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Enviro-economic assessment of buildings decarbonization scenarios in hot climates: Mindset toward energy-efficiency

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Abstract

As buildings consume a considerable portion of the global energy output and have a key role in greenhouse gas emissions, several steps have been taken to lower the energy and emissions from buildings especially through the adoption of renewable energy sources. The emerging building integrated photovoltaic (BIPV) technologies act as replacements for conventional building envelopes as well as energy generation sources. The purpose is examining, through parametric analysis, the potentials of energy-efficient building solutions in different hot climatic regions. Through an enviro-economic assessment, a building envelope solution is proposed that enhances the building energy performance in terms of reducing the building energy use, generating green energy, and reducing indoor thermal discomfort. Results showed that CO_2 emission reductions ranged from 9% to 31% and the discomfort hours reductions ranged from 10% to 25% based on the model specifications. Moreover, several financial elements were considered such as IRR, ROI, NPV and the Payback period were calculated for each model. Promising numbers were obtained in terms of the economic analysis of the models. The models demonstrate an IRR index of 26.45%, 21.6%, and 16.85% for Aswan, Cairo, and Alexandria, respectively, an ROI index of 18.32%, 15.68%, and 13.23% for Aswan, Cairo, and Alexandria, respectively, with nearly half the PBP in all locations. According to the techno-economic outcomes, the Reflective paint model integrated with the Glazing Integrated PV tends to be the most cost-effective implementation in the three different locations.

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Keywords: Building envelope; Building energy performance; Enviro-economic assessment; GIPV; Energy-efficiency

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Nomenclature and Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
B.L	Baseline
BIPV	Building Integrated Photovoltaic
CO_2	Carbon Dioxide
CVRMSE	Coefficient of Variation of the Root Mean Square Error
DCH	Discomfort Hours
EUI	Energy Use Intensity
GHG	Green House Gases
GIPV	Glazing Integrated Photovoltaic
GW	Gigawatts
GWh	Gigawatt Hours
HVAC	Heating, Ventilation and Air-Conditioning
Ins	Insulation Material
IRR	Internal Rate of Return
kWh	Kilowatt-hours
LPD	Lighting Power Density
NMBE	Normalized Mean Bias Error
NPV	Net Present Value
NZEB	Net Zero Energy Building
PBP	Payback Period
PV	Photovoltaic
RP	Reflective Paint
ROI	Return On Investment
SHGC	Solar Heat Gain Coefficient
U	Overall Heat Transfer Coefficient
WWR	Window-Wall Ratio
XPS	Extruded Polystyrene

1. Introduction

Buildings consume approximately 30%–40% of the global energy output and contribute to a considerable amount of greenhouse emissions, approximately 19% [1–3]. Several strategies can be adopted in buildings to lower greenhouse gas emissions, i.e.: energy, water, and material efficiency measures [4]. One possible practice is replacing conventional electricity sources with renewables which are globally used in buildings [5]. One of the possible renewable solutions is photovoltaics (PV) and especially the building integrated photovoltaics (BIPV). BIPV systems use photovoltaic panels embedded in a building's outer envelope to produce electricity. BIPV plays two key roles in buildings. First, BIPV performs the function of a building skin and thus must have specifications such as protection from noise, insulating properties, strength, and other properties that are standard in any building envelope. Second, the BIPV system generates power for the building [6].

BIPV systems can modify the indoor ambience since it allows daylight to pass through. This is because BIPVs are usually transparent or semi-transparent [7]. BIPV module improvements in the last few years have made this technique more architecturally beneficial. For example, it is now easier to integrate PV in building parts due to the flexibility and lightweight of glass PV. Also, they are being integrated into buildings aesthetically and pleasingly. All these factors help in urging the adoption of BIPV [8].

Various studies in the literature [9–11] were conducted on BIPV systems taking into account their performance, installations, materials and designs, etc. Kumar et al. [12], investigated the performance of BIPV through contrasting two different placement techniques: horizontal and vertical BIPV. The findings indicated that horizontal BIPV generates more energy than vertical BIPV. Yadav et al. [9] determined the optimal angles for the BIPV system to assess the incident solar irradiance on the BIPV using a model. Kumar et al. [13] demonstrated that various photovoltaic cell technologies have a substantial effect on energy supply. According to the findings in [14], the energy efficiency of BIPV varies based on the application.

