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Compliance with Building Energy Code for the Residential Sector in Egyptian Hot-Arid Climate: Potential Impact, Difficulties, and Further Improvements

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Abstract: Building energy codes are considered to be an effective policy tool for energy reduction worldwide. However, their application and effectiveness are still limited in developing countries. In Egypt, the residential sector is promising for energy savings, as most of the existing residential buildings are aged with low thermal performance and non-conformance with energy codes. This study aims to raise the awareness of promoting the Egyptian residential energy codes among construction parties, especially end-users, by quantifying the environmental impacts, in terms of energy savings and thermal comfort enhancement. Moreover, it attempts achieving a nearly zero energy building by integrating several energy-efficient measures with renewable energy sources. Thus, in this study, a typical residential building in Cairo was chosen for simulation. The simulation results revealed that applying energy code instructions for building envelope, lighting enhancement and increases in cooling set-points, from 24 °C to 25 °C, saved 37.85% of annual electrical energy and resulted in a cooling reduction of 50.53%. Furthermore, the photovoltaic system incorporation succeeded in transforming the building into a nearly zero energy building. Concerning thermal comfort, the application of passive energy-efficient measures significantly influences indoor thermal comfort, with a 30% reduction in discomfort hours during the cooling season, which represents the main concern in hot climate regions.

Keywords: residential buildings; energy efficiency; thermal comfort; building energy codes; energy efficient measures; nZEB; hot-arid climate; building envelope

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1. Introduction

Boosting building renovation rates, as well as enhancing the thermal energy performance of the current stock, is receiving noticeable political attention worldwide, due to the increasingly great effect buildings have in outlining the environment and society that everyone works and lives in. Besides the main role that buildings play in energy usage and emissions of greenhouse gases (GHG), many countries assist in the concept of evolution towards more sustainable and low-carbon societies [1]. In the European Union (EU), buildings contribute around 40% to the final energy consumption and are responsible for 36% of the greenhouse gas (GHG) emissions, which have made buildings one of the most relevant and strategic issues debated in recent years [2,3]. Most European cities have had urban renovation problems, since around 35% of EU buildings exceed 50 years of age, almost 75% of the built stock is energy inefficient, and an average of 0.4–1.2% yearly replacement rate is clearly insufficient, and even virtually absent in some regions [3,4]. In particular, by following the energy performance rating schemes, only around 10% of the existing residential building stock has an A or B rating, since almost two-thirds of the residential buildings were built before 1979, which precedes the adoption of EU energy policies in the building sector [1]. In addition, the COVID-19 pandemic highlighted the building's importance and fragilities. Thus, the European community ambitiously seeks to overcome this crisis, through the help of buildings' sustainable renovation policies and strategies that require fostering the renovation rate in the following decades [3]. Moreover, the EU directives and country-specific guidelines are becoming more stringent to reduce energy consumed by buildings. European building policies, such as that of Energy Performance of Building Directive (EPBD Directive 2002/91/EC) and EPBD recast have stated that the implementation of nearly zero energy buildings, from 2018 onwards. A nearly zero energy building (nZEB) can be described as a high-energy performance building, in which the nearly zero or very low amount of energy required should be covered, to a very significant extent, by energy from renewable sources produced on-site or nearby [5]. The application of the nZEB concept is one of the main pillars to obtain energy efficiency and sustainability in the building sector, and it has been addressed in several researches. The research findings have demonstrated that the nZEB target can be achieved using appropriate technologies and best practices; high efficient solutions minimize the energy needs, while renewable energy sources (PV, solar thermal, wind power, and heat pumps) supply the remaining demand, to a large extend [6–11]. Most NZEBs implemented technologies are passive (sunshade, natural ventilation, lighting, thermal mass, and night cooling) and active (mechanical ventilation with heat recovery, heat pumps or district heating), in combination with efficient lighting and appliance. For renewables, PV and solar thermal are commonly implemented.

Similar to the EU, the Middle East and North Africa (MENA) regions are characterized by their old and poor building quality in many countries. In addition, the MENA region is facing rapid population growth and rising urbanization, accompanying economic growth, which increases the demand for building space, comfort, and services and raises the demand for residential energy in a non-efficient way [12]. Egypt, as one of the MENA region countries, is moving, along with the world's interest, in improving the energy efficiency of buildings. Energy conservation is witnessing interest from the public, designer, and decision-maker levels, due to the increasing burden of energy consumption in the building sector, specifically residential buildings [13]. Moreover, residential buildings constitute a large proportion of the Egyptian building stock, about 83.2% of the existing buildings, compromising of 13,467,333 million units that, out of 16,185,063 million buildings, are residential buildings. Thus, the residential sector is the major consumer for energy, compared to other sectors, representing about 42.4% of the total electricity consumption, as a result of several factors, the most relevant being the excess use of air conditioning in the cooling season [14,15], and it is anticipated that the energy needed will continue to increase in the coming years, with the rapid urban development and growth of the population, which exceeded 100 million in 2021 [16].

Building informality, in terms of the contravention of building laws and regulations, as well as buildings low thermal efficiency, are the main challenges facing the existing residential buildings. The majority were built more than half a century ago, exceeding 67% of the total existing residential building stock [14]. Furthermore, it has been estimated that more than 70% of the existing building stock is built informal, due to several reasons, for example, the lack of strict code control and enforcement, and the complication of construction permit approval process [17,18]. In the same context, the traditional passive design strategies for buildings were abandoned, which negatively affected the indoor thermal comfort and led to an excessive energy consumption in buildings [19,20]. Besides, climate change, energy subsidies, and the lack of knowledge and awareness needed for promoting energy efficiency measures in buildings led to a wasteful increase in the rates of energy consumption, especially in the summer season [21,22]. Furthermore, despite increasingly stringent building energy regulations worldwide, non-compliance and a lack of knowledge exist, in practice, in both developed and developing countries [23], where energy standards for buildings in developing countries are often ineffective or less effective than expected [24]. In Egypt, the Housing and Building National Research Center (HBRC), affiliated with the Minister of Housing, Utilities, and Urban Communities (MHUC), which is the sole entity nationwide responsible for issuing the Egyptian codes, published the residential building energy standard for Egypt in 2006. Nevertheless, buildings energy codes are far from being applied into the Egyptian construction industry, as a consequence of the absence of awareness, concerning the issue of energy efficiency, by the construction stakeholders, as well as the lack of enforcement and legislative support [25]. Thus, informality and non-compliance with building laws do exist in Egypt [18].

Even though the residential sector is very promising for energy savings, at the moment, based on the abovementioned facts, it is undeniable that the application of energy codes for building retrofitting is hindered, due to the lack of knowledge of the construction practitioners and buildings' occupants, discarding the beneficial gains, in terms of energy savings associated with the level of comfort enhancement that will be achieved. Thus, it is essential to resolve these issues by filling the gaps in research, in order to avoid more deterioration and, consequently, take immediate action in boosting the Egyptian existing residential efficiency. Therefore, this work aims to investigate and quantify the potential energy savings and extent of its impact on the residential building's indoor thermal comfort, in order to originally provide a basis for the future development of technical and economic guidelines that are essential for helping the Egyptian government in raising awareness of promoting the Egyptian building residential energy code (EREC) among end-users and practitioners. This will be achieved by applying the minimum building energy requirements, stated by the EREC, on a representative residential building in Egypt. Moreover, the representative building will be subjected to an incorporation of onsite produced renewable energy, in order to achieve nZEB.

