efficient building strategies in developing nations, emphasizing the significance of including both technical considerations and occupants' comfort factors. • This study offers significant assistance in creating sustainable building envelopes and enhancing indoor environmental conditions through the utilization of dynamic simulations and a multi-approach decision-making technique.

Souto et al. [67]	• The ESP-r software was utilized to create a simulation of a semi-detached residential building. • Various parametric studies were conducted, exploring the effects of many factors such as TSR, the temperature setpoint, building envelope properties, climate conditions, and indoor temperature control strategies.	• The selection process was conducted with great care. The enhancement of indoor thermal temperatures is achieved by the utilization of total solar reflectance, without the need for mechanical heating or cooling systems. • Buildings equipped with heating/cooling systems can achieve energy savings of up to 32% by optimizing the Total Solar Reflectance.	• This study examines the importance of Total Solar Reflectance (TSR) in paint coatings as a means to enhance the thermal performance and energy utilization of residential buildings positioned in Mediterranean climates.
Chaowanapanit et al. [68]	Two residential structures that are identical in all aspects were assessed, with one of them being coated with high solar reflective paint and the other house being coated with conventional paint. The study focuses on quantifying energy consumption patterns in Thailand during periods of high temperature and heavy rainfall. The energy simulation was performed utilizing the EnergyPlus program.	• The application of high solar reflective paint has been found to result in a reduction of up to 8.1°C in the temperature of outdoor surfaces. • A reduction in heat gain via the building envelope has resulted in a notable drop in the cooling load, leading to energy savings of 31.24%. • The energy simulation software EnergyPlus demonstrates a savings rate of 32.69%, which is consistent with the observed outcomes.	• This study showcases the tangible advantages of utilizing high solar reflective paint in residential buildings, specifically in terms of energy conservation. By effectively reducing cooling loads, the use of this paint significantly contributes to the total reduction in energy consumption.
Yin Zhang et al. [69]	• A model for transient heat transmission in building envelopes has been developed and verified using experimental data. • This research aims to conduct an investigation of the thermal performance of building walls coated with retro-reflective material. Assessment of the possibilities for energy savings in cooling systems through the utilization of an illustrative case study involving an office building located in Chengdu.	• On average, retro-reflective coatings have been seen to reduce interior air temperatures by around 2.4°C. • The cooling load was observed to decrease by approximately 9.1 W/m^2, resulting in a reduction of power consumption by 15.2% throughout the summer season. According to the findings of the economic study, it has been determined that the investment payback period is estimated to be around 9.1 years. • The utilization of coating material is more suitable in cities located in the southern region of China with hot climates, primarily due to the relatively shorter payback periods associated with its implementation.	• This study showcases the efficacy of retro-reflective coatings in mitigating cooling loads, resulting in energy savings. • Additionally, it offers economic perspectives on the integration of these coatings into building envelope design, with a specific focus on regions characterized by hot climates.

Barozzi et al. [70]	• A one-year experimental monitoring study was conducted. • The primary objective of this study is to examine the impact of various vegetation kinds on wide green roofs on the variance of surface temperature. • This study aims to analyze the energy and environmental implications associated with alternative roofing systems in comparison to conventional flat roofs.	• Vegetative solutions that are deemed suitable have the capacity to effectively decrease exterior surface temperatures to a significant degree. • The thermal gradients of planted surface temperatures during winter exhibit minimal deviation from zero in comparison to the floor. • The summer air conditioning loads were decreased and the winter heating usage approached conservation. The temperature gradient within the growth media is controlled by both solar radiation and soil insulation.	• This study showcases the capacity of vegetative solutions implemented on green roofs to effectively mitigate exterior surface temperatures and thereby decrease energy loads in temperate regions. • This analysis emphasizes the thermal insulating properties of soil and its influence on temperature differentials.
Mahmoud et al. [54]	• The utilization of DesignBuilder software for modeling base cases and green roofs. Verification of the initial condition using empirical evidence. • The energy and economic analyses in this study are conducted using the net present value (NPV) approach, spanning a time horizon of 40 years.	• Green roofs are considered to be passive energy-saving solutions that offer a range of environmental and aesthetic advantages. • This study evaluates the energy and economic feasibility in the context of a hot and humid climate in Saudi Arabia. • Green roofs have been found to yield energy savings ranging from 24% to 35%. The economic advantages of green roofs are typically observed towards the latter stages of a building life cycle.	• This study showcases the capacity of green roofs to effectively conserve energy and presents the economic benefits they bring within a hot and humid climatic context. • This analysis focuses on delineating the timeline associated with the attainment of economic advantages stemming from the use of green roof technology.
Sattler et al. [71]	• The focus of this study is on the advancement of designs that incorporate photovoltaic (PV) systems into rooftop gardens. • This study focuses on the examination and evaluation of prototypes pertaining to structural, plant, and energy issues.	• Green roofs have been found to effectively alleviate the adverse impacts of urban heat island effects. Photovoltaic systems have a high degree of compatibility with rooftops that are devoid of any obstructions or shading. • The utilization of lightweight construction facilitates the simultaneous integration of photovoltaic systems (PVs) with green roofs.	• This study proposes a multifunctional method that integrates green roofs and solar systems as a means to mitigate the urban heat island (UHI) phenomenon, harness renewable energy, and provide recreational areas.

http://dx.doi.org/10.21622/RESD.2024.10.2.924

A. Scope, Objectives, and Novelty

This research reveals the novelty of examining the distinctive impacts of solar green roofs relative to other roof-enhancement techniques in various climatic regions within Egypt. Previous research has primarily focused on evaluating individual roof approaches in specific environments. However, this study takes a new approach by conducting a comprehensive examination of the performance of different roof enhancement techniques in various climatic zones. The present investigation sheds new light on the potential of solar green roofs to mitigate energy consumption by analyzing the unique interplay between these roofs and varying environmental conditions in four geographically distinct locations. The findings offer a distinct viewpoint on the adaptability and expandability of solar green roofs as a sustainable solution to the environmental issues posed by urban growth. The thorough evaluation of the effectiveness of solar green roofs in different locations is a significant and valuable addition to the current knowledge on sustainable urban development methods in Egypt.

