IOP Conference Series: Earth and Environmental Science

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To cite this article: Salwa El Gindi 2024 *IOP Conf. Ser.: Earth Environ. Sci.* **1283** 012012

IOP Conf. Series: Earth and Environmental Science 1283 (2024) 012012 doi:10.1088/1755-1315/1283/1/012012

Investigation of the Performance of Zero Energy Homes in Hot Climates

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Abstract. Globally, the rate at which buildings use resources and energy has been rising. Due to population growth, rise in living standard, and global warming, strategies for energy conservation have been adopted lately in zero energy buildings. Over the past decade, the energy consumption in constructions has increased at an unprecedented rate. Therefore, it is of great importance to mandate energy rationalization in building construction. This research investigates the impact of applying zero energy concept in homes in Egypt. The study begins by analysing the current situation of the energy sector and existing buildings in Egypt, the NZEB concept is defined and its different aspects are highlighted. Energy simulation by DesignBuilder simulation software is used to evaluate energy performance for a residential single family house model after applying Passive and Active design strategies. A number of energy saving strategies have been examined to optimize the building envelope with minimum energy requirements. The building energy consumption was reduced when various energy efficient strategies were combined. Besides utilizing energy efficient HVAC systems . a solar PV system is installed to meet the reduced energy. The case study was transformed into a zero-energy house. Results show that passive and active techniques can be dependable for steady energy production in buildings in hot dry regions.

1. Introduction

Recently, the incremental rates of electricity consumption, accompanied by increasing greenhouse gas emissions are deemed as major global threats. Climate change, growth of population, and prosperity rising are all contributing to an ever-increasing demand for energy and other resources from buildings worldwide [1]. Commercial and residential structures consume around 60% of the global electrical power and around 40% of global primary energy. Buildings contribute by around 33% of the greenhouse gases emissions (UNEP-SBCI). The world’s usage of thermal energy is anticipated to rise by 32.5% in 2050 [2]. In a similar vein, Egypt's electricity consumption has increased significantly (27.8 percent) over the past decade [3]. This is specifically true in the construction industry, which accounts for the majority of Egypt' usage of energy.

Globally, the building sector contributes with one third of greenhouse gas emissions and 40% of total energy consumption. In Egypt, the numbers are considerably larger, reaching 51% of total energy sold in 2014. [3] Concerning Egypt's harmful emissions, the most recent CAPMAS statistics show that CO_2 per capita reached 3.88 tons per year in 2011, up from 2.93 tons per year in 2008.[4] As a result, the construction industry has a significant opportunity to significantly reduce energy use.

By embracing the idea of net Zero Energy Buildings (NZEB), this could be attained. Therefore it is a promising alternative for conservation of the ecosystem. A ZEB is one whose annual total energy consumption is equivalent to the quantity of renewable energy produced on the site [5]. A high-performance building known as a "nearly zero energy building" (nZEB) has a rationalized energy demand that is largely met by "renewable sources generated on-site or nearby" [6]. Zero Energy Building (ZEB) concept applicability have been investigated on various building types by various researchers . To accomplish this idea, the initial step is to foster guidelines by gathering information and giving recommendations for best practices [7]. The following step is utilizing the gathered information to further develop energy codes. Numerous energy analyses have been carried out on both existing and virtual buildings to support this endeavor and provide recommendations for achieving a ZEB. To reduce energy utilization, ZEBs depend heavily on energy rationalization methods, for example utilization of natural lighting, natural ventilation, shading, evaporative cooling, thermal storage, and high-efficiency equipment. [8]

Research demonstrates that conservation of energy can decrease consumption of energy by 30–80% according to the techniques applied. Obviously, orientation of buildings, shape, envelope design, air-conditioned space percentage, and glazing play an important role in the energy demand of buildings, and its carbon footprint as well.

2. Literature review

2.1. Net Zero Energy Building

According to Hootman [9], the net-zero energy is defined as "net zero energy is a measure of a building's energy performance, whereby it produces as much or more renewable energy as it uses over the course of a year in operation". According to The National Renewable Energy Laboratory (NREL), net-zero energy building are classified to four categories, from A class where the energy is produced by renewable sources situated in the building, through D class in which renewable energy is purchased for buildings operations. [9].

Research into nearly zero energy building began around the 2000 [10] Various investigations are being pursued primarily for the purpose of determining the prospects of NZEB. An in-depth examination of contemporary buildings from an economic and environmental point of view, as well as their energy consumption, is a critical challenge [11,12]. In 1976, the principle of zero energy structures was first introduced.

The first zero-energy buildings developed at the Technical University of Denmark by Esbensen and Korsgaard [13]. Since 1977, various definitions for zero – energy buildings have been introduced in many researches [13]. Even though the concepts are different, their intended goals are to use less fossil fuels, use as much sustainable energy as possible, and use energy-saving strategies.[15,16]. described the criteria of ZEBis described as follows: (1) significant decrease in energy utilization, (2) balance in energy requirements from energy sources, (3) minimize net CO_2 emissions and (4) financial feasibility. [17,18].