This study is organised in sections, where Section 2 presents the methodology used for selecting the typical residential building for the case study and a review of the simulation tool and the proposed simulation scenarios, while Section 2.2 defines the building's comfort model selection and evaluation methods used. In Section 3.1, the chosen building energy model is described and calibrated, followed by Section 3.2, which contains verification to the building envelope compatibility with the EREC requirements [26]. Section 3.3 presents the energy efficient measures that are going to be used throughout this study. Furthermore, in Section 3.4, the energy saving simulation scenarios are defined and described. Section 4 presents the results and discussion of the simulated energy saving scenarios and thermal comfort assessment. Finally, the conclusions and recommendations are presented in Section 5.

2. Methodology

2.1. Case Study Selection and Simulation Scenarios

In this study, the case study selection was aimed to represent the most common type of housing in Egypt. Reinforced concrete (RC) skeleton structures, as well as load-bearing structures, were the most commonly used structural construction systems in Egypt, comprising of more than 78% of the total existing residential buildings, based on the Egyptian Ministry of Housing, Utilities, and Urban Communities geographic information systems (GIS) database [14]. In the same context, it was found that around 80% of the existing residential buildings in Cairo are constructed from a concrete skeleton, which comprises of a network of columns and connecting beams that forms the structural "skeleton" of the building with brick infill and reinforced concrete flat roof [27]. Based on the census, the air-conditioned residential apartments are classified, according to their gross area, into classes, from A to D, where the majority of the apartments lie in class B, with a gross area ranging between 110 and 130 m^2. Thus, a typical air-conditioned residential building was selected as a case study, based on a previous study on benchmarks of Egyptian residential buildings [19].

Egypt is a large country, with an area of approximately 1,000,000 km^2, located between 22° N–31°37′ N latitude and 24°57′ E–35°45′ E longitude. Egypt possesses a diversity of climate conditions, ranging from extremely hot conditions in the desert regions, such as the

Western Desert, to cold conditions in Mountain St. Catherine in the Sinai Peninsula [28]. The Egypt climate classification was developed by the HBRC, the classification divided Egypt into eight climatic zones, i.e., the northern coast, delta and Cairo, northern upper Egypt, southern upper Egypt, east coast, highlands, desert, and southern Egypt zones, as shown in Figure 1 [26].

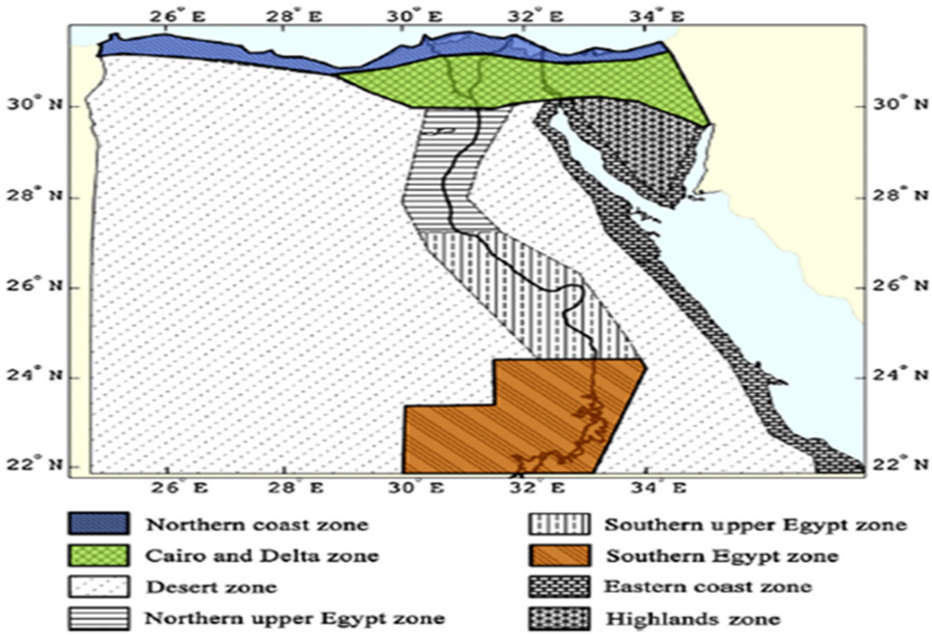

Figure 1. Egypt's climatic zones classification map, according to EREC [13].

Egypt has a significant variation, regarding climate conditions, and the building prototype was simulated in the Cairo and delta zones, which are considered semi-arid climate zones, as defined by the EREC (Cairo governorate: 30.13° N and 31.0° E). The monthly average highest temperature in Cairo ranges from 19.2 in January to 38.1 °C in August (the warmest); on the other hand, the monthly average lowest temperature ranges from 11.0 °C in January (the coldest) to 26.9 °C in July. The highest average relative humidity is 58%, which occurs in November, while the lowest is 44%, which is recorded in May [16]. Moreover, Cairo heating degree days (HDD) and cooling degree days (CDD), HDD 10 and CDD 18 °C, averaged over 2016–2020, are equivalent to 5 HDD and 2327 CDD [29]. In this study, dynamic simulations for the building prototype were carried out using DesignBuilder energy modeling software, version 6.1 (DesignBuilder Software Ltd., Stroud, UK). DesignBuilder is an EnergyPlus-based (National Renewable Energy Laboratory (NREL), Golden, CO, USA) software tool, widely used for building design evaluation and performance comparison of the design alternatives [30]. The accuracy of DesignBuilder has been validated by the BESTEST (building energy simulation test) method, which is regarded by the American Department of Energy and wider international community of building modelers as a basis for verifying the capabilities of computer simulation programs [31].

The simulation scenarios included the application of energy-efficient measures (EEMs) to the building case study. Individual and integrated simulations scenarios were performed, where individual simulation scenarios were conducted by changing the value of one parameter at a time; then again, all the recommended EEMs were performed in an integrated simulation scenario to deliver an enhanced building energy model. Furthermore, an incorporation of renewable energy techniques, to the enhanced building model, were performed to balance the energy demand, in order to achieve an nZEB.

2.2. Comfort Model Selection

Indoor environmental quality depends on several aspects, where thermal comfort is the primary concern of those aspects, as it greatly affects the comfort, health, productivity, and overall sense of well-being of occupants since the time spent by the majority indoors is 90% of their total time [26]. In this study, a mixed-mode (MM) building condition was selected for the representative residential model, since residential buildings are often in steady-state conditions, as a result of several factors, the most important of which is the occupants' complete control of the building systems [32]. MM condition refers to a hybrid ventilation approach that integrates natural and mechanical ventilation for space conditioning, in order to provide indoor-acceptable thermal comfort. The conditioning of space in MM building is achieved by combining natural ventilation through the operable windows and/or passive inlet vents, controlled either automatically or manually, as well as the switch to air conditioning mode, whenever natural ventilation is insufficient, to meet indoor thermal comfort, while minimizing the energy consumption and air conditioning operational costs [33]. The MM buildings comfort models suffer from the lack of attention in current standards, however, various studies consider that MM buildings act more like buildings that are naturally ventilated, rather than the fully air-conditioned buildings, in terms of their operation [32–35]. These studies were a good base for building the comfort model in this research.

The comfort range analysis in this study will be evaluated using two different methods; (1) using the adaptive model of ASHRAE 55, as was agreed by the above-mentioned studies, and (2) using the EREC recommended thermal comfort limits, ranging between 21.8 to 30 °C, when humidity levels range between 20% and 50% and inside wind speed is from 0.5 to 1.5 m/s [26,36]. The two methods are used to assess the impact of applying the EREC requirements on the reduction of discomfort hours between the simulated reference building base-case scenario and the building retrofit scenario (the enhanced building model).

