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Thermal-lighting Behavior Using Semi-transparent Photovoltaic (STPV) Windows for Office Spaces Retrofit in Egypt

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Abstract

The integration of PV systems into buildings became more significant in the context of decreasing energy consumption and energy costs. Building retrofit offers the opportunity to reduce energy consumption, improvs energy efficiency and increases the use of renewable energy sources. Technological advancement in Building Integrated Photovoltaics (BIPV) has converted the building façade into a renewable energy-based generator. Both electrical power and useful thermal energy can be obtained from BIPV façade along with conventional design objectives such as aesthetics and environmental control. In order to estimate this potential under real world and codes, we carried out simulations based on two office spaces retrofit (3.5m by 8m) using DesignbBuilder software as the graphical interface and EnergyPlus as the simulation engine. The aim is measuring the effect of replacement of standard clear glass windows with new windows integrating amorphous-Si (a-Si) semi-transparent photovoltaic modules. In particular, the features directly influenced by the proposed modifications are investigated in details, including the overall energy consumption for heating, air conditioning, and artificial lighting, compared with the overall energy given by the building-integrated photovoltaic modules. Results will demonstrate that significant yearly savings could be obtained from integrating Semi-transparent Photovoltaic (STPV) in office building facades under certain climatic conditions.

Keywords: STPV Window, Building Integrated Photovoltaic (BIPV), Office Spaces, Retrofit, Egypt.

I. INTRODUCTION

One of the major challenging affairs facing Egypt today is the energy crisis. Through the last two decades, the energy demand in Egypt has been growing significantly [1]; contributing to increasing degree of power cuts and blackouts with important economic, political and social influences. Certainly, buildings are main cause of worldwide energy consumption and CO2 emissions mainly when considering the existing building stock; accounting for around 40% of global energy demand [2,3]. Until now, the energy retrofit of existing buildings is still a debating issue. One of the most important renewable energy sources in this context is solar energy, which could be efficiently used in buildings for power generation and water heating. This is even more effective in hot climates because of the plentiful obtainability of solar radiation.

Building-integrated photovoltaics (BIPVs) is one of the most promising solar technologies to produce electricity in buildings [4]. Integration of renewable energy sources like PVs in the buildings components is a key element to reach energy consumption minimization. Consequently, studies in the field of BIPV are now becoming more relevant. Photovoltaic modules are usually attached on the external parts of building envelopes (rooftops and/or facades), representing architecturally related elements [5]. As a multifunctional component, BIPV can both improve the architecturally quality of building envelopes and generate electricity from solar radiation in the variable urban contexts [6].

I.I BIPV Concept and STPV Window

Building-integrated photovoltaic (BIPV), means the integration of PV panels into the building envelop with the dual function of replacing building elements and producing electricity. BIPV develop PV modules from a simple electrical device to a construction component that could be used to enhance the architectural concept [7]. ATTOYE, Daniel et al. mention that BIPV may replace conventional materials of the building facade in a variety of methods. This contains curtain walls, window glazing, external devices, and innovative applications as shown in figure 1 [8].

STPV window, Architects always work to enhance the quality of internal spaces by making openings for daylighting and views to the outdoor. This can result in excessive solar gains. PV Window and glazing are used as a passive strategy to decrease this effect [7].

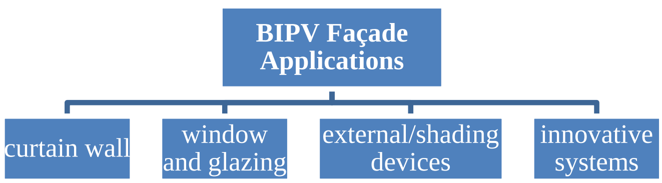

Fig. 1. BIPV façade types [8].

Changing the conventional clear glazing of a window with STPV glazing will not only provide on-site electricity production but will also result in: a reduction of solar heat gain; a growth of lighting energy demand. STPV glazing influence can be measured by the balance between the produced electricity and the, difference of heating, cooling and lighting energy consumption, which might be increased or decreased on the overall building energy efficiency. It is extremely dependent on the window size (represented by Window-to-Wall Ratio (WWR), which is the ratio of the area of window to the area of wall), the orientation of the STPV glazing and its transmittance, as well as the climatic conditions that the building placed [9].