In the Zero Energy Construction Action Plan on Climate Change, Korea introduced a design strategy for zero energy structures and stated that zero energy building can maximize efficiency of insulation, cut down energy consumption as well as acknowledge renewable energy sources. Moreover, zero energy building was categorized into 3 categories, the high – rise, low-rise, and town for zero energy buildings. Japan has officially adopted the "Energy-Saving Technology Strategy 2011", which aims to keep buildings' energy and emissions to zero [19]. ZEB were established as greenhouse in Germany under the guidance of German Passive House Institute [20].According to the definition of a "passive home," the building's heating needs would be reduced to 15 kWh/(m^2/y) [21].

The general idea is to build a building that uses no energy at all, balancing the energy it uses for its work with the energy it generates, either on-site or off-site, in accordance with a set of key factors like conserving energy and using energy from sustainable sources. The meaning of the particular qualities

IOP Conf. Series: Earth and Environmental Science 1283 (2024) 012012 doi:10.1088/1755-1315/1283/1/012012

depicting the zero energy structures definition, beginning from the declaration, is vigorously dependent on the chosen methodology as well as the goal.

Panagiotidou et al. Conducted an analysis of construction activities, strategies, and definitions [10] on the outcome of the ZEBs. The most important findings are as follows: Despite the fact that ZEB was a widely discussed issue all over the world, neither a concept nor a solution is still widely accepted. Each nation should define the ZEB concept locally based on actual and distinct contexts. Weather conditions, configuration of envelope , energy schemes, installation and maintenance facilities, indoor environment efficiency, the actions and activity of residence all have a significant impact on construction energy use [20]. In the current concepts, the balance between passive strategies, sustainable technology, management practices has not been well thought out. It is emphasized that ZEBs require users' active cooperation in addition to providing construction efficiency.

Therefore, ZEB are composed of two methods: reducing demand through the use of sustainable methods (passive design) and utilizing renewable energy generation in conjunction with other techniques (active design) to meet additional energy requirements. Second, the passive techniques that can diminish the ZEB's energy needs are passive as much as possible. The passive methods include shading, no-thermal bridge, air tightness, efficient lighting and ventilation. The active techniques include fresh air heat recovery technology, powerful lighting, and environmentally friendly appliances with high efficiency Critically determining the cost-optimal design of ZEBs using both passive and active techniques is essential. The technical standard specifies minimum requirements for ZEBs' compliance with the associated energy demand indicators, airtightness measures, and indoor climate standards. [22].

2.2. strategies and Design guidelines for NZEB in hot climates

NZEBs utilize ample renewable energy sources. Building design that take benefit of natural energy sources help reduce energy consumption and generate the building's own energy requirements [23]. This part of the research reviews different passive and active environment responsive systems. In warm environments, it is generally important to avoid heat gains for comfort conditions achievement while decreasing consumption of energy.

Passive design combine two main strategies, heat release and heat rejection. Solar and thermal control, as well as the concepts of thermal zoning and buffering, are among the environmentally friendly heat rejection strategies [24]. Heat rejection strategies reverse the effect of heat by cooling and incorporate passive cooling methods. While Active design techniques aim at rejecting and releasing heat through mechanical means. On site generation of electricity is what distinguishes active design from passive design, in addition to mechanical intervention. [25]

2.2.1. Passive Design Strategies:

Passive Cooling: Passive cooling is utilized in hot climates for releasing heat from buildings. Evaporative cooling of the outdoor air used for ventilation, or cooling of the structure of the building by convection and radiation are examples of this. Passive cooling incorporates ventilation as well.

Solar Control: Building envelope configuration ought to control solar radiation absorption. Sun protection and shading can reduce the amount of heat gain. The ideal selection of orientation, form, compactness and window to wall ratio (WWR) is significant. Light colored external finishes could as well diminish solar radiation absorbtion.

Thermal Zoning: Thermal comfort can be improved through the placement of the buildings' spaces with respect to the sun path and prevailing winds. It is recommended that spaces. It is suggested that spaces with transient use should be put on the side of the structure that is exposed to the sun to act as buffer zones and protect other spaces from solar radiation.

The idea of heat buffering involves as well, creation of semi-controlled outdoor areas to suppress the heat in the spaces' mass. These incorporate porches, courtyards, and earth sheltered parts. Combining natural ventilation and shading as well plays essential role in thermal zoning process.

Thermal Control: It is significant to control heat and humidity for the structure's envelop in hot climates. The utilization of thermal mass, cavity walls and thermal insulation reduce heat gains.

Active Design Strategies : Active Strategies are referred to technological and mechanical systems. Thermal and Electric energy production. (wind turbines, photovoltaic panels, etc.) are among active design strategies. Dynamic shading, air conditioning, and mechanical ventilation. The effectiveness of the appliances used to implement active strategies for NZEBs is one of the most pressing issues. This includes high-performance ceiling fans, efficient household appliances, and HVAC equipment.

3. Methodology

A two-stage approach is applied to achieve the zero-energy building concept. The initial stage includes rationalization of energy and the subsequent step includes energy generation. In the previous, the energy rationalization is achieved by applying various techniques addressing the demand side, or the supply side. Regarding the demand side, rationalization of energy can be accomplished by improving the building envelope by using improved wall construction materials, improved glazing types, using shading devices and natural ventilation. With regards to the supply side, energy consumption can be reduced by utilization of high efficiency equipment. To fullfill the energy requirements, PV panels are utilized to generate renewable energy on-site. The process followed was first analyzing the climate. Second, by choosing a standard Egyptian single-family home design as a base model. Third, the performance of the base model is examined using simulation software DesignBuilder. Fourth, various strategies are proposed to reduce the energy use, through the improvement of the construction of the wall, glazing type, using shading devices and ventilation . Subsequently, HVAC system improvements are applied. Particularly utilizing a high COP chiller system. Finally, Photovoltaic panels are utilized to cover the building energy requirements. The proposed improvements are evaluated and compared to the reference building from an energy saving perspective.