The adaptive comfort model by ASHRAE 55-2017 is appropriate for hot climatic conditions and outdoor temperature, ranging between 10 to 33 °C [37]. This model represents a relation between the mean outdoor air temperatures and its respective acceptable indoor air temperatures, which represent the two parameters needed for the prediction of the comfort hours within the year under study. The comfort temperature (T_c) is calculated using Equation (1) (where T_{out} is the mean hourly outdoor temperature). The comfort range was specified from $T_c \pm 3.5$ °C, as shown in Equations (2) and (3):

$$T_c = 0.31\ (T_{out}) + 17.8 \tag{1}$$

$$\text{Upper 80\% acceptability limit } (^\circ\text{C})\text{: } T_{c\,max} = 0.31\ (T_{out}) + 21.3\quad 10\ ^\circ\text{C} \le (T_{out}) \le 33\ ^\circ\text{C} \tag{2}$$

$$\text{Lower 80\% acceptability limit } (^\circ\text{C})\text{: } T_{c\,min} = 0.31\ (T_{out}) + 14.3\quad 10\ ^\circ\text{C} \le (T_{out}) \le 33\ ^\circ\text{C} \tag{3}$$

Moreover, the upper and lower acceptability limits are constant (extended horizontally) for the monthly mean outdoor air temperature values, outside of the ASHRAE-stated outdoor temperature range of 10 to 33 °C [32].

3. Building Energy Model

3.1. Energy Model Description and Calibration

The chosen modeled building prototype structural system is an RC skeleton, with column and beam structure, with a thickness of 0.15 m brick infill walls, without insulation, representing the most common techniques used in Egyptian construction. The building's façade has no solar protection, where the window to wall ratio (WWR), corresponding to the area of glass used in the northern and southern façades approximately lie between 45% and 35% of the total area of each façade, respectively. Windows are single-glazed with a 0.003 m thick transparent glass pane and wooden frames. The building studied is rectangular 25 × 11 m, consisting of six stories, each 2.8 m high. Each story consists of two identical apartments, as presented in Figure 2, the total volume of an apartment is 336 m^3 with a total floor area of 122 m^2 including a 60 m^2 net conditioned area [19]. A rendering of the prototype building model is presented in Figure 3.

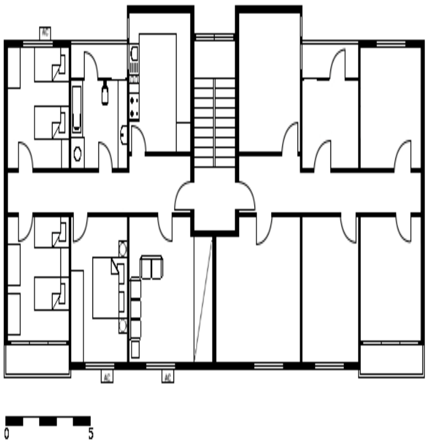

Figure 2. Typical floor plan [19].

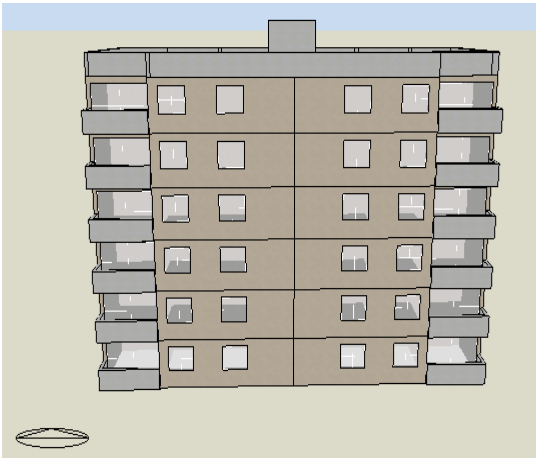

Figure 3. Rendering of the prototype building.

This was based on the data collected and results presented in Attia, Evrard, and Gratia study [19] which provided a good basis for investigating the potential energy savings of applying the EREC requirements to an Egyptian benchmark residential building. The performance of the prototype building is primarily examined by inserting the simulation input parameters into the simulation model and its energy performance was assessed, compared, and calibrated with Attia, Evrard, and Gratia study results to be used as the reference base case for this study. The building energy model was calibrated using DesignBuilder software over one year (8760 h). The Egyptian Meteorological Authority (EMA) was the source to attain the simulation weather readings (per hour). The readings were obtained in Excel format and then converted to EPW format, to be fed into Energy Plus [38]. The simulation results had an acceptable relative error equals to 4% [39] between the reference Base-Case model of this study and the simulated model by Attia, Evrard, and Gratia study, as shown in Figure 4. The results showed a direct proportional relationship between electricity consumption and air temperature, which emphasizes the fact that most of the electricity is consumed during the cooling season that lies between June and September.

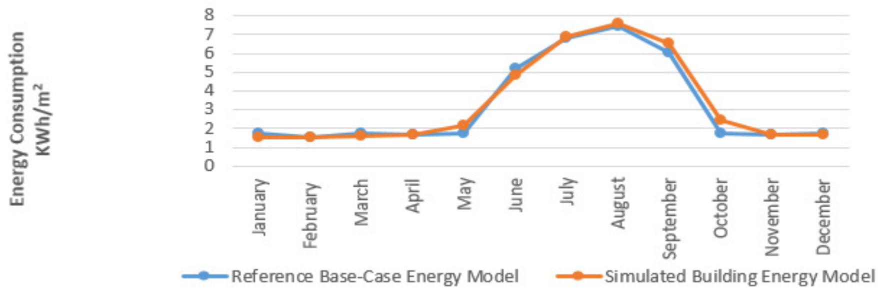

Figure 4. Building Energy Model Calibration.

A summary of the main model input parameters that characterize the reference building case study are defined in Table 1, Figures 5 and 6.

Table 1. Building envelope properties and operational parameters of the reference simulation model adapted from [19].

Model Input Measures		
Building Envelope	The Window to Wall ratio (WWR), in %	45 (N), 35 (S)
	Windows U-value, in W/(m^2.K)	U = 6.25
	Shading coefficient for glass (SC)	0.70
	Solar Heat Gain Coefficient (SHGC)	0.75
	Overhangs, projection factor (PF), for E, W, and S	0
	Shading glass ratio (SGR) (blind/screen)	0
	Exterior Wall U-value, in W/(m^2.K)	U = 2.50
	Roof U-value, in W/(m^2.K)	U = 1.39
Air Conditioning	Coefficient of Performance (COP)	2.00
	Energy Efficiency Ratio (EER)	6.8
	Temperature cooling set point, in (°C)	24
	Relative humidity set-point, in (%)	60
Lighting	Installation power density, in (W/m^2), living rooms	17
	Installation power density, in (W/m^2), bedrooms	13
	Installation power density, in (W/m^2), other	9
Plug loads	Average installation power density, in (W/m^2)	6
Occupancy Density	Five people per apartment	
Activity (metabolic rate)	Metabolism level	0.9
Clothing	Summer clothing (clo)	0.5
	Winter clothing (clo)	1.0
HVAC systems Schedules	Living rooms(Summer Season 1 June–30 August)	Operating 17:00 to 23:00
	Living rooms(Ramadan Season 31 August–29 September)	Operating 15:00 to 23:00
	Bedrooms(Summer and Ramadan Season)	Operating 23:00 to 5:00
Occupancy Schedules	Figure 5 shows the occupancy percentages	
Lighting Schedules	Figure 6 shows the operating hours of the lighting system	

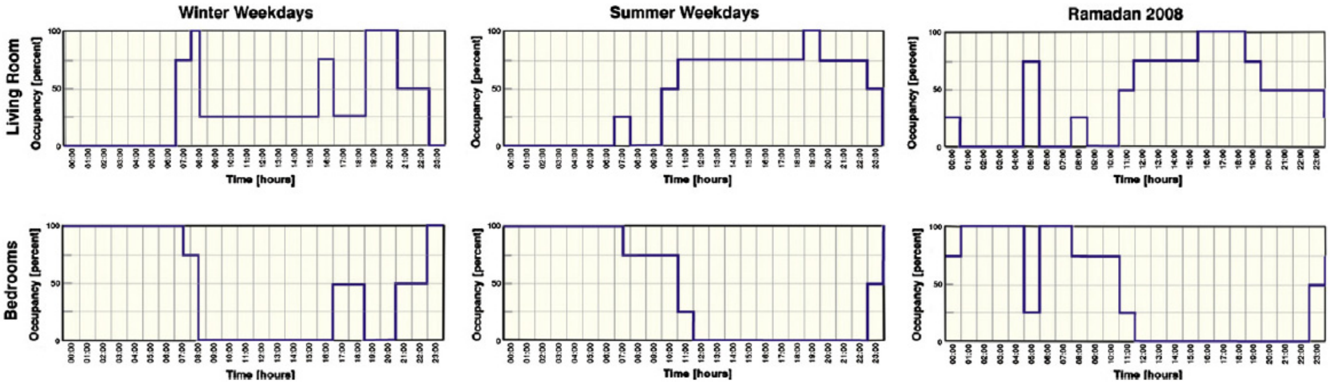

Figure 5. Occupancy schedules [19].