PV window prototypes made by crystalline silicon solar cells such as mono-crystalline (mono c-si) and poly-crystalline (poly c-si), thin film solar cells such as Amorphous Silicon (a-si) and Cadmium telluride (CdTe), and organic solar cells such as Organic PV (OPV) [10]. Crystalline silicon solar cells have the highest cell efficiency but they are opaque. This means the light transmission through the panels can be reached only by changing the space between the cells. Glazing and windows integrated with thin-film and organic solar cells can achieve a uniform appearance and semi-transmittance for daylight transmission without cast shadow inside the room, as shown in Figure 1. This offer a well architectural acceptance when compared with crystalline silicon-based PV glazing and windows [11–12].

Fig. 2. Visual effect of an a-Si PV module with 20% transmittance from inside to outside [11].

Earlier researches in this field measure the impacts of STPV glazing on the whole energy performance of a building through considering many parameters such as window to wall ratio (WWR), Visible light transmittance (VLT) and orientation. In Singapore, the simulation tool EnergyPlus is used to examine six commercially available STPV amorphous silicon to evaluate the overall energy performance on office buildings' heating and cooling loads, daylighting, and electricity production. The results showing that STPV glazing can save energy with amount between 17 and 41 % compared to conventional window glazing for large façade openings from 70% to 100% WWR [13]. However, in Tokyo, the results of simulation revealed that VLT of 40% and WWR of 50% reached the minimum energy consumption in the building with artificial lighting controlling [14]. In Madrid, it was found that all investigated STPV modules with VLT from 0 to 40% can improve the building energy performance compared to the conventional glass. They can achieve an energy reduction between 22 % for VLT 40 and 32% for VLT 20 [15]. While, in Hong Kong, the whole energy performance of STPV glazing window is investigated by integrating the simulation results of thermal, power, and visual performances. The main result of this work was that among five examined orientations, south-east is the optimum orientation for overall energy [16]. Chow et al. [17] reports an assessment of semi-transparent a-Si integrated glazing performance considering a small office room in Hong Kong. A simulation module is used in EnergyPlus to examine the performance of a semi-transparent a-Si window. Their results showed that VTL in the rate of 0.45 – 0.55 reaches the greatest energy saving when the WWR is 33%. Cannavale, Alessandro, et al study the influence of the replacement of standard clear glass with integrating perovskite-based STPV windows, and the replacement of the transparent shading system with opaque perovskite-perovskite tandem cells. Results presented that under optimal conditions (no adjacent buildings) annual savings up to 18% could be attained. In presence of nearby buildings savings dropped to 14% [5].

Until now, there is still a lack of research on the thermal performance of STPV in Egypt's climate where the cooling demand became high almost during the whole year. This research assesses the impact of window integrated semi-transparent a-si PV glazing on building energy performance and indoor environment quality. using a small office room with Window-to Wall ratio 30% in New Damietta city in Egypt. From the previous review glazing with integrated a-si solar cells with 40% transparency was selected due to its better compatibility with WWR and also high electrical conversion efficiency. DesignBuilder (v6) software as a graphical interface with EnergyPlus as a simulation engine were used for energy and daylight performance simulations to demonstrate how the integrated a-si PV window system influences office environment under the distinctive climates in Egypt's climate with considering the effect of using the artificial lighting control system. The results will propose ways in which STPV window glazing might be used in future building applications, providing criteria for architects, designers and engineers.

I.II BIPV Status in Egypt

Egypt is considered the main primary fuel consumer in Africa, reaching more than 20% of total oil demand and more than 40% of total natural gas demand in 2013, which used to cover energy requirements, accounting for 94% of the country's total energy usage in 2013 [18]. Office building sector is responsible for consuming a great amount of energy for mechanical cooling systems, in addition to a poor indoor environmental quality. The existing buildings are significant matter in the environmental design because the changes and relating environmental techniques are limited [19]. BIPV can play an important role in this context to harness solar power, which is the most plentiful, unlimited and clean of all the existing energy resources.