3.1. Climate analysis

The climate in Egypt is considered a hot-dry climate (BWh) according to Köppen Classification [26]. In Cairo, the weather pattern is characterized by being hot and dry. The average daily temperature during July is 35.4 ^{o}C while average annual precipitation is 11mm. Summer temperatures often rise above 39^{o} C. Average relative humidity in summer is 62%.

3.2. Base model description

The house is a single family house. It is composed of two floors. The gross floor area is 80 m^2. The building form is almost rectangular 10 m x 8m x 3m. As shown in Figures 1a,1b, 2.

Figure 1.a. Ground floor plan

Figure 1.b. First floor plan

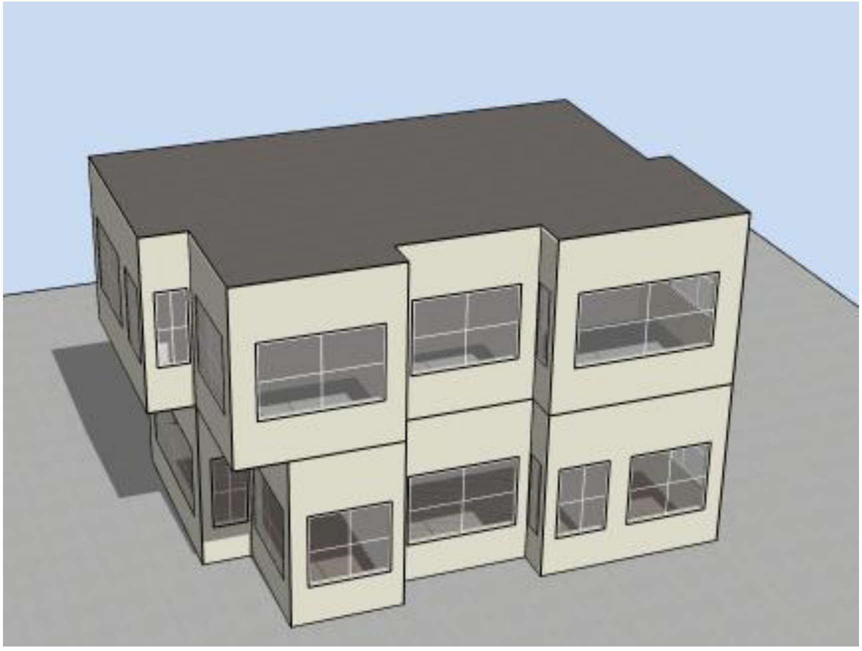

Figure 2. Base case building model.

The construction of the house is brick walls and concrete skeleton. The walls are uninsulated. The (WWR) is 35% of the total wall area. The facades are without solar protection. For space cooling, split units are used. The base-case has dimensions 10m × 8m × 3m. The description of the base case model and characteristics of the utilized construction materials are listed in Table 1. Several passive and active techniques were implemented on the base case. The implemented strategies feature the principals discussed in section 2-2. Table 2 lists the properties of the NZEB model. The properties of the implemented passive and active strategies are listed in Table 3. The base-case variations were simulated by DesignBuilder simulation software to identify the annual consumption of energy. Various iterations took place to optimize electric use.

Table 1. Base case building simulation model description.

Base model description			
Building shape		Rectangular (10 m x 8m)	
Number of floors and height		2 floors - 3 m height per floor.	
Floor area		80 m^2	
Total built up area		160 m^2	
WWR		35%	
Exterior wall		0.02m Cement plastering +0.12m outer brick work + 0.02m Cement plastering	
U value	**walls**	2.55 W/m^2K	
	Roof	0.25 W/m^2K	
	Floors	1.59 W/m^2K	
	Glazing	5.8 W/m^2K	
Single clear glass		Tv = 0.88	
SHGC		0.75	
Total consumption		Average annual energy use	115 KWh/m^2