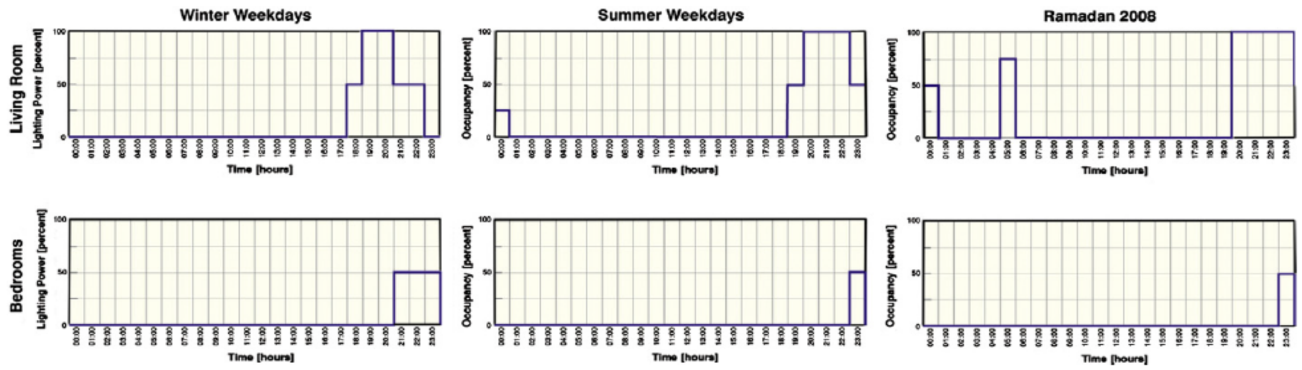

Figure 6. Lighting schedules [19].

3.2. Verifying Building Envelope Compatibility with EREC Requirements

By examining the properties of the building envelope for the reference case study, it was found that the thermal transmittance (U-value) of opaque surfaces, whether external walls or roofs, did not achieve the minimum requirements set by EREC. The same applies to windows, as they too did not comply with the EREC requirements. Windows are single-glazed, with no solar protection for the façades, resulting in exceeding the maximum allowable solar heat gain coefficient (SHGC). As in compliance with EREC guidelines [26], the building's envelope minimum requirements for Cairo and Delta climate zone are listed in Table 2.

Regarding the opaque surfaces, each element must meet the required minimum R-value "Assembly Min R-value" in (m^2 °C/W) stated by the EREC which depends on the external surface absorbance (α) of 0.70 stated by the EREC based on the building exterior painting color along with the element orientation. As for transparent surfaces, the EREC has divided the WWR % into four intervals, as shown in Table 2. The WWR intervals less than 30% must meet either one of the requirements of EREC in terms of: solar heat gain coefficient (SHGC) and shaded glass ratio (SGR), both according to the climatic zone of the building and direction of the openings, in order to prevent the penetration of excess quantities of heat, which would increase the indoor thermal loads. While, for the WWR interval that exceeds 30%, the SHGC must meet the allowable values given for each façade direction, and the SGR must not be less than 90% of the opening total area in all façades, except the north direction. SHGC is the fraction of the solar radiation hitting the window that is transmitted through it either directly and/or absorbed, and subsequently released as heat to the indoor environment and the shaded glass ratio (SGR) is defined as the ratio between the shaded glass areas to the total area of the opening during the period, from 9:00 am to 5:00 pm, on 21st of September. In the case of incompatibility with EREC requirements, three methods of improvement are recommended by the EREC: (1) reduction of the openings' size, (2) use glazing with better properties or execute frame replacement, and (3) using an external shading technique, through adding partial or full shading for the openings [26].

Table 2. Building Envelope Characteristics for Cairo according to EREC Requirements, adapted from [26].

Orientation		External Surface Absorptivity (α)	Required Min. R-Values for Insulated External Walls				Max. Solar Heat Gain Coefficient Values				Min. Shaded Glass Ratio			
Cairo and Delta Zone			Assembly Min. R-Value (m^2 °C/W)	Min. R-Value Insulation (m^2 °C/W)			WWR %							
				0.40	0.60	0.80	<10	10–20	20–30	>30	<10	10–20	20–30	>30
							SHGC				SGR			
Roof		0.7	2.7	2.7	2.3	2.1								
Wall	N	0.38	0.70	0.30	NR	NR	NR	NR	0.71	0.67	NR	NR	60%	70%
		0.50	0.74	0.34	0.14	NR								
		0.70	0.82	0.42	0.22	NR								
	NE/NW	0.38	0.89	0.49	0.29	NR	0.65	0.50	0.45	0.35	60%	80%	90%	90%
		0.50	1.00	0.60	0.40	0.20								
		0.70	1.18	0.78	0.58	0.38								
	E/W	0.38	1.07	0.67	0.47	0.27	0.50	0.40	0.35	0.27	70%	80%	90%	90%
		0.50	1.23	0.83	0.63	0.43								
		0.70	1.50	1.18	0.90	0.70								
	SE/SW	0.38	0.97	0.57	0.37	0.17	0.50	0.40	0.35	0.27	60%	80%	90%	90%
		0.50	1.23	0.83	0.63	0.43								
		0.70	1.32	0.92	0.72	0.52								
	S	0.38	0.82	0.42	0.22	0.02	0.71	0.64	0.55	0.50	60%	70%	90%	90%
		0.50	0.90	0.50	0.30	NR								
		0.70	1.04	0.64	0.44	0.24								

For the EREC minimum requirements to be complied, a set of EEMs will be defined in the following section, to be applied to the reference building, in order to determine the energy savings obtained, due to the application of energy code instructions.

3.3. Energy Efficiency Measures (EEMs)

3.3.1. Energy Efficiency Measures for Building Envelope Enhancement

The building's envelope thermal performance plays a major role in the building energy consumption. Since the residential sector is characterized by its poor quality and non-compliance with the energy code, in order to reduce the building energy needs (especially cooling energy needs), the enhancement of the building's thermal performance is an essential task, and investigating the building's envelope EEMs, in terms of thermal insulation and glass specifications, is recommended by the EREC.

The thermal insulation materials are commonly used in the local market are classified by the EREC and Egyptian specifications for thermal insulation work items and divided into four categories as shown in Table 3 [26,40]. Thermal insulation systems for building envelopes commonly use expanded polystyrene (EPS) and extruded polystyrene (XPS) as insulation materials [41]. Their ability to enhance building thermal performance is mentioned in previous studies conducted on Egyptian case studies [36,39,42–44]. Moreover, the EREC recommended polystyrene for thermal insulation of building envelope for the existing buildings in hot regions [4]. In addition, the Egyptian market has large manufacturing capacity of polystyrene, which is characterized by its high durability and moisture transfer resistance [36,43]. All thermal characteristics data for construction materials, glass properties, and shading specifications needed were obtained from the EREC [26].