Ensuring compliance with the Sustainable Development Goals (SDGs) is crucial to this research. The investigation examines the effects of roof improvements on energy efficiency and environmental preservation, directly contributing to many Sustainable Development Goals (SDGs). The analysis focuses on technologies such as green roofs and solar integration, which contribute to the achievement of SDG 7 (Affordable and Clean Energy) by advocating for energy-efficient solutions and sustainable building practices. Furthermore, there are noticeable decreases in energy usage and CO_2 discharges, which are in line with SDG 13 (Climate Action) by addressing the necessity for mitigating climate change. The study further enhances the achievement of SDG 11 (Sustainable Cities and Communities) by promoting approaches for sustainable urban development [72].

II. METHODOLOGY

As shown in Figure 2, the methodology section delineates the methodical approach employed in this investigation. The research process commenced by conducting a comprehensive literature review, employing suitable keywords and sources. Subsequently, the papers underwent a screening process to determine their congruence with the specific topic of the study, resulting in a more selective compilation. The data extraction process was conducted, and essential information was extracted from each publication chosen for analysis. The aforementioned data served as the foundation for a comprehensive analysis, wherein repeating patterns and areas of deficiency were determined. The results derived from this study encompassed the essential findings, critically assessed the existing body of information, and proposed potential avenues for future research. The technique employed in this study facilitated a thorough investigation of the research subject.

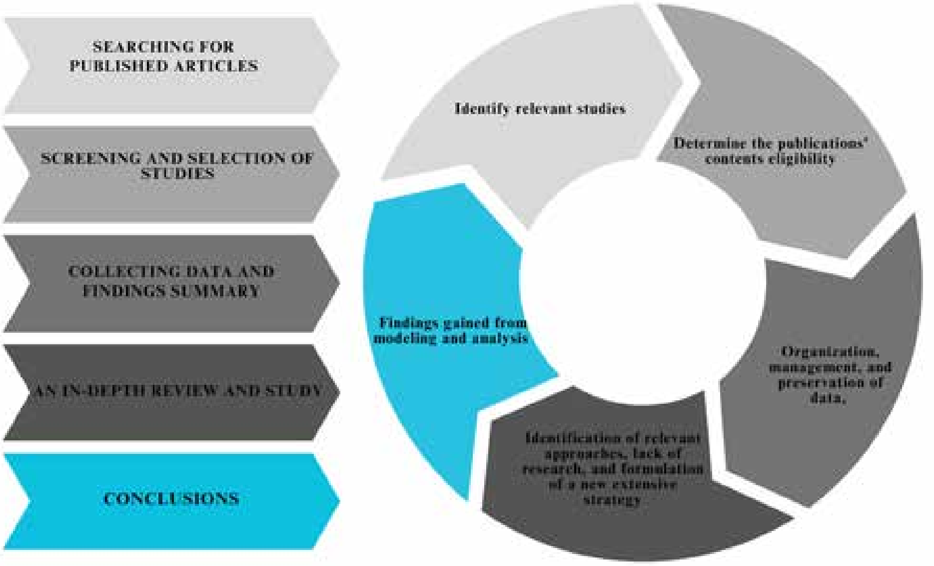


Fig. 2. Research methodology

The data derived from the review were utilized for the analysis of the potential of green and green solar roofs in mitigating the negative ecological impacts of urbanization. This study examines the effects of different roof modifications, including thermal insulation, reflective paint, green roofs, and solar green roofs, on a baseline building model at multiple sites across Egypt.

A. Model Description

The simulated model illustrates the base-case 600 building with a rectangular form and a low mass. As shown in Figure 3, it comprises a single zone with interior dimensions of 8 x 6 x 2.7 meters. The building south-facing façade has two glass windows of 3 x 2 meters each.

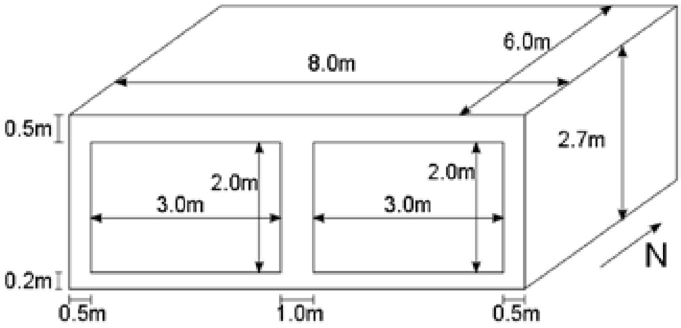


Fig. 3. Room model [73]

The building cooling and heating units are referred to as "ideal" since they are 100% efficient, without duct losses and no capacity constraints. The material and thermal properties of the wall, floor, and roof of the building are provided in Ref. [73].

The building air infiltration rate is 0.5 air changes per hour. Internal heat gains 200 watts. It is distributed as 60% radiative and 40% convective and remains steady throughout. Latent internal gains are nonexistent, meaning no moisture-induced heat transfer within the building walls exists. The heating system operates when temperatures drop below 20°C, and the cooling system turns on when temperatures rise beyond 27°C.