Over 150 countries signed the Paris Climate Change Agreement in 2016, committing to significantly reduce GHG emissions by 2050. Several studies have investigated the possible ways for the transition [15–17]. Sorgato et al. [18] analyzed the feasibility (techno-economic) of the BIPV arrangement for a facility in 6 different cities in Brazil. Results demonstrated that the energy could be fully supplied by the BIPV applications. Moreover, results revealed the major effect that climate has on the energy generated by the BIPV. The effectiveness of the first Italian BIPV initiative is assessed, technically and economically by Aste et al. [19]. Wang et al. [20] investigated the ecological consequences and economic impacts of a BIPV technology. This was accomplished by computing the net present value (NPV) and payback period (PBP) of a facility's BIPV system in Shanghai, China. PBP was retrieved in 6.52 years. Alnaser [21] assessed the performance of a BIPV system with a capacity of 8.6 kW located in a facility in Bahrain. The PBP of the BIPV installation exceeded 600 years due to Bahrain's extremely cheap electricity costs. According to their assumption of one kg CO_2 emissions per one kWh of electricity in Bahrain, nine tons of system GHG emissions would be saved annually. Thermal insulation is another parameter significantly affecting building heat gains [2,22–27]. William et al. [2] recently investigated the effect of thermal insulating materials in terms of energy performance, environmental impact, and resulting thermal comfort. They concluded that among conventional insulations, 25 mm polystyrene (XPS) reduced energy use, CO_2 emissions, and enhanced thermal comfort. Through a weighting decision matrix, they postulated that a decision that is balanced would be the implementation of reflective paints, due to its highest cost-effectiveness.

Considering the global attention toward renewable energy and sustainability goals, this study analyzes the energy performance of a building under three different climatic regions with an active photovoltaic layer integrated into the envelope. Moreover, reduce the building energy consumption through the adoption of clean renewable energy sources taking into account economic, environmental and thermal comfort factors. Section 2 presents the methodology adopted followed by Section 3 that demonstrates the building model specifications. Section 4 shows the results and findings obtained and finally, Section 5 highlights the conclusions of the paper.

2. Methodology

With the global attention nowadays toward Net Zero Energy Buildings (NZEB) and the Egyptian vision 2030 toward sustainable Egyptian communities, this study aims to reduce the building energy consumption by implementing a clean renewable energy source that enhances the buildings' energy performance in different hot climatic zones by considering the thermal comfort as well as the economic and environmental factors. Based on data availability, an Egyptian institutional facility is chosen for analysis. The methodology utilized in this study predicts building energy performance using the EnergyPlus solver via the DesignBuilder interface [28].

This simulator uses the heat balance method (HBH) for the Surface Heat Balance and Air Heat Balance are computed for each thermal zone by incorporating defined internal heat gains, air exchange between zones, air exchange with the external environment, and convective heat transfer from the zone surface into consideration. The HBM, dynamically solved by EnergyPlus, is an iterative calculation approach that necessitates the instantaneous solution of a set of equations for the zone air and all of the external and internal surfaces for each hour of the day. The use of EnergyPlus allows the dynamic calculation of the energy balance depending on the initial conditions as (building envelope, volume, energy systems) and the boundary conditions as (weather files). [29,30].

The analysis begins with baseline modeling, the ASHRAE design conditions are adopted, as well as the occupant densities, ventilation requirements, and interior gains indicated by ASHRAE standards [31–33]. The model is validated by comparing it to the actual consumption and according to ASHRAE's validation measures [34]. The analysis is followed by an enviro-economic evaluation in line with thermal comfort assessment to facilitate decision-making in three hot climatic zones. Fig. 1 illustrates the methodology graphically.

3. Building model

All of the relevant data for the baseline model is obtained, including geometries, envelope properties, building zones, and internal gains. The model's validity is determined by comparing the baseline model outputs to the actual measured values in a building in Cairo. Finally, the impact of building uses has been investigated, emphasizing the significance of façade properties.