Table 3. Insulation materials specifications, adapted from [26,40].

Insulation Materials Categories	Material Name	Thermal Conductivity (K) (W/m.°C)	Density (kg/m^3)
Loose Fill Insulating Materials	(1) Vermiculite	0.065	1000
	(2) Perlite	0.039–0.06	32–176
Semi-Rigid Insulating Materials	(1) Cork	0.039–0.052	100–115
	(2) Wool		
	(a) Glass wool	0.043–0.078	72
	(b) Rock wool	0.043–0.055	72
	(c) Slag wool	0.036–0.058	72
Rigid Insulating Materials	Polystyrene		
	(a) Expanded Polystyrene	0.0343	29
	(b) Extruded Polystyrene	0.0289	29
Foamed Insulating Materials	(1) Polyurethane	0.026	NA
	(2) Foamed concrete	0.1–0.25	400–880

3.3.2. Efficient Lighting System and HVAC Cooling Set-Point

The light-emitting diode (LED) is one of the fastest developing lighting technologies, due to its potential impact on reducing electricity consumption and longer lifespan, compared to other lighting types. Furthermore, integral LED lamps have become obvious options for replacing low-efficacy fluorescent and halogen lamps in recent years. In Egypt, there is a limited use of LED lamps in households, as an energy efficient lighting technology [22]. Although, the government introduced a large amount of LED lamps, to be distributed to residential customers by electricity distribution companies, through installments added to the electricity bill to encourage the replacement of low-efficacy lamps as financial incentives [15]. Regarding the HVAC system, the units are kept as in the base case scenario, with EER = 6.8 and the same operational schedules. EER is defined as the capacity for cooling (kW), divided by the rated power input for cooling (kW) of a unit, when providing cooling [45]. However, in order to achieve a reduction in building's energy consumption, the HVAC system cooling set-points are maintained based on the recommendation of the Egyptian Ministry of Electricity [46].

3.3.3. Solar Photovoltaic Panels

Solar energy represents the most abundant resource of renewable energy in Egypt and, according to the solar atlas of Egypt, photovoltaic technology (PV) is recognized as the preferred solution across renewable technologies [47]. Figure 7 shows the means of the monthly global horizontal irradiances (GHI) for Egypt in W/m^2 for the 15-years period (January 1999–December 2013), where GHI refers to the intensity of solar radiation received horizontally at a certain location. Thus, solar PVs are selected for this study. The GHI values showed a typical summer maximum in all Egypt, reaching means values around 350 W/m^2, while the lowest GHI is about 180 to 190 W/m^2 in winter months.

3.4. Building Energy Simulation Scenarios

3.4.1. Building Envelope and Operational Energy-Saving Scenarios

Building simulation programs became common design tools and approved for code compliance in several countries [48]. Several studies have analyzed the utilization of simulation tools in evaluating the energy and thermal performance of buildings [49–53]. In this study, dynamic simulations for the reference building prototype were carried out using DesignBuilder energy modeling software version 6.1. DesignBuilder is an EnergyPlus based software tool, widely used for building designs evaluation and performance comparison of the design alternatives [30]. Building retrofitting is applied according to the EREC instructions and recommendations, implementing energy-efficient measures that compensate for the inefficiencies of the current building status. The EREC instructions were applied to the reference case study throughout seven proposed scenarios: (1) enhancing the exterior walls thermal efficiency; (2) enhancing the roof thermal efficiency; (3) glazing replacement and shading devices; (4) building envelope enhancement, through the integration of the first three scenarios; (5) Lighting enhancement; (6) HVAC temperature control; and (7) enhanced Building Envelope and Operational (BE&O) retrofit scenario, which is an integration of all proposed scenarios.

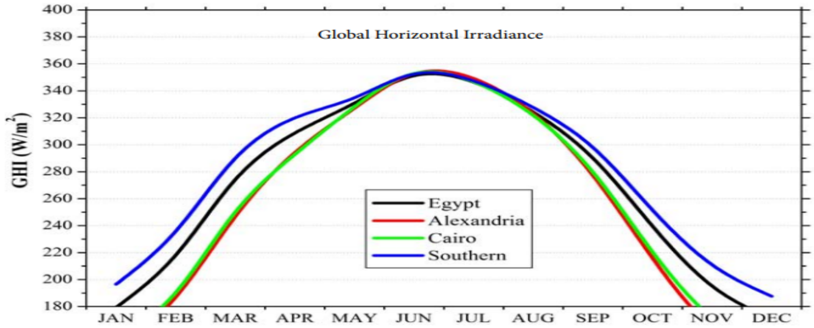

Figure 7. GHI solar atlas of Egypt—15 years climatology [47].

In this study, extruded and expanded polystyrene, and polyurethane foam have been proposed for the enhancement of the roof and exterior walls thermal insulation, in order to achieve minimum required thermal resistance (R-value) stated by the EREC. Thus, the application of either 8 cm extruded or expanded polystyrene or 6 cm polyurethane foam to the roof will comply with the minimum required R-value by the EREC equals to 2.7 (m^2 °C/W). While for the minimum required R-value for the walls, the value has been fixed for all directions to be 1.5 (m^2 °C/W) to standardize insulation thickness to be easily implemented from the exterior direction of the building; this can be achieved by applying either 4 cm extruded or expanded polystyrene or 3 cm polyurethane foam. The construction material and thermal conductivity of each layer for opaque surfaces are shown in Figure 8.

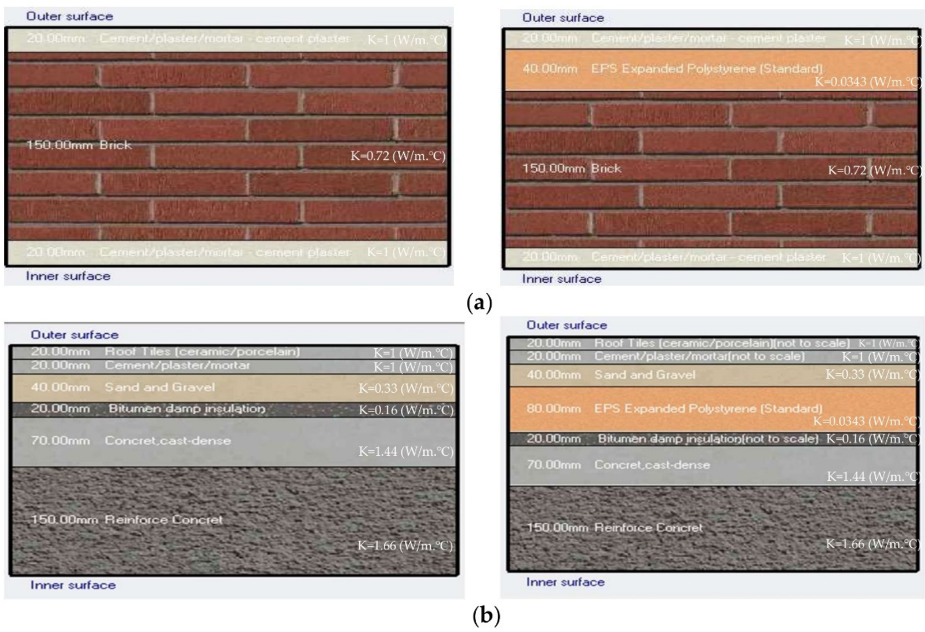

Figure 8. Construction materials layers for opaque surfaces: (**a**) exterior walls, (**b**) roof.