The simulation included four regions in Egypt: Alexandria, Cairo, Hurghada, and Asyut. These locations were chosen to replicate the various climatic zones throughout the country accurately. As depicted in Figure 4, selecting these locations was deliberate to assess the suggested roof improvements across different environmental circumstances thoroughly. The simulations were conducted using DesignBuilder software, a comprehensive tool for simulating building performance. DesignBuilder enabled comprehensive building energy modeling by incorporating energy analysis, HVAC system design, and thermal comfort evaluation functions. The user-friendly system interface has advanced features, such as dynamic thermal simulation using hourly weather data. This allows for comprehensive evaluations of the effectiveness of proposed improvements in various climate conditions.

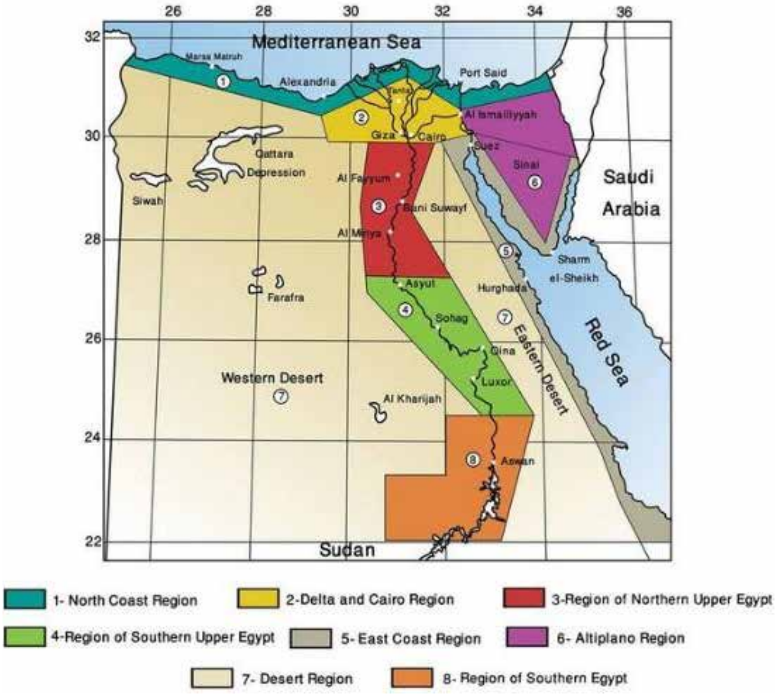


Fig. 4. Classification of climatic zones in Egypt according to HBRC [74]

Volume 10, Issue 2, December 2024 - ISSN 2356-8569
http://dx.doi.org/10.21622/RESD.2024.10.2.924

Furthermore, for the globality of the research findings, Table II provides essential climatic information for different locations in Egypt, including ASHRAE climatic zone classifications and relevant climatic design conditions such as dry-bulb temperature (DBT), wet-bulb temperature (WBT) and mean wind speed. The importance of this rests in the act of placing study findings within the specific context of climate circumstances. Geographical locations being associated with ASHRAE zones allows the prevalent climate features to be comprehended, which are essential for understanding building energy efficiency and design issue.

TABLE II
ASHARE CLIMATIC ZONES AND CLIMATIC DESIGN CONDITIONS FOR SELECTED LOCATIONS[75].

Location	ASHARE Climatic Zone	DBT (C°)	WBT (C°)	Wind Speed (m/s)
Alexandria	2A	33.9	22	4.2
Hurghada	1B	39.9	22.3	6.1
Asyut	2B	41.7	21.1	5.1
Cairo	2B	38.8	21	5.2

This study examines the effects of four distinct roof enhancement alternatives shown in Figure 5 on the building energy performance and environmental impact. These techniques were chosen after comprehensively examining the literature and gap analysis. The approaches include:

Thermal insulation: This approach entails incorporating an additional layer of 25 mm of polyurethane onto the existing roof structure. Polyurethane functions as an insulating substance, diminishing the flow of heat through the roof. This contributes to the preservation of indoor temperature, hence improving energy efficiency by diminishing the necessity for heating or cooling.

Reflecting paint: The roof is coated with a solar reflective coating. The utilization of reflective paint diminishes the quantity of solar radiation that is absorbed by the surface of the roof. Increasing the amount of sunlight that is reflected aids in reducing the temperature of the roof, which in turn decreases the amount of energy needed for cooling and enhances the overall efficiency of energy usage.

Green roof: This is the incorporation of a vegetated roofing system onto a specific part of a roof. Green roofs offer several advantages, such as enhanced insulation and a decreased urban heat island effect. The vegetation ability to reduce heat transfer aids in the building cooling process.

Solar green roof: This approach carefully combines an 8 m^2 solar panel array with a green roof system to establish a mutually beneficial relationship between the two technologies. This design achieves optimal energy generation and promotes healthier growth of the green roof vegetation by carefully balancing the covering of solar panels with the vegetative area.

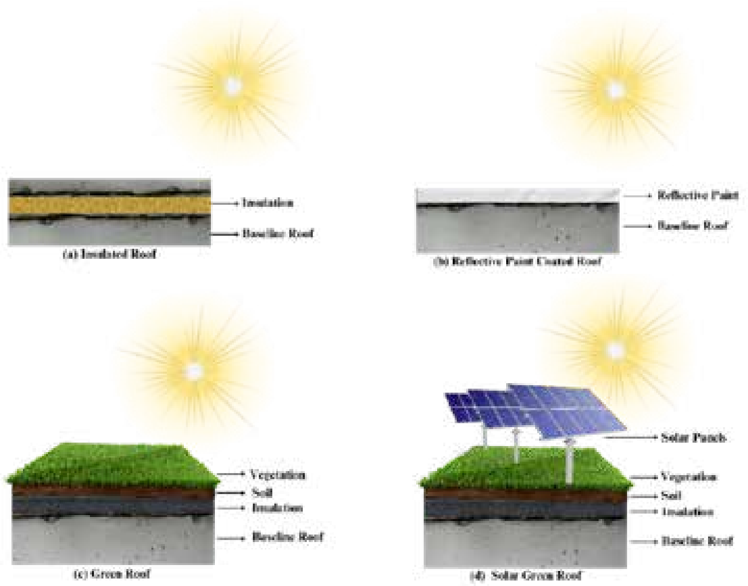


Fig.5. Schematic representations of different roof types illustrating their key components: (a) Insulated Roof; (b) Reflective Paint Coated Roof; (c) Green Roof; (d) Solar Green Roof