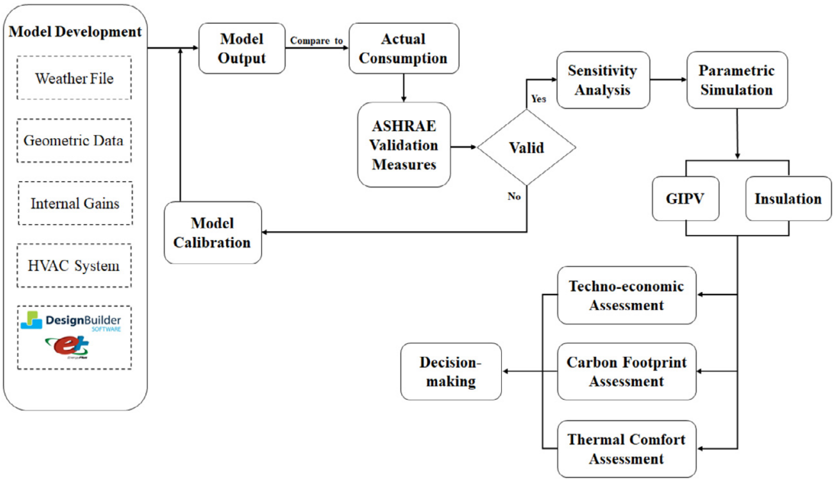

Fig. 1. Graphical methodology.

3.1. Building location

This study's baseline model is a facility in Cairo, Egypt. Cairo is a hot-arid climate region and identified as a hot climate according to Köppen Geiger classification [31,35,36]. The institution, as represented in Fig. 2, consists of six stories with a total area of around 11,350 m^2 and is operating five days a week from 08:00 AM to 4:00 PM.

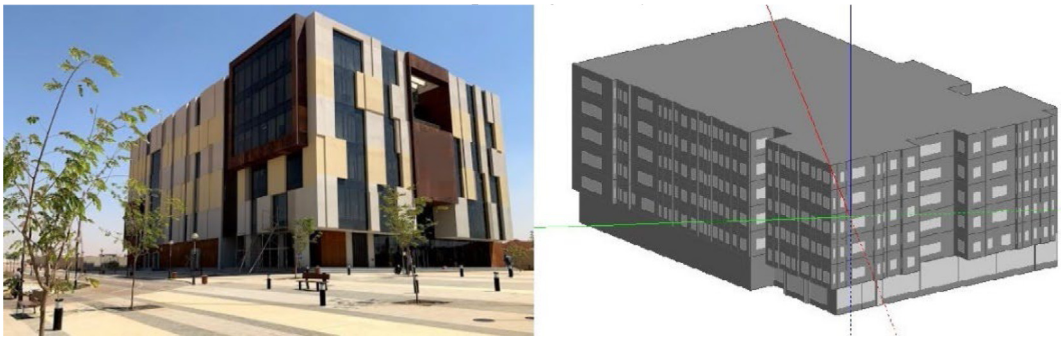

Fig. 2. Case study building and model.

3.2. Envelope specifications

The components of the baseline building envelope are nearly identical to those present in the majority of non-residential buildings in Egypt. The walls and roof overall heat transfer coefficients (U-Value) are 1.924 and 2.27 W/m^2 K, respectively [2,27,37]. The building has a 6 mm Blue Double Glazing/6 mm air gap with a U-value and SHGC specifications of 3.094 and 0.503, respectively [2].

3.3. Climatic data

In this study, the analysis is carried out in 3 different ASHRAE climatic zones represented by 3 cities in Egypt which are: Aswan, Cairo, and Alexandria. The recommended annual climatic design conditions are summarized and tabulated in Table 1.

Table 1. Recommended annual design conditions [2,31,38–40].

Location	Cooling degree days	ASHRAE climate zone	Dry-Bulb temperature (°C)	Wet-Bulb temperature (°C)	Direct normal irradiation (kWh/m^2)	Wind speed (m/s)
Aswan	6564.1	1B	44.1	21.1	2254	4.04
Cairo	4861.7	2B	38.2	21.2	2036	3.58
Alexandria	3739.9	2A	33.2	22.4	1955	3.92

3.4. Internal heat gains

Loads generated internally, such as occupants heat gains, lighting, and equipment are known as Internal Gains. These values are as per ASHRAE standards. Table 2 summarizes the recommended values according to ASHRAE standards [31–33].

Table 2. Recommended ventilation rates, occupant densities, and LPD of Institutional buildings [31–33].