Moreover, the proposal for glazing replacement was applied to the north façade by replacing the existing glass by a double clear 3.2 mm transparent/transparent (6.0 mm air) glass, with specified SHGC equal to 0.66 and an U-value of 3.71 W/(m^2.K). A combination of clear reflective glass and external venetian blinds was chosen to be used in the south façade openings to achieve the EREC requirements. Clear reflective 6.4 mm (stainless steel Cover 8%) glass, with specified SHGC equal to 0.18 and an U-Value of 5.36 W/(m^2.K), was used since this glass type was found to have the maximum long run effect in respect of consumption of energy and thermal comfort [54]. The external Venetian blinds are considered to be closed from 9:00 am to 5:00 pm, only during the cooling season.

3.4.2. nZEB Energy-Saving Scenario

The nZEB energy saving scenario is an integration of renewable energy, in terms of solar photovoltaics (PV) to the enhanced BE&O retrofit scenario, mentioned in Section 3.4.1. The PV panels are installed on the building's roof to equalize the remaining building's energy demand of the enhanced BE&O retrofit scenario. The PVWatts® a web application, developed by the National Renewable Energy Laboratory (NREL, Golden, CO, USA), is used for the PV design modelling and calculations to estimate the annual electricity production of a grid-connected roof photovoltaic system [55]. To meet the building's energy need after retrofit, the building PV system design calculations are limited to an annual average solar radiation of 5.66 kWh/m^2/day, a PV installation area of 145 m^2, including 66 polycrystalline panels, with an area of 2.2 m^2 each panel, a module efficiency of 16%, system losses of 14.08%, and an inverter efficiency of 96%. The panels are oriented towards a southern aspect, with an angle of inclination of 30°.

4. Results

4.1. Simulation Results

In this study, EEMs, as a way to enhance building energy thermal performance, are proposed, evaluated, and simulated for a reference residential building case study in a hot dry climate. The proposed solutions depend mainly on minimizing building energy demand, through applying the EREC minimum requirements for building envelope enhancement, as well as applying the recommendation of the Egyptian Ministry of Electricity, regarding lighting enhancement and HVAC set-point temperatures, in order to obtain an enhanced BE&O building that acts as a base case for PV installation, to generate the rest of energy needs for reaching nZEB. As generally noted in this study, more than 48.2% of the reference building total energy consumption (18.83 kWh/m^2/year out of 39.03 kWh/m^2/year) was used for cooling, as a consequence of the lack of thermal insulation for the opaque surfaces, the glazing type used and the high WWR, which exceeds 30% the in northern and southern façades, allowing for excess heat gains during the cooling season.

In a hot dry climate context, such as Egypt, where the diurnal range of temperature is always in the range of 10 °C, the mass of the building components and location of thermal insulation for the opaque surfaces showed a considerable effect on the total thermal performance of the building. As recommended by several studies conducted in hot climates, the application of external thermal insulation has a significant energy savings impact, as it minimizes the heating of the thermal mass [43,49,56–59]. For the cooling season in hot dry climates, it is has been estimated that almost half the urban peak load of energy consumption is used to satisfy air-conditioning cooling demands [27]. During the cooling season, the wall predominantly acts to retard heat transfer from the exterior to the interior during the day, when the outside temperatures are too high. Increasing thermal mass in building walls has the effect of time-shifting for heat loads, which reduce the heat gain inside the building and helps decreasing cooling load. When temperatures fall at night, the walls re-radiate the thermal energy back into the night sky. However, the optimum insulation thickness for wall and roof configurations, to reduce the heat transfer, will depend on building type, orientation, climatic conditions, the efficiency of the air conditioning system, etc.

On the other side, the solar radiation absorbed by glazing could lead to an overheated indoor environment and increase in cooling energy loads. Therefore, windows enhancements, in terms of glazing replacement and shading devices, could help in reducing the quantity of the solar gains and, as a result, cooling needs in the summer. Several studies demonstrated that the use of overhang, other types of shading, such as horizontal, vertical, and egg-crate, are widespread in hot regions and hot/warm seasons, as a result of their significant impact on reducing energy demand [60]. Moreover, studies conducted in Egypt have highlighted the use of horizontal shading on southern facing facades to eliminate the solar heat gains in cooling season [43,61]. Shading devices, as integrated components of the building envelopes, are the elements designed for stopping excessive amounts of direct and indirect sunlight passing through, as well as for avoiding undesirable admission of light into buildings. In order to benefit from the shading devices, various types of shading devices are to be investigated to find a proper design and some parameters must be taken into consideration, the most important of them the climatic characteristics of the building location, glazing type of the façade, and position of the building, etc.

The study results showed great similarity with the abovementioned studies, conducted in hot climates, in terms of energy savings using building envelope enhancement measures. As illustrated in Table 4, the improvement of exterior walls, with outside thermal insulation, achieved an annual reduction of 6.97% and 13.17% in electricity and cooling consumption. As for the windows, glazing replacement and the use of external Venetian blinds during cooling season aid to significant annual savings by 14.36% for cooling electricity. Moreover, by applying an integration of the EREC minimum requirements, the building envelope EEMs achieved around an 18% reduction in building electricity annual energy demand and exceeded 35% savings in annual cooling electricity demand, besides 17.84% of building's CO_2 emissions reduction from 23.65 to 19.43 kg/m^2. Concerning the energy efficiency of lighting and HVAC temperature, replacing the incandescent lamps used in the reference case by LED lighting and the HVAC set-point temperature to 25 °C, besides the building envelope enhancements, resulted in building annual electricity savings of more than 37% and a reduction of more than 50% for cooling electricity for the BE&O retrofit scenario. Concerning primary energy consumption (PEC) assessment, Egypt relies mainly on natural gas and oil products, besides hydro, wind, solar, etc., to produce electricity. The primary energy conversion factor (PEF) for electricity was computed based on the recently available data for Egypt energy balances, and it was set to be equal to 3.06, which implies that each unit of electricity requires an input of 3.06 units of primary energy [62]. Building primary energy demand for the reference case scenario is equal to 119.42 kWh/m^2/year, and the primary energy consumptions for the retrofit scenarios are assessed as shown in Table 4. For building envelope retrofit scenarios, the roof thermal insulation has achieved the least primary energy savings of only 1.68 kWh/m^2/year, contrary to the exterior wall insulation scenario and window enhancement scenario, which has achieved respectively 8.32 and 8.27 kWh/m^2/year. The integration of thermal insulation for opaque surfaces, with the enhancement of windows, as a building envelope enhancement scenario, having attained a significant reduction of 21.32 kWh/m^2/year. A noticeable primary energy reduction of 18.54 kWh/m^2/year has been achieved by the lighting enhancement scenario followed by a reduction of 6.85 for the HVAC temperature control scenario. Additionally, the BE&O retrofit scenario achieved the most primary energy savings of 45.19 kWh/m^2/year compared to the reference case scenario.

Table 4. Building simulation results.