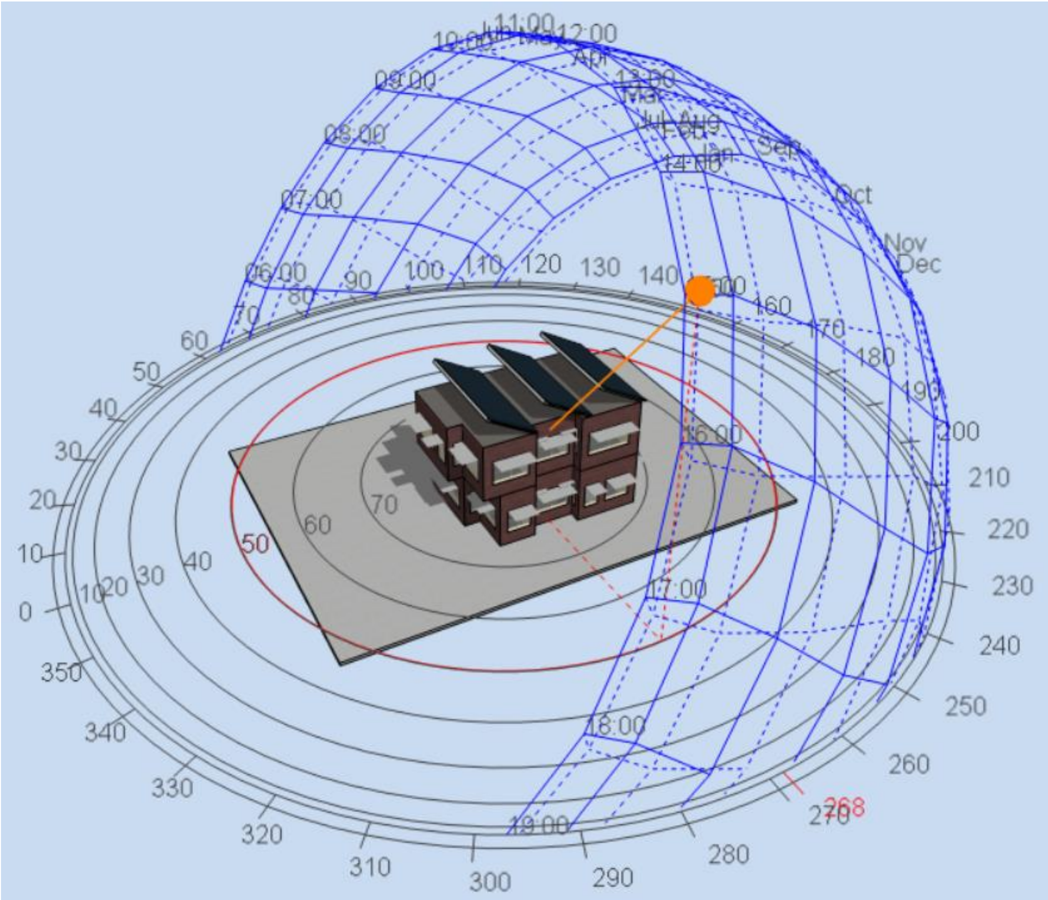

Figure 3. Simulated building model using Design-Builder

Table 2. NZEB building simulation model description.

NZEB model description			
WWR		35%	
Exterior wall		0.02 m Cement plastering +0.05m XPS Extruded polystyrene +0.12 m outer brick work + 0.05 m air gap +0.12 m inner brick work + 0.02 m Cement plastering	
U value	**Exterior wall**	0.5 W/m^2K	
	Roof	0.25 W/m^2K	
	Floor	0.77 W/m^2K	
Glazing		Triple LoE (e2=e5=1) Clr 3mm/13mm Arg.	
Glazing U-value		0.993 W/m^2K	
SHGC		0.468	
Overhangs projection		1 m	
Lighting			
Installation power density (W/M^2		living room	17
		bedroom	13
		other	9
Visible transmittance (VLT)			0.35
Ventilation and AC		COP/EER	3.00/6.8
		Outside air (m^3/h per person)	20

	Temperature set point (^{O}C)	24
	RH set point (%)	60
Plug loads	Average installation power density (W/m^2)	6
DHW	October to April (1/m^2/day)	
	May to September (1/m^2/day)	
Total consumption	Average annual energy use	60 KWh/m^2

3.3. Parametric analysis

Several strategies were implemented on the base case. The original properties are maintained, while the performance of every alteration is evaluated using Design-Builder energy simulation software. Then improvement of the base case through active design strategies were implemented and evaluated as wel l. Regarding the photovoltaic system size, the utmost available surface area of the roof was utilized. The monthly and annual consumption were evaluated.

Table 3. Implemented Passive and Active design strategies.

Passive strategies	Shading	Horizontal overhangs 1m and internal blinds.
	Glazing	Triple LoE (e2=e5=1) Clr 3mm/13mm Arg, U value = 0.993 W/m2K - SHGC = 0.468- VLT=0.661
	Insulation	0.05 XPS Extruded polystyrene - Wall U value = 0.5 W/m2K
	Thermal mass	Light medium heavy wall
	Natural ventilation	20 ACH
Active strategies	Efficient lighting	0.05 KW
	HVAC efficiency	3 COP
	Photovoltaic system	Monocrystalline PV (Area = 65 m^2, tilt angle= 30^0, oriented towards south)

4. Results and discussion:

Several strategies were applied including Shading, changing the glazing type, insulation, ventilation and using efficient HVAC system.

4.1. Energy Simulation Analysis of the base case.

The outcomes reveal that the annual electricity consumption of the base case is 12,132 KWh. About 62 % of the annual energy use is by HVAC which is 7168.35 kWh, 16% by lighting ,1807.34 KWh, and 22% by miscellaneous equipment, 2595.62KWh as shown in Figure 4. The electricity consumption varies monthly, but the maximum consumption occurs in August as shown in figure 5.