Zone	Ventilation rate (L/s-person)	Ventilation rate (L/s-m^2)	Occupant density (#/100 m^2)	LPD (W/m^2)
Classroom	3.8	0.3	65	13.4
Coffee stations	2.5	0.3	20	7
Computer lab	5	0.6	25	18.4
Conference/Meeting	2.5	0.3	50	13.3
Corridors	–	0.3	–	9.9
Laboratories	5	0.9	25	15.5
Lecture hall	3.8	0.3	150	13.4
Libraries	2.5	0.6	10	11.5
Lounge	2.5	0.6	50	7.9
Main entry lobbies	2.5	0.3	10	9.7
Office spaces	2.5	0.3	5	12
Reception areas	2.5	0.3	30	5.9
Restaurants	3.8	0.9	70	11.6

3.5. Model validation

The baseline model is validated in this study by correlating it to the energy usage of the real building, as shown in Fig. 3. Two indices have been computed, as indicated by the ASHRAE [34], to demonstrate the simulation model's representativeness based on the variability of the observed data. The simulation is valid with a 6% Normalized mean bias error (NMBE) and 3% Coefficient of Variation of the Root Mean Square Error (CVRMSE).

For the validated baseline prototype, a sensitivity analysis was undertaken to assess the fraction of each factor affecting the building energy utilization, indicating that the building envelope contributes for about 50% of the heat gain. The energy breakdown of the baseline model indicated that the HVAC contributed to around 45% of the entire energy use, which is consistent with HVAC energy usage in similar climates [2,27,37,41–45].

3.6. Proposed models

In developing countries, viable building practices are yet unsuitable to reach zero energy structures. Besides, to ensure thermal comfort standards in non-residential buildings, the HVAC systems use the bulk of the building's energy. This results in large capacity equipment and components using the majority of the existing roof area [46]. Bearing this in mind, the study aims to propose a cost-effective building envelope reducing both environmental impact and enhancing the indoor thermal comfort represented by discomfort hours (DCH). DCH is simply "an assessment based on whether the temperature and the moisture content indoors are within the ASHRAE thermal comfort range or not" [2]. As a solution for renewable energy implementation, solving the issue of limited roof space, the model studies the use of building-integrated photovoltaics (BIPV) system in building envelopes and the

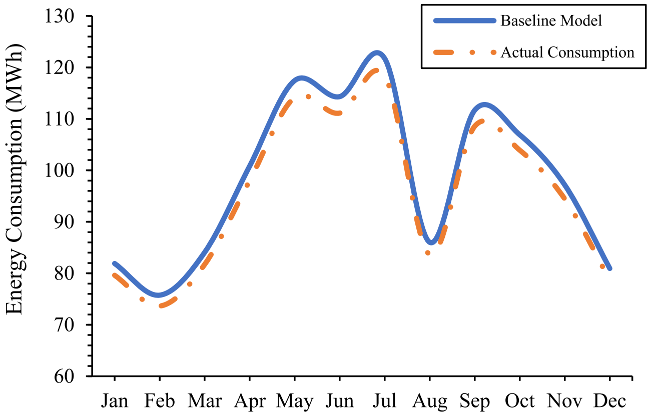

Fig. 3. Cairo baseline model validation.

energy performance enhancement in buildings, specifically through glazing integrated photovoltaics (GIPV) [46]. The model is then tested for integration possibilities with a conventional insulation material (Ins) and reflective paints (R.P) recently analyzed in detail by William et al. [2]. The proposed solutions are applicable in both new designs/constructions, and in retrofitting.

4. Results and findings

The retrofits' results are visualized and analyzed in order to assess the building's performance. An enviro-economic analysis is conducted with the goal in mind to address the energy and carbon footprint savings, as well as the consequent thermal comfort. For the three locations, the simulation outcomes including both energy reductions, and carbon footprint is graphically illustrated in Fig. 4a, b, and c.

As shown in Fig. 4, and Table 3, the proposed models show the potentials of reducing energy use, and CO_2 emissions by about 31.2%, 29.7%, and 27% for Aswan, Cairo, and Alexandria, respectively. Regarding thermal comfort, integrating the insulating materials with the GIPV shows a potential solution toward reducing net energy consumption, environmental impact, while reducing the discomfort hours indoors.