Summary of All Energy-Saving Scenarios						
ID #	Scenario Description	Electricity Consumption kWh/m^2/year	Cooling Consumption kWh/m^2/year	Annual Electricity Saving %	Annual Cooling Electricity Saving %	Comment
Building Envelope & Operational Energy-Saving Scenarios						
1	Enhancing the exterior walls' thermal efficiency	36.31	16.35	6.97	13.17	-
2	Enhancing the roof thermal efficiency	38.48	18.28	1.41	2.92	-
3	Glazing replacement and shading devices	36.32	16.12	6.93	14.36	-
4	Building Envelope enhancement	32.06	12.10	17.86	35.74	-
5	Lighting enhancement	32.97	17.84	15.52	5.24	-
6	HVAC temperature control	36.79	16.59	5.74	11.89	-
7	Building Envelope & Operational (BE&O) retrofit scenario	24.26	9.31	37.85	50.53	-
nZEB Energy-Saving Scenario						
8	nZEB Scenario (Solar Photovoltaics-PV installation area = (145 m^2)			100	100	nZEB

Finally, nZEB has been achieved through the installation of a PV system connected to the utility grid on a 145 m^2 roof area to offset the remaining building's energy demand of the enhanced BE&O scenario. A net metering system was proposed to achieve the nZEB concept based on a previous study that concluded net metering as the optimum approach for investment and offsetting or eliminating electricity bills in Egypt [63]. This system allows end-users to establish solar plants within their buildings to meet all or part of their needs from electricity and feed any surplus into the national grid with the option to claim it back in the following months when needed or sell it back to the electricity company. A monthly analysis over a year for the PV electricity production versus the building's electricity demand has been done as shown below in Figure 9. It clearly detected that the monthly PV electricity production for the whole year except the cooling season exceeded the monthly building's energy consumption. But according to the nZEB perspective, the PV system has successfully balanced the building energy consumption along the year.

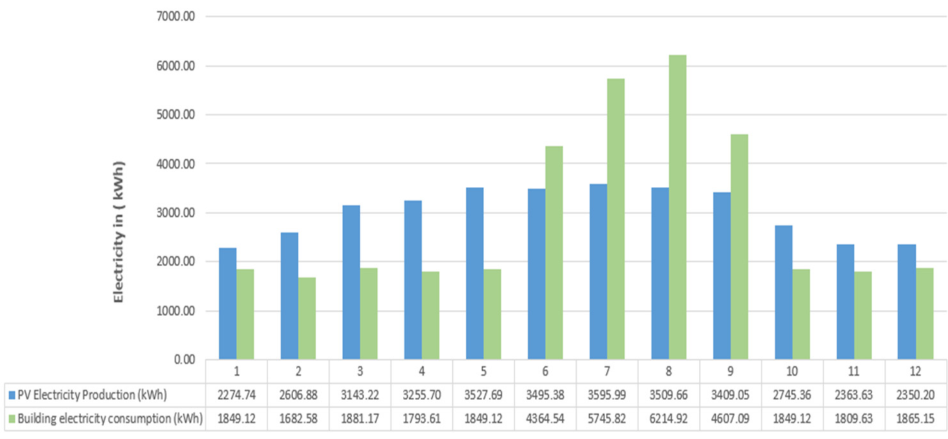

Figure 9. PV Electricity Production vs. Building Electricity Consumption.

The overall results illustrated in Table 4, demonstrate a significant improvement in building energy performance and reduction in total energy supplied to the building for all simulation scenarios as compared to the reference case study, where primary energy consumption refers to the equivalent primary energy consumed to produce the electricity needs. Electricity consumption refers to the total consumption of cooling, lighting, and appliances, while cooling consumption refers to the electrical consumption used only for cooling purposes. Moreover, the study assured the achievability of nZEB by offsetting the enhanced BE&O building energy needs (24.26 kWh/m^2/year), throughout the PV system that produced (24.78 kWh/m^2/year).

4.2. Thermal Comfort Evaluation

In this study, the thermal comfort for the building was evaluated for the reference case and the building envelope retrofit scenario to assess the effect of applying the EREC minimum requirements. The building is occupied most of the time with different occupant densities, even the building is occupied with full occupant density on the weekends (Fridays and Saturdays). As a consequence, simulations were performed to study the thermal condition of the building over a year (8760 h), considering 84 thermal zones. All thermal zones were simulated according to their different space activities, HVAC schedules, occupancy schedules, Lighting schedules, etc. The evaluation is based on two methods: (1) EREC comfort zone temperature boundaries; and (2) ASHRAE 55 adaptive method.

According to the EREC method, as shown in Figure 10, the thermal comfort for the building envelope retrofit case has improved only by 4.04% along the year, as discomfort hours reduced from 3763 to 3409 h compared to the reference case. It is clear that the temperatures between the comfort limits not only became lower in Summer but also in Winter (the temperatures in winter, are significantly below the lower limit of comfort), which makes the decrease in discomfort not very significant for the whole year. These results highlighted that the tested EEMs for the building envelope (thermal insulation, windows glazing replacement, or both together) have negatively impacted the indoor thermal comfort during winter. However, they had a great impact on electricity cooling reduction, associated with a significant reduction in discomfort hours during the cooling season that begins from the 1st of June to the 30th of September, where the discomfort hours decreased by more than 21.14% from 1110 to 491 h, as compared to the reference case scenario. Thus, other EEMs should be examined separately or combined, for instance, horizontal shading devices for the southern aspect reducing solar gains in summer, modifications to the WWR % and moveable shading devices, allowing for an increase of solar gains in winter, without compromising summer comfort, and experimenting with other types of glazing, or by a combination of several window enhancements.

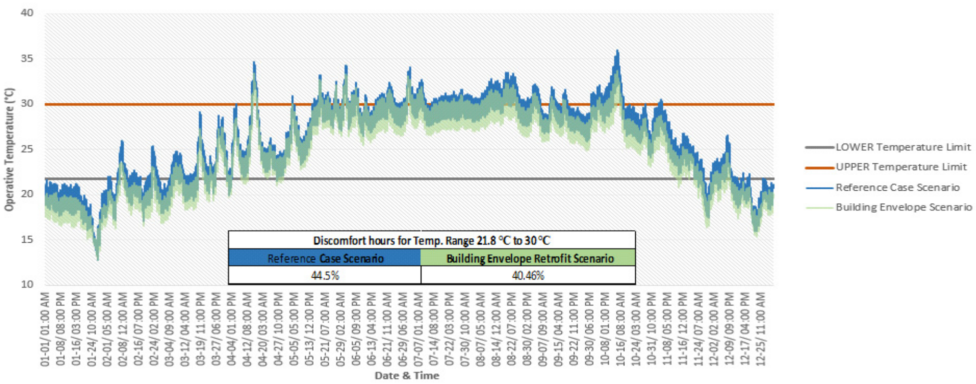

Figure 10. EREC Thermal Comfort Analysis—Thermal Comfort Zone between 21.8 °C to 30 °C (all year—8760 h).

On the other hand, according to the ASHRAE-55 adaptive comfort as shown in Figure 11, it was found that thermal comfort of the building envelope retrofit scenario has been improved by 7.35% yearly, as discomfort hours reduced along the year from 2304 to 1660 h compared to the reference case. While the cooling season from 1st of June to 30th of September, showed a noticeable thermal comfort enhancement, as discomfort hours decreased by more than 30.1% from 965 to 84 h as compared to the reference case scenario.