1. PV Panel Placement

To enhance sunlight exposure and mitigate shading effects, the 8 m^2 photovoltaic (PV) panels have been placed at the center of the roof. The placement of the panels in the central region of the roof facilitates an optimal and equitable distribution of sunlight over the course of the day. This configuration optimizes the solar panels exposure to direct sunlight, reducing the risk of shade from nearby buildings or roof elements.

The centralized location of the photovoltaic (PV) array, as shown in Figure 6, allows for sufficient sunlight to reach the surrounding green roof area, particularly at the periphery, where the panels exert less obstruction. Furthermore, this configuration facilitates efficient air circulation surrounding the panels, contributing to the maintenance of a cooler climate on the roof and enhancing overall energy efficiency.

This balanced placement is essential in regions where sunlight is intense, as it reduces the likelihood of over-shading the vegetation on the green roof, which could result in uneven plant growth and diminished efficiency of both the PV system and the green roof.

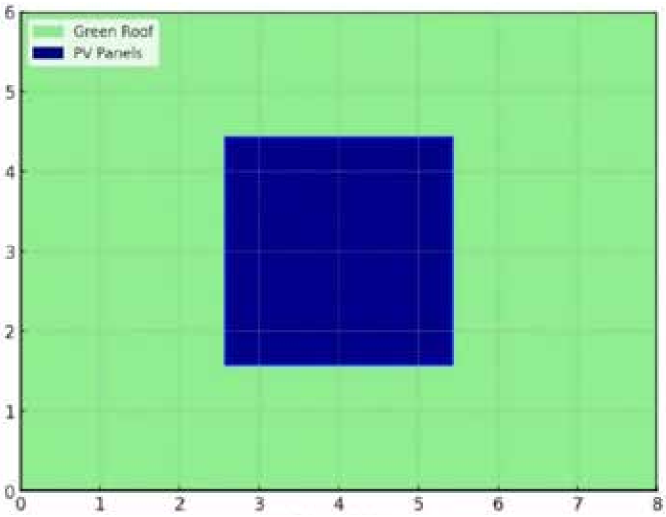


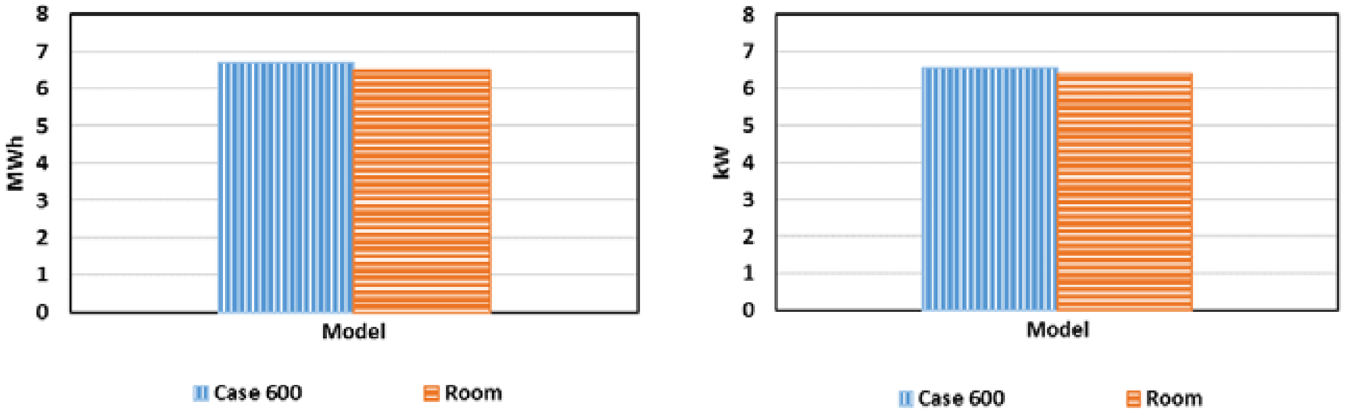
Fig. 6. Centre positioned PV

To enhance clarity, a comprehensive explanation of the green roof and photovoltaic (PV) models employed in the proposed simulations has been included. The green roof implemented the Advanced EcoRoof model, which was equipped with a moisture transport system that employs a finite difference method to divide the soil into layers and disperse moisture. This approach was based on the model described by Schaap and van Genuchten (2006). To achieve precise moisture dynamics, a continuous rate of twenty-time steps per hour was employed. The "decoupled" mode was chosen for the photovoltaic (PV) system, in which the cell temperature is determined by calculating the energy balance in relation to the optimal operating conditions (NOCT). This mode facilitated the simulation of the shadowing effects on the underlying building surfaces, namely the diminished solar gain observed on roofs equipped with a vented cavity beneath the panels. The integration of both models was meticulously implemented to encompass the interplay between the photovoltaic shading effects and the moisture and temperature performance of the green roof, guaranteeing a precise simulation of these intricate dynamics [76].