Table 3. EUI, CO_2, and DCH outcomes.

Model	Aswan, Egypt			Cairo, Egypt			Alexandria, Egypt		
	EUI (kWh/m^2)	CO_2 Reduction	DCH Reduction	EUI (kWh/m^2)	CO_2 Reduction	DCH Reduction	EUI (kWh/m^2)	CO_2 Reduction	DCH Reduction
Baseline	115.55	–	–	103.77	–	–	96.09	–	–
B.L + GIPV	98.45	14.80%	–	93.16	10.22%	–	87.14	9.31%	–
Ins + GIPV	85.81	25.75%	25%	85.89	17.23%	17%	82.50	14.14%	18%
R.P + GIPV	79.54	31.20%	20%	72.95	29.70%	11%	70.08	27.07%	10%

Table 3 numerically illustrates the resulting Energy Use Intensity (EUI), Carbon footprint reduction, and the Discomfort hours (DCH) outcomes of the simulated models.

As with any engineering proposal, the implementations should undergo a comprehensive techno-economic assessment, with the current Egyptian electrical tariff for commercial applications of US \$0.102/kWh [2,47]. The areas are about 3473 m^2 and 1913 m^2 for walls and roof, respectively, while glazing is about 1186 m^2. The latest prices and cost of the proposed implementations per m^2 are surveyed and considered as 25 mm XPS (\$ 4), RP (\$ 3.56), and GIPV (\$110) respectively [2,48]. Considering both the initial and operating costs of the facility, a techno-economic[1] assessment is adopted [2,27,49] and the findings are represented in Table 3.

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[1] 1 USD = 15.74 EGP, Discount rate = 10%.

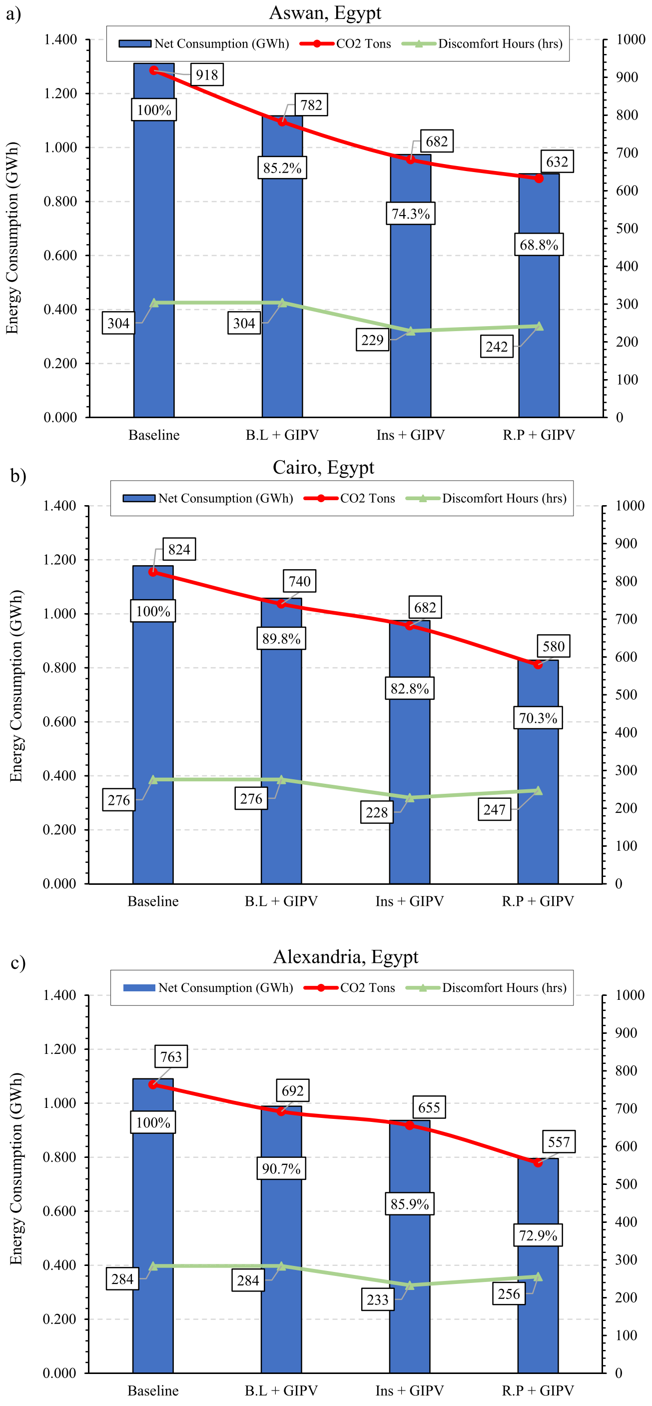

Fig. 4. Proposed models outcomes, (a) Aswan, (b) Cairo, (c) Alexandria.