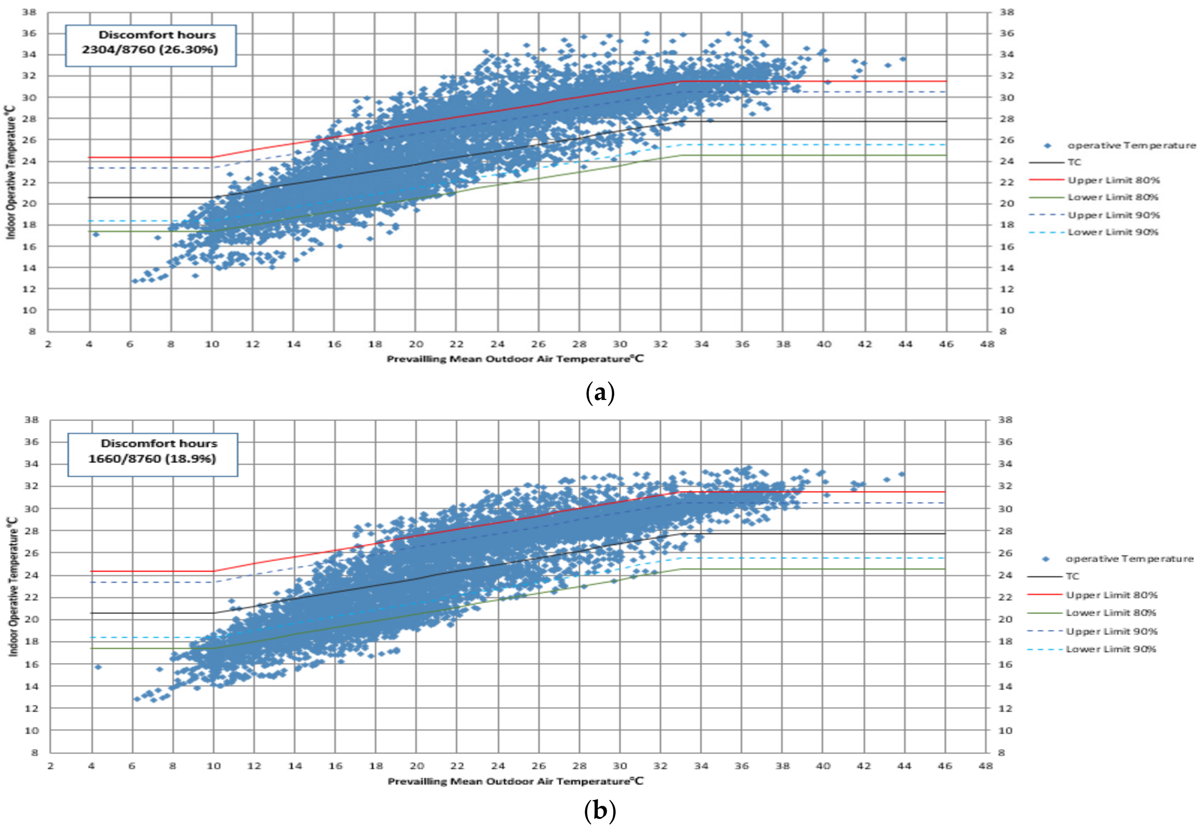

Figure 11. ASHRAE-55 adaptive thermal comfort analysis, based on 8760 h for (**a**) acceptable operative temperature ("Reference-Case") and (**b**) acceptable operative temperature ("Building Envelope Retrofit-Case").

Thermal comfort during hot period always represents a main concern in hot climate regions, such as Egypt. Noticeable variation in the results between the EREC and ASHRAE methods was observed, where the EREC evaluation method has recorded 1459 discomfort hours more than the ASHRAE adaptive method. This difference is due to the adoption of constant lower and upper EREC thermal comfort temperature limits throughout the year that ranges between 21.8 °C to 30 °C, respectively, while, in the contrary, the ASHRAE method depends on a relation between mean outdoor air temperatures and its respective acceptable indoor air temperatures, within 80% acceptability comfort limits. Furthermore, in both methods it was noticed that the enhancement of comfort hours during the cooling season has improved more than the comfort hours along the year. This assures that the building's envelope enhancement scenario has succeeded in decreasing the discomfort hours during the cooling season, but on the other hand, as discussed above, it has a negative impact by increasing the discomfort hours during the rest of the year, especially in winter season.

5. Conclusions and Recommendations

Egypt is the largest country in the Middle East region, in terms of population, and is, thus, facing an increase in energy demand, as well as low indoor thermal comfort, as a consequence of the acceleration of population and economic growth, besides the construction expansion. However, the existing Egyptian residential sector is struggling from poor quality, non-compliance, and the absence of enforcement and legislative support for buildings energy codes. Furthermore, there is a noticeable lack of awareness of the topic of energy efficiency in residential buildings, among both the end-users (households) and construction practitioners. Consequently, the present research study focused on raising the awareness of promoting EREC by quantifying the energy savings, due to the application of the EREC instructions, besides the indoor thermal comfort evaluation associated with the enhancement of building energy efficiency. The study showed great energy savings potential for existing residential buildings, which could be a path to encourage the use of sustainable retrofit strategies in all buildings, either new or existing, thus achieving higher standards of energy efficiency within the Egyptian building stock, in order to eliminate buildings energy consumption. Moreover, the study considered reaching the nZEB concept, using the PV solar system, to keep pace with Egypt's vision 2030 aspirations towards sustainable development for a better standard of living to all Egyptians, which aims to save 25% of current energy consumption.

Referring to the aim of this research, the compliance effect of building envelope elements for a prototype residential building, with the minimum EREC requirements, has been evaluated for Cairo and delta zone climates. The results have revealed that the passive EEMs, such as thermal insulation for opaque surfaces, in addition to windows enhancements, achieved up to an 18% reduction in electric energy demand and more than 36% savings in cooling electricity. Added to the former measures, based on the recommendation of the Egyptian Ministry of Electricity, the use of LED lighting and an HVAC set-point temperature of 25 °C allowed for a total saving of more than 37% of total electricity demand and more than 50% of the electricity used for cooling. Finally, the installation of PV panels easily succeeded in transforming the studied residential building into a nZEB. Concerning the indoor thermal comfort, it has been evaluated using two different methods: (1) the EREC comfort zone temperature boundaries; and (2) the ASHRAE-55-2017 adaptive comfort model at 80% acceptability limits. The thermal comfort results for both methods highlighted a noticeable reduction of up to 30% of discomfort hours, compared to the reference case scenario in the cooling season, which is the main concern in hot climate regions like Egypt, contrary to the rest of the year, especially the winter season; thus, particular attention must be taken to the implications of certain measures, in terms of comfort in winter. Based on the study results, it clearly demonstrated that the existing residential building renovations could play the main role in reducing energy consumption, which helps reduce the financial burden on the government, regarding energy subsides. In addition, the results of the study could help with other research, in promoting the energy-efficient measures suitable for residential buildings, through conveying the technical and economic data of each efficient measure and its environmental and economic feasibility to the end-users. Furthermore, this paper reveals that government intervention and persistence are critical in making energy efficiency a pillar of building construction, particularly focusing on:

- Egyptian residential energy code enforcement in all buildings, either new or existing. In addition, new code updates should provide clear retrofit guidance.
- Establishing a training program for those responsible for activating the energy efficiency code in buildings, as well as those responsible for implementation and control.
- Develop a guideline that conveys, to end-users, the technical data of the available energy-efficient measures in the Egyptian market, as well as their applications and effect on energy savings and thermal comfort levels.
- Develop an economic analysis for each energy-efficient measure, alongside the developed guideline. The economic analysis includes the initial costs and payback periods, in order to highlight the financial benefits to end-users. Furthermore, the economic analysis can assist in classifying the retrofit applications to different categories of end-users (e.g., high, medium, and low-income end-users), which can help in developing more realistic investment plans.
- Use the guideline and economic analysis to offer new investment measures, in order to facilitate and encourage the end-users of the private sector to invest in the retrofit of existing buildings. These measures would include providing governmental funding plans that facilitate grants and bank loans for buildings retrofit.

- Developing awareness campaigns, regarding the importance of activating the energy efficiency code in buildings for all sectors, either public or private.
- Starting a plan for applying retrofit to all governmental existing buildings in Egypt, following the European paradigm, in order to help reduce energy consumption and provide a leading example for the private sector.

A step further, this study contributes to the promotion of the nZEB concept and its inclusion in the Egyptian energy codes, in order to align with the Egyptian vision 2030, towards sustainability, through representing the potential of renewable energy sources, in the form of PV solar panels, used to successfully transform a representative residential building into a nZEB. Moreover, It is clearly understood that the Egyptian forthcoming policies should move in two directions: the reduction of the energy consumption of the buildings through more strict rules and legislations and promotion of green energy for the building sector, produced either on- or off-site.

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