Furthermore, the potential for heat accumulation during the day in regions covered by the PV panels on the green roof is acknowledged. Nevertheless, prior studies have demonstrated that the cooling effect at night effectively alleviates this concern. The selected locations, characterized by a minimum average wind speed of 4.2 m/s, facilitate air circulation, hence facilitating the dissipation of heat from the photovoltaic (PV) panels and preventing its transfer to the green roof during the night. This strategy effectively prevents the formation of a layer of hot air. The research was conducted using a conservative approach to photovoltaic (PV) energy generation.

III. MODEL VALIDATION

The primary objective of this part is to validate the room model by employing case 600 as specified in the ANSI/ASHRAE Standard 140. Standard 140 provides an alternate methodology for documenting a thermal zone simulated yearly energy performance by utilizing several building energy simulation technologies. The dissimilarity in simulation outcomes among the tools can be attributed to variations in underlying assumptions, physical models, and implementation methodologies. Nevertheless, the range of variation in the simulation results tends to be within a reasonable threshold [77]. A simulation of the defined zone was run for a year to verify this research findings using the meteorological information included in ANSI/ASHRAE Standard 140 [77].



(a) (b)

Fig. 7. (a) Annual sensible cooling load (MWh),
(b) Peak sensible cooling loads (kW)

The evaluation of the room model validity, as demonstrated by Case 600 model, involved a comprehensive examination of its performance. As shown in Figure 7(a), The comparison between the yearly sensible cooling load of 6.712 MWh (Case 600) and the simulated value of 6.498 MWh obtained from the room model resulted in an error percentage of about 3.19%. In a comparative analysis of the peak sensible cooling load, the Case 600 model demonstrated a magnitude of 6.558 kW. However, the simulation of the room model produced a peak load of 6.4 kW, as shown in Figure 7(b). This discrepancy resulted in an error percentage of roughly 2.42%. The error percentages obtained by the model provide valuable insights into the precision of the results, indicating a strong agreement between the simulated outcomes and the values specified in the ANSI/ASHRAE standard. The validation technique emphasizes the room model dependability and precision in replicating simulated incidents, hence augmenting its appropriateness for predictive and analytical purposes.

IV. RESULTS

The building model and its specified improvements are subjected to simulation in all the locations chosen. An analysis is conducted on the energy consumption and other important factors associated with each method of enhancing roofs. In order to assess the effectiveness of the proposed methodologies in mitigating the environmental consequences of urbanization, the simulation results are compared to the baseline scenario. The simulation results are meticulously assessed and elucidated within the framework of the performance of each strategy across diverse locations. Comparative evaluations provide insight into the potential benefits associated with each method of enhancing roofs.

A. Alexandria Case Study

The findings presented in Figure 8(a) illustrate the net energy consumption (measured in kilowatt-hours) of different Alexandria models, namely the baseline model (8151.25 kWh), the insulated model (8004.93 kWh), the green roof model (6248.36 kWh), the solar garden configuration (4394.73 kWh), and the model with reflective paint (7121.9 kWh). Insulation has been shown to have minimal impact on reducing consumption, but green roof techniques have been seen to have a significant effect on reducing consumption. Additionally, the integration of solar technology into the green roof (Solar Garden) has been shown to decrease consumption significantly, while the use of reflective paint has been found to provide intermediate savings.

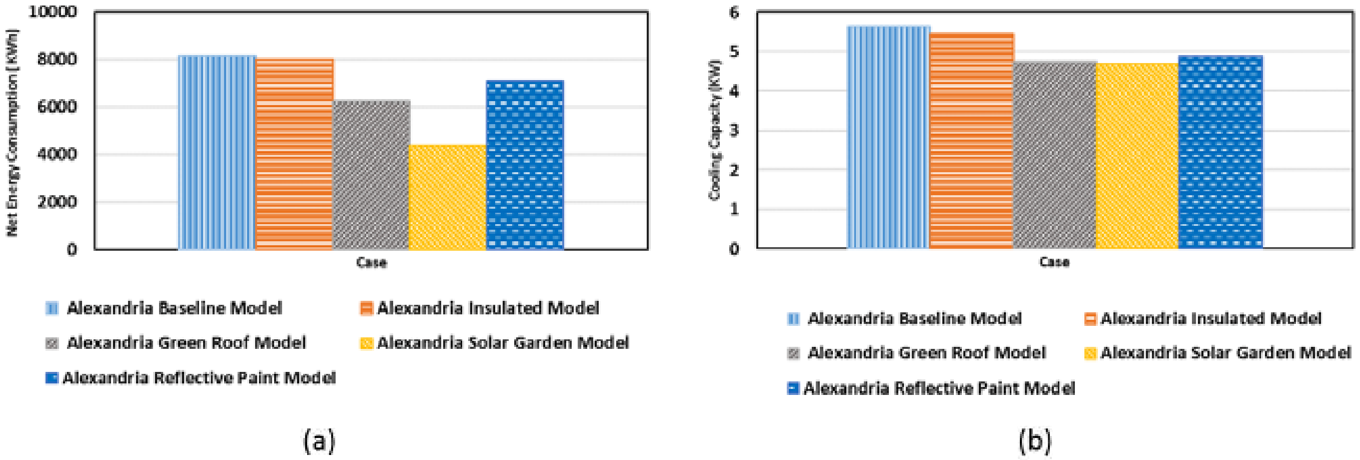


Fig. 8. (a) Net energy consumption for Alexandria models, (b) Cooling capacity for Alexandria models

The analysis also encompasses the cooling capacity findings for the different Alexandria models. The cooling design capacity, expressed in kilowatts (kW), is provided for each scenario: 5.64 kW for the Baseline Model, 5.44 kW for the Insulated Model, 4.73 kW for the Green Roof Model, 4.7 kW for the Solar Garden Model, and 4.87 kW for the Reflective Paint Model, as illustrated in Figure 8(b).