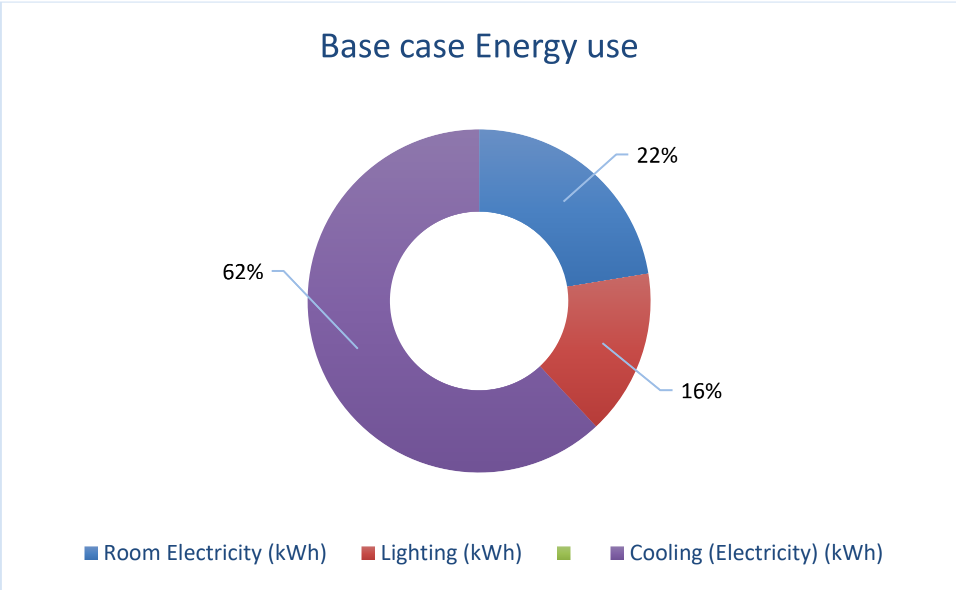

Figure 4. Base case Energy use.

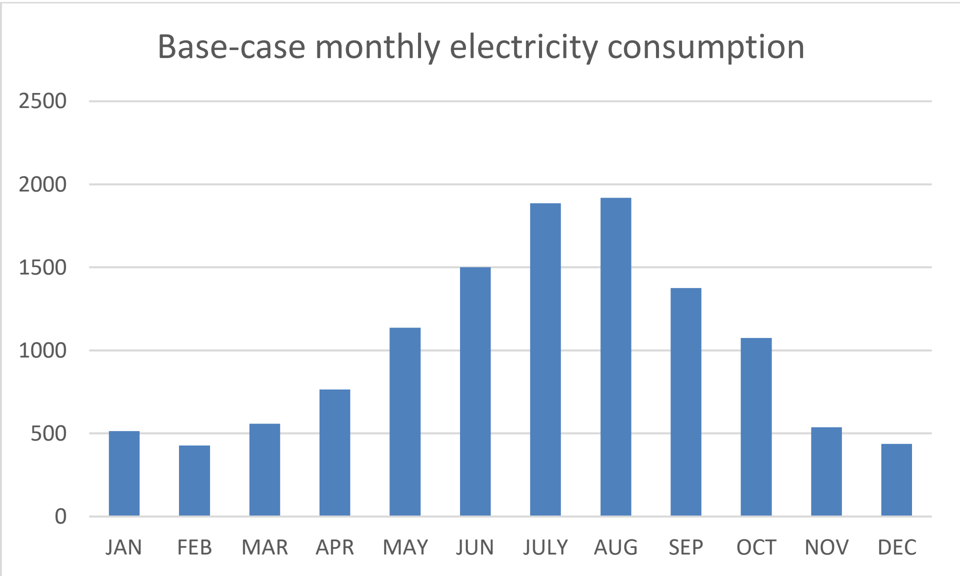

Figure 5. Base case monthly electric consumption.

4.2. Energy simulation analysis of the NZEB.

By comparing the base case with the NZEB, a significant decrease in energy consumption was observed as shown in figure 6. The annual electricity consumption was reduced from 12132.51 kWh/ year to 5348.17 kWh / year. The high efficient building envelope makes the building consume 56 % less electricity than the base case , which is about 6784.3 kWh less per year than the base case electricity consumption.