Four financial measures are assessed in this study which is Internal Rate of Return (IRR), Return on Investment (ROI), Net Present Value (NPV), and Payback Period (PBP) [2,49]. In financial evaluation, the index IRR is utilized to assess the profit margins of potential investments. The ROI index is identified as a ratio used to estimate the return on capital invested. The higher the IRR and ROI, the more cost-efficient investment. Due to the time value of money,

money in the present is worth more than money in the future. The index NPV is the difference between the current value of cash inflow and cash outflow. A positive NPV denotes that the investment's expected returns will exceed its anticipated costs. Lastly, the PBP metric measures how long it takes for cash inflows to return the original investment.

According to the techno-economic outcomes, the implementation of the GIPV only to the building façade shows an IRR of about 10%, 0.39%, and −2.54%, and ROI of about 10%, 6.19%, and 5.22% with a PBP of around 6.1, 10, and 11.6 years, for Aswan, Cairo, and Alexandria, respectively. Through integrating the R.P with the GIPV in the building envelope, the models show a dramatic increase in the IRR index to be of 26.45%, 21.6%, and 16.85% with another increase in the ROI index to be of 18.32%, 15.68%, and 13.23% for Aswan, Cairo, and Alexandria, respectively with almost half the PBP in all locations. Summarizing Table 4, the outcome measures of the R.P model integrated with the GIPV tends to be the most cost-effective implementation in the three different locations with the highest IRR, ROI, NPV and the least PBP.

Table 4. Techno-economic assessment.

Model	Aswan, Egypt				Cairo, Egypt				Alexandria, Egypt			
	IRR	ROI	NPV (USD)	PBP (Years)	IRR	ROI	NPV (USD)	PBP (Years)	IRR	ROI	NPV (USD)	PBP (Years)
B.L + GIPV	9.95%	9,98%	−4,967	6.1	0.39%	6.19%	−782,695	10	−2.54%	5.22%	−981,266	11.6
Ins + GIPV	20.10%	14.89%	1,169,987	4.1	7.57%	8.95%	−251,521	6.8	2.11%	6.80%	−765,104	8.9
R.P + GIPV	26.45%	18.32%	1,959,295	3.3	21.6%	15.68%	1,337,432	3.9	16.85%	13.23%	760,896	4.6

5. Conclusions

BIPV technologies are being widely used nowadays because of their dual nature, i.e.: replacing standard building envelopes and generating electricity. Environmental and economic assessments have been conducted which in return proposes a building envelope that improves the energy performance of the building. The proposed solutions tend to reduce building energy use, generate green energy through GIPV and reduce indoor thermal discomfort. The results shown are obtained by comparing the baseline case and three studied cases where the envelope is improved in addition to using photovoltaic. The improvements obtained are not produced exclusively by the inclusion of PV but, to a large extent, by the improvement in the building envelope. Results of the different climates and models showed reductions in the CO_2 emission in the range of 9% to 31% and reductions in the discomfort hours in the range of 10% to 25% depending on the model specifications. Moreover, IRR, ROI, NPV and PBP were calculated for each model and showed very promising financial performance of the models, especially the integrated reflective paint GIPV model which is the most cost-effective implementation in the three different locations with an IRR of 26.45%, 21.6%, and 16.85% and an ROI index of 18.32%, 15.68%, and 13.23% for Aswan, Cairo, and Alexandria, respectively. Results from this study can be further used by researchers and practitioners in the energy domain to further expand on studies related to GIPV and on implementing real-life energy-efficient solutions especially in hot climates that would lead to a considerable decrease in energy use, increase the energy generated, enhance the thermal comfort, and provide a sustainable alternative for the conventional fossil fuels solutions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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