B. *Hurghada Case Study*

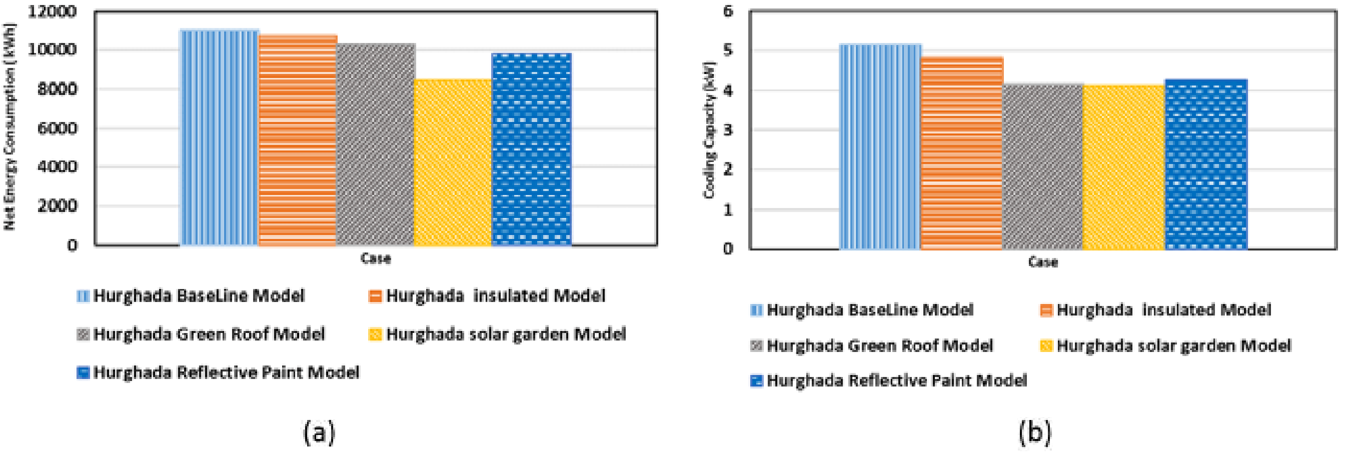


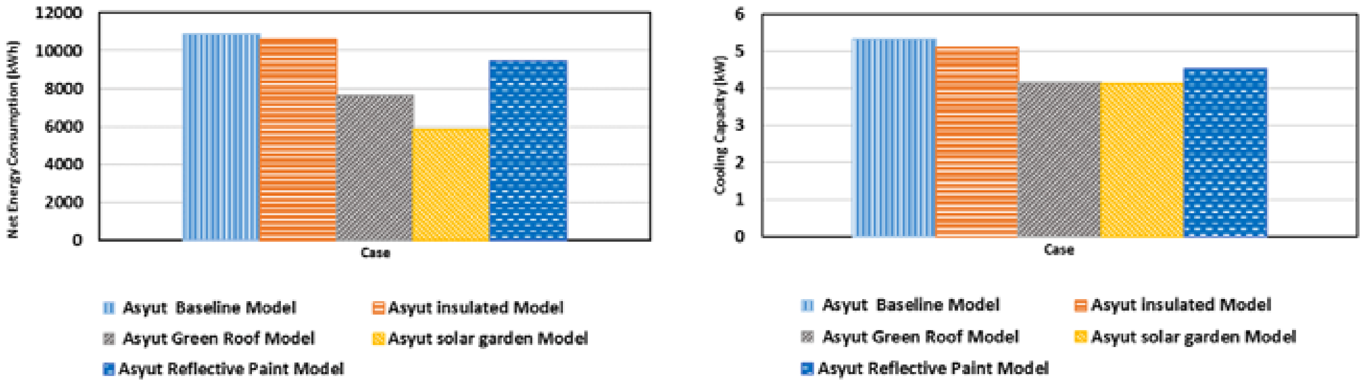
Fig. 9. (a) Net energy consumption for Hurghada models, (b) Cooling capacity for Hurghada models

Data are shown in Figure 9 (a) and (b) including energy consumption (in kWh) and cooling design capacity (in kW) values for several Hurghada models. Hurghada Baseline Model mainly utilizes the most energy, at 11008.27 kWh. The Insulated Model ranks second with usage of 10746.62 KWh, representing a 2.37% reduction over the Baseline Model. Hurghada Green Roof Model saves energy, spending 10280.87 kWh, a percentage reduction of roughly 6.55% compared to the baseline model. Hurghada Solar Garden Model impressively demonstrates considerably lower usage at 8489.09 kWh, representing a considerable percentage reduction of approximately 22.91%. Meanwhile, the Reflective Paint Model falls somewhere in the middle, with a usage of 9816.51 kWh, reflecting a 10.81% reduction.

C. *Asyut Case Study*

As shown in Figures 10(a) and 10(b) and following the examination of results from Alexandria and Hurghada, the emphasis now switches to the Asyut location data. This dataset compares the energy consumption (in kWh) and cooling design capacity (in kW) of several Asyut models. The Baseline

Model has the highest usage at 10860.94 KWh, followed by the Insulated Model at 10599.91 KWh, demonstrating a reduction of 2.40%. Additionally, the Asyut Green Roof Model saves 7655.58 KWh, representing a substantial savings of 29.57% compared to the Baseline Model. Asyut Solar Garden Model is remarkably efficient, with a consumption of 5834.93 kWh, representing a significant 46.30% reduction. On the other hand, the Reflective Paint Model records a consumption of 9446.54 KWh, which indicates a decrease in consumption of roughly 12.87%.