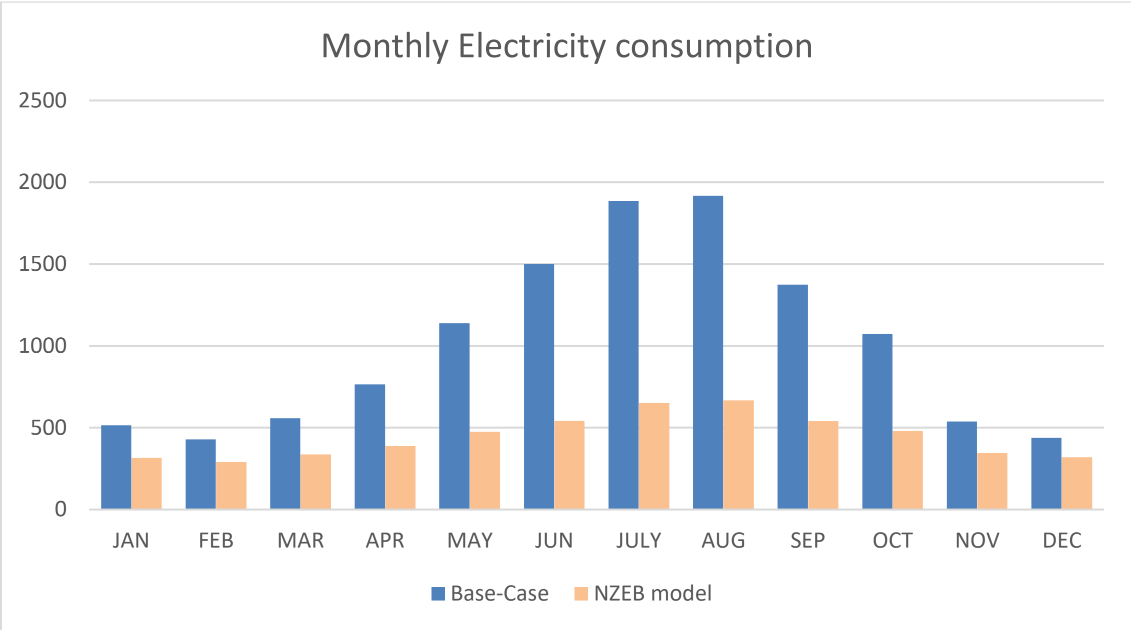

Figure 6. Monthly electric consumption comparison.

To determine the most efficient strategies, the original properties are maintained, while the performance of each strategy is evaluated. Figure 7 shows Monthly electricity consumption of NZEB strategies. It is clear that the most efficient strategies in Summer are improving HVAC system efficiency followed by shading and improving glazing. While in winter, the most efficient strategy is thermal insulation. The annual electric consumption after applying each design strategies was evaluated and the percentage of reduction for each strategy was calculated as shown in figure 8.

The most impactful strategies installing efficient HVAC system, shading, efficient glazing, and insulation.

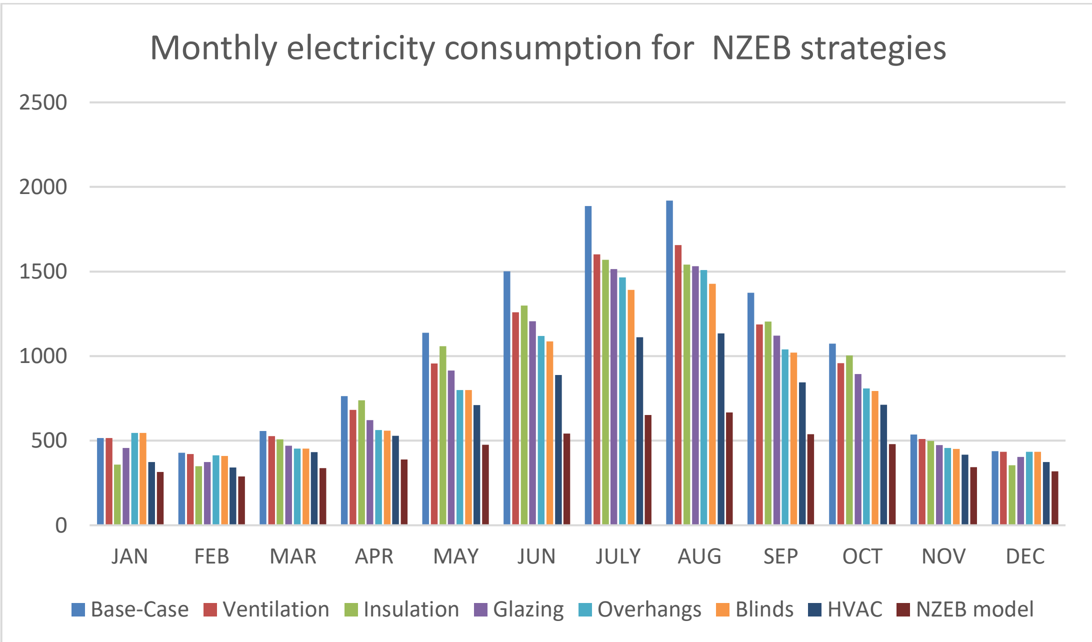

Figure 7. Monthly electricity consumption of NZEB strategies.