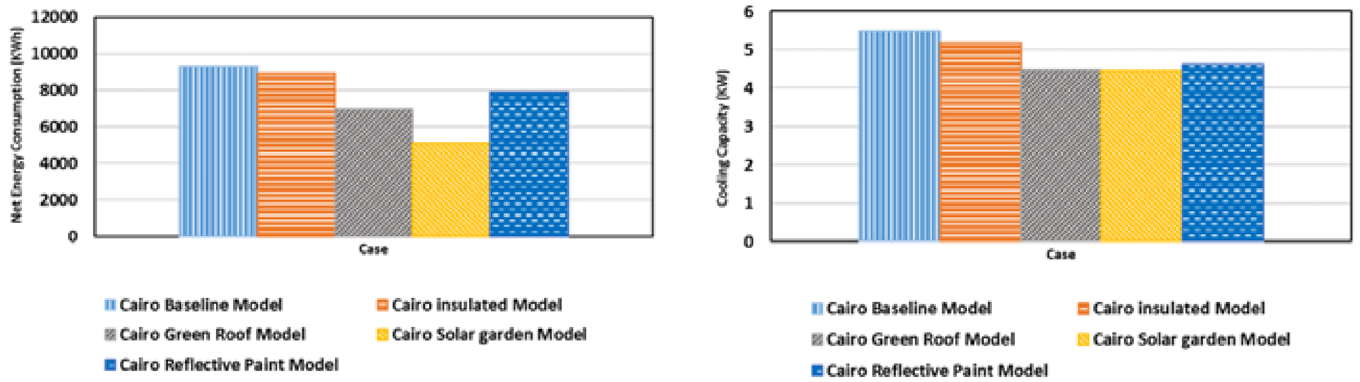
(a) (b)

Fig. 10. (a) Net energy consumption for Asyut models,
(b) Cooling capacity for Asyut models

Regarding cooling capacity, the Baseline Model holds the record with 5.32 kW, with the Insulated Model next in line at 5.1 kW. The Green Roof Model distinguishes out with a cooling capacity of 4.16 kw, a reduction of 21.80% when compared to the Baseline Model. At 4.13 kW and 4.53 kW, accordingly, the Solar Garden and Reflective Paint models have comparable cooling capacities.

D. Cairo Case Study

Similarly, to prior sites, an evaluation of net energy consumption (kWh) and cooling design capacity (kW) for several models in Cairo setting was carried out. Figure 11 (a) illustrates that the Cairo Baseline Model consumed the most net energy, at 9314.71 kWh. Cairo Insulated Model consumption was lowered to 8938.25 kWh, representing a percentage reduction of roughly 4.27%. Cairo Green Roof Model, illustrating the impact of green roof technology, demonstrated a significant energy conservation of 6956.42 kWh, representing a significant reduction of roughly 25.36%. Cairo Solar Garden Model demonstrated exceptional energy efficiency, with a consumption of 5137.39 kWh, representing a significant reduction of around 44.89%.



(a) (b)

Fig. 11. (a) Net energy consumption for Cairo models,
(b) Cooling capacity for Cairo models

In Cairo, however, the Reflective Paint Model consumed 7880.92 KWh. Concerning cooling design capacity, the Baseline Model reached 5.5 kW, while the Insulated Model achieved 5.19 kW. The Green Roof Model had a cooling capacity of 4.47 kW, whereas the Solar Garden and Reflective Paint models had cooling capabilities that were comparable at 4.45 kW and 4.62 kW, correspondingly as shown in Figure 11(b).

In order to highlight the variations, the data shown in Figure 12 show substantial disparities in energy consumption and cooling capacity caused by different design techniques in different locations. Notably, the use of insulation regularly results in modest savings in energy use. In contrast, including renewable energy sources, such as solar gardens, leads to significant energy performance benefits, with percentage reductions topping 46% across many locations.

Furthermore, unusual technologies such as green roofs result in substantial energy savings of up to 29.5%. The reflective paint technique achieves modest to significant energy savings, emphasizing its potential to improve energy efficiency. This in-depth examination highlights the delicate interplay between design decisions, regional circumstances, and strategy implementations, all of which impact energy consumption and cooling capacity outcomes.