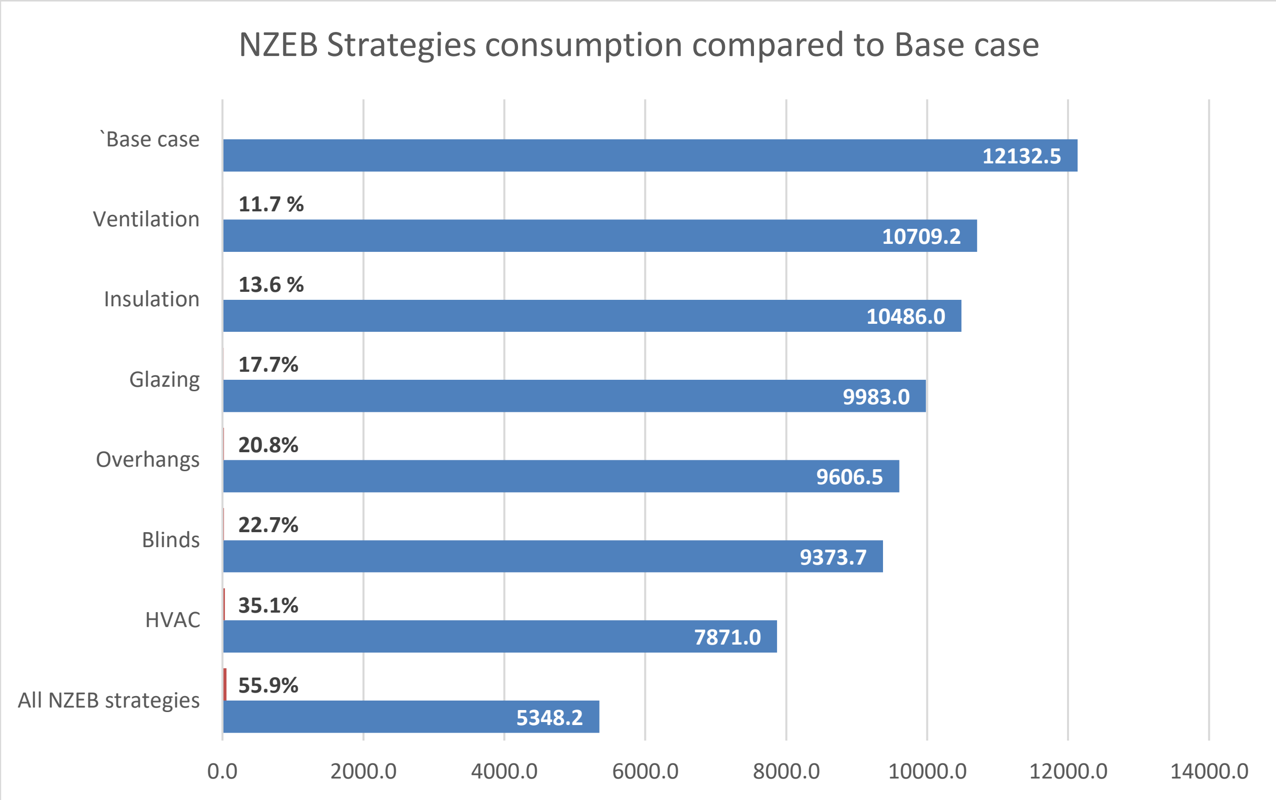

Figure 8. Annual electricity consumption of NZEB strategies.

4.3. Photovoltaics System.
various factors can impact the output of the photovoltaic system. The most influential factors are the type of PV, the tilt angle and area of PV. The area of PV panels which are mounted on the roof is 65 m^2 with a 30^0 tilt which is the optimum angle for Egypt according to previous studies. The panels are oriented towards the south to give maximum production.
The PV system produce up to 17,093 kWh annually, and the house utilizes about 5348.17 kWh of electricity annually. Thus, implementing PV system fullfilled the electric demand, generating almost triple the building consumption (319%).

Figure 9 shows the monthly PV generation and energy consumption of the base case. There is a relative monthly match except for July and August months due to the high electricity consumption. Figure 10 indicates a relative monthly match between PV electricity generation patterns and electricity consumption patterns of the NZEB for all months of the year.

Finally, by combining passive and active strategies, the building energy requirements was met, exceeding the NZEB goal.

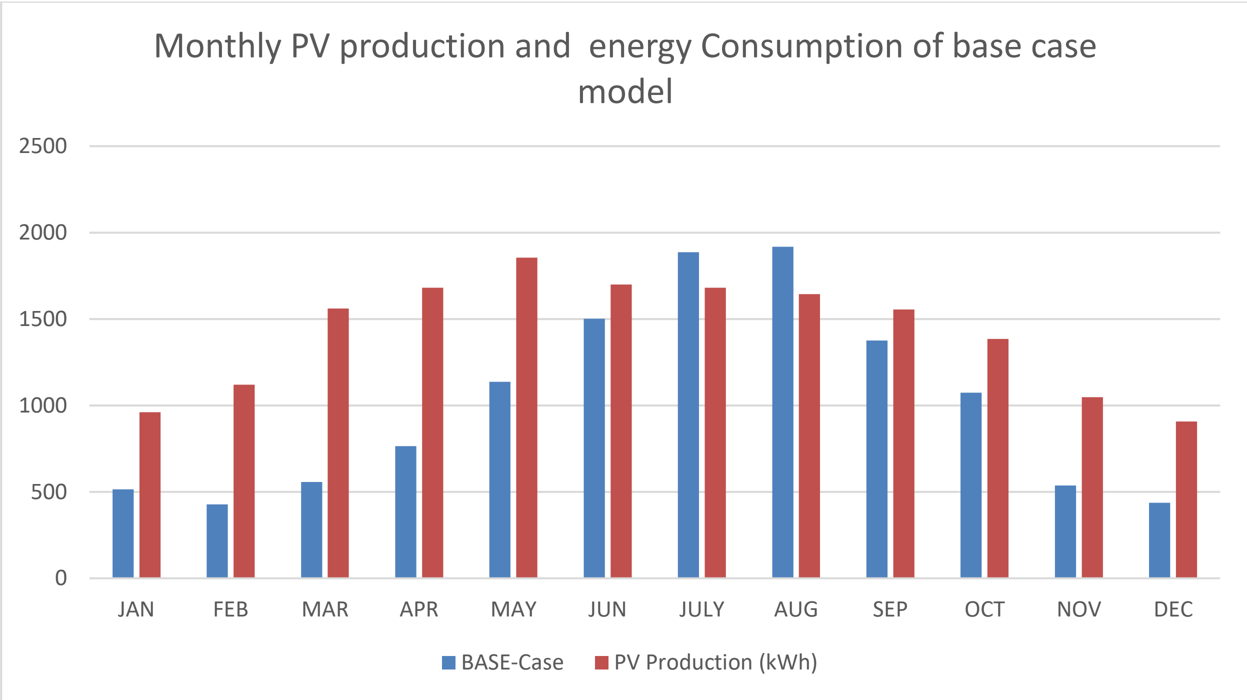

Figure 9. Monthly PV production and energy consumption of the base case model.

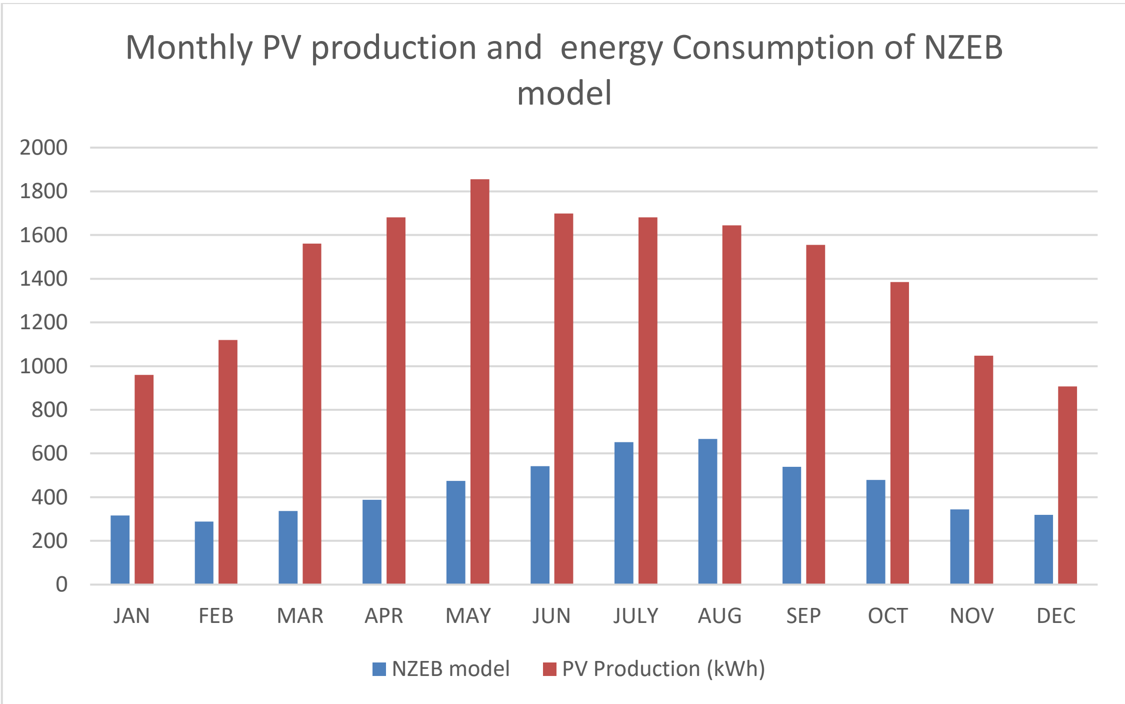

Figure 10. monthly PV production and energy consumption of NZEB model.

5. Conclusion:

Net-zero energy buildings concept is promising due to its environmental benefits. This research aimed to investigate their performance and to highlight their efficacy to solve the problem of increased energy use in single family homes in hot dry climates.

These energy saving strategies were applied to the base model and examined using DesignBuilder energy simulation software. The method utilized to investigate the thermal performance was conducting a parametric analysis using energy simulation. The performance of different alterations is evaluated using energy simulation. Then improvement of the base case through actives design strategies were implemented and evaluated as well. The monthly and annual energy consumption was quantified.

The simulation results indicated that a building with an efficient envelope had around 56% less electricity consumption than the base case.

The photovoltaic panels generate up to 17,093 kWh annually, and the house consumes 5348.17 kWh of electricity annually. Thus, implementing PV system fulfilled the electric demand, generating almost triple the building consumption (319%)

The case study was transformed into a zero-energy house with an annual energy use intensity EUI of 60 kWh/m^2. Therefore, transforming the house to a net-zero energy structure became viable by photovoltaics panels installation on an area of 65m^2. Moreover , the simulation results revealed that the shading was the most effective strategy.

The most essential strategies are installing of shading, efficient glazing, and insulation. Thermal mass was not effective. Regarding active strategies, the installation of an efficient HVAC system is an effective strategy.

The passive strategies are fundamental for performance optimization; however active systems will be required for achieving the NZEB. Implementation of passive strategies during early design stages is essential for having a successful NZEB. Passive strategies are deemed to be the initial step in NZEB design. Several passive design principals have proven to be beneficial.

The methodology introduced in this research to achieve NZEBs in hot dry climates can be implemented in different climates. However, the outcomes are specific to hot dry climate.

A greater variety of envelope configurations and materials are among the aspects not covered in this paper that may be useful for subsequent research. According to the house's proposed design in Egypt, this study demonstrated that the achievement of the net-zero energy target can be quite easy by improving the building envelope and HVAC system in hot, dry regions. This proposed model represents a prototype that could be adapted for various hot dry regions.

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