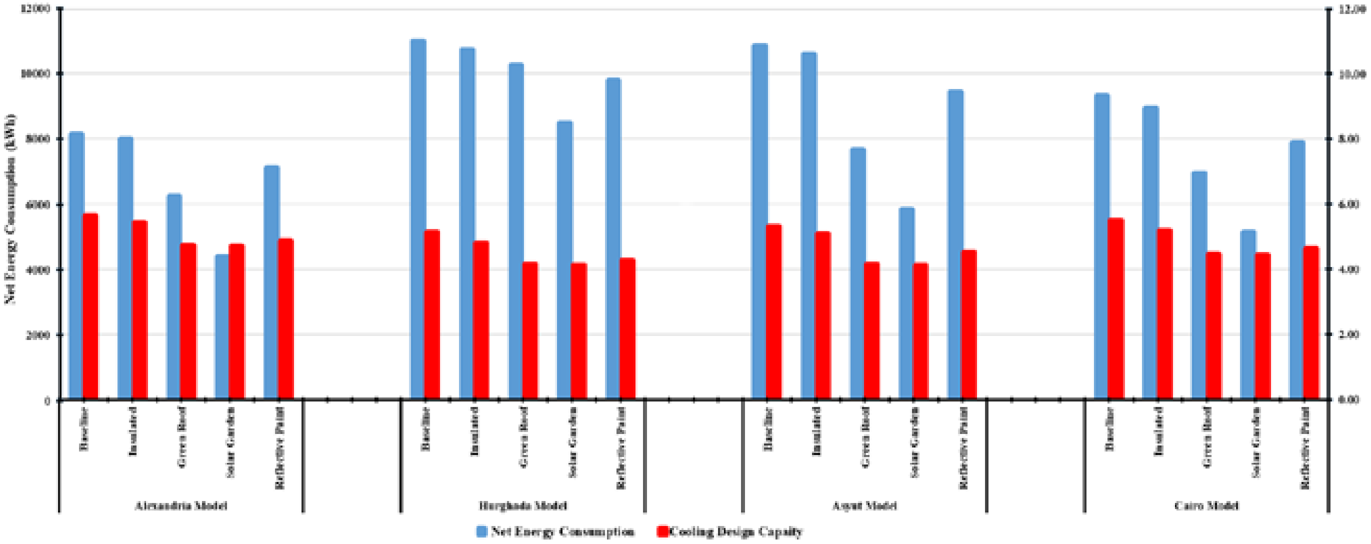


Fig. 12. Net energy consumption and cooling capacity for different locations

E. Cost Analysis

The information presented in Table III meticulously delineates the cost complexities associated with various roof improvement approaches.

The reflective paint technique stands out in Alexandria for its incredibly low reduction cost per kWh, demonstrating its cost-effectiveness in energy reduction. Green roof and solar garden approaches have low reduction cost per kWh values, with the former having more significant upfront expenditures. The insulated type also has a low reduction cost per kWh, indicating a well-balanced economic performance.

In Hurghada, the green roof approach has the highest reduction cost per kWh, owing to significant overall expenditures, but the reflective paint approach continues to show its financial usefulness. The solar garden technique has a reasonable reduction cost per kWh, but the Insulated model has a well-rounded cost per kWh reduction.

With competitive reduction cost per kWh estimates, Asyut green roof and solar garden solutions demonstrate their efficacy. The reflective paint method continuously offers benefits, whilst the Insulated Model achieves a compromise between expenses and energy conservation.

Lastly, Cairo insulated and solar garden techniques provide favorable cost per kilowatt-hour (kWh) values. The green roof technology is reasonably priced per kilowatt-hour (kWh), while the reflective paint approach remains economically advantageous.

TABLE III
COST ANALYSIS FOR DIFFERENT ROOF ENHANCEMENT TECHNIQUES IN DIFFERENT LOCATIONS.

Location	Case	Total cost ($)	Reduction Cost per each kWh ($/kWh)
Alexandria	Insulated	307.2	2.1
	Green Roof	5265.6	3
	Solar Garden	7854.6	2.09
	Reflective Paint	170.88	0.17
Hurghada	Insulated	307.2	1.17
	Green Roof	5265.6	7.24
	Solar Garden	7854.6	3.12
	Reflective Paint	170.88	0.14
Asyut	Insulated	307.2	1.18
	Green Roof	5265.6	1.64
	Solar Garden	7854.6	1.56
	Reflective Paint	170.88	0.12
Cairo	Insulated	307.2	0.82
	Green Roof	5265.6	2.23
	Solar Garden	7854.6	1.88
	Reflective Paint	170.88	0.12

V. CONCLUSIONS

This research examined the effectiveness of various roof enhancement strategies in mitigating the environmental impacts of urbanization across different climatic regions. Through a combined approach of literature review, data extraction, and simulations, the study provided insights into energy consumption and cooling capacity implications.

The study highlights the efficacy of several roof enhancement models that have been implemented across various regions of Egypt. The insulated model consistently showed reductions in the net energy usage, ranging from around 1.80% to 4.04% across Alexandria, Hurghada, Asyut, and Cairo. The Solar Garden Model also demonstrated substantial decreases, ranging from around 22.88% to 46.28% in the same regions. On the other hand, different models, like the Reflective Paint Model, showed different levels of decrease in net energy usage, ranging from around 10.83% to 15.39%. These findings demonstrate the various choices for reducing energy consumption and improving sustainability in the built environment in different climatic zones of Egypt, hence stressing the originality of our work.

Furthermore, a thorough analysis of the overall expenses and cost reductions per kilowatt-hour (kWh) for a range of roof improvement methods executed in different locations across Egypt. It provides astute observations regarding the financial aspects of these techniques. Specifically, the data illustrate that the green roof approach involves significant upfront costs around $5265.6 in different regions. Nevertheless, these investments result in substantial decreases in the price per kilowatt-hour (kWh), ranging from $1.64 to $7.18. In contrast, the reflective paint type has a comparatively low initial price of $170.88 and a low cost per kilowatt-hour reduction, averaging around $0.12. These demonstrate the complex relationship between initial investment and long-term savings associated with each improvement method. This sophisticated understanding is crucial for stakeholders navigating the field of sustainable building practices in Egypt. It helps them make educated decisions that maximize energy efficiency and financial feasibility.

Although this study offers valuable insights into ways for improving roof thermal performance, further investigation is required to tackle specific difficulties associated with heat management.

Subsequent research should concentrate on the possibility of heat accumulation beneath photovoltaic panels and the formation of a hot, air-laden layer, specifically on green roofs. This involves analyzing the interactions between solar panels and green roof vegetation, as well as evaluating the effects of various PV system designs on energy generation and thermal efficiency.

In conclusion, this research highlights the significance of implementing approaches that are appropriate to the context in order to achieve sustainable urban development. It emphasizes the critical role of tailored enhancement strategies in constructing sustainable cities. These results support the global effort to create urban environments that are more environmentally friendly and resilient by harmonizing with the Sustainable Development Goals (SDGs), including Goal 11: Sustainable Cities and Communities. By implementing these tailored strategies, the aim is to make significant advancements in creating inclusive, secure, resilient, and sustainable cities for everyone, as specified by the United Nations.

Funding

No particular grants from funding agencies in the public, private, or non-profit sectors were obtained for this research.

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