Egypt is one of the solar belt countries enjoying more than 250 sunshine yearly days with high intensity of direct solar radiation from north to south which provides a variety of solar applications. In Egypt, PV systems and application have been extended for lighting, water pumping, telecommunications, cooling and advertisements purposes on the commercial scale in Egypt. Several plans are applied or under research by the Ministry of Electricity & Renewable Energy and New and Renewable energy authority (NREA). Consumers are applying PV systems in industrial facilities as the simplest way to avoid the progressive rate associated to the growth in total peak load. PV decrease the whole energy charge for the facility and can provide extremely great earnings on investment. Industrial clients with high energy demand might suppose a payback on their investment in the PV system over 5 to 8 years through a very low discount rate, regularly 5% [20]. This makes investment in the PV systems a critical approach in Egypt, considering the continuous growth of electricity demand. However, the use of BIPV systems is still not a common practice in the architecture of Egypt. This forms a missing chance that should be invested in as soon as possible. As for research, integration options of PV into the building fabric have to be highlighted. Thus, this study aims to investigate this issue with reference to the use of BIPVs as window glazing in building facades.

II. PROFILE OF EGYPT'S CLIMATE (Weather Data in Building Simulation)

Egypt belongs to the international sun-belt. In 1991 solar atlas for Egypt was issued demonstrating that the country enjoys 2900-3200 hours of sunshine every year with annual direct normal energy density 1970-3200 kWh/m^2 and technical solar-thermal electricity producing potential of 73.6 Peta watt hour (PWh) [20]. When conducting building associated studies and practices, Egypt is separated to eight climatic regions; Northern coast, Cairo and Delta, North upper, South upper, Eastern coast, Highlands, Desert and South Egypt as shown in figure 5. Each climatic region has changed features [21].

For this research, New Damietta city in Northern coast region is chosen to examine the thermal performance of Semi-transparent a-si PV integrated in office building facades using the weather data are arranged by World Meteorological Organization Region and Country on the EnergyPlus program website. The thermal analysis was carried out using the climate data for Ismailia city (Ismailia 624400 (ETMY)) as the closest point to the selected location [22].

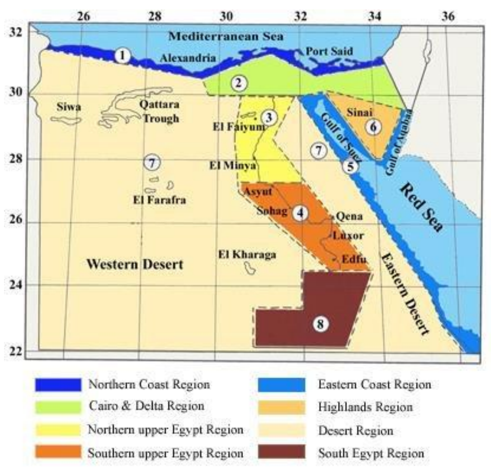

Fig. 3. Egypt climate zones [21].

III. MATERIALS AND METHODS

Commercially available semi-transparent thin film a-si glazing with 40% transparency (60% area of the glazing is covered by solar cells) was chosen in this research, which attain daylight penetration and outdoor views [15]. Then DesignBuilder (v6.1) software as a graphical interface with EnergyPlus (v8.9) as the simulation engine were used. Energyplus is building energy simulation program having the abilities for modelling building heating, cooling and lighting loads as well as other energy flows [23] which helps to discover the effect of a-si glazing on heating, cooling and lighting energy demand as well as the power generation rate of implementing window integrated PV under the distinctive climate in Egypt. The module used in the study is defined through many points such as geometry, using schedule, climatic conditions and façade properties. The specifications of STPV a-si module used in the simulation is identified, considering the effect of using the artificial lighting control system. All the results are then compared with the results in case of using the conventional glazing of single clear glass (Sgl Clr glass).

III.I Amorphous Silicon (a-si) Glazing Characterization

In this research, commercially available semi-transparent thin film a-si glazing with 40% transparency was selected as the example technology. The specifications of chosen STPV module required for the simulation are presented in Table 1; visible light transmittance degree and thermal properties (u-value and SHGC), in addition to specifications of single clear glass (CG).

Table 1. Specifications of Semi-transparent a-si PV glazing and conventional single clear glass [15].

Glazing type	Thickness mm	VLT %	U- value W/m^{2}K	SHGC %
a-si PV	21	40%	2.783	0.367
Sgl Clr 3mm	3	88%	6.121	0.81

III.II Prototype Office Description

Two office` rooms inside a large south and west facing façade building were used in the simulation study. The prototype office has dimensions of 3.5m (width) × 8m (depth) × 3.5m (height) as shown in Fig. 1. Effects from adjacent buildings, vegetation or other obstructions were considered negligible in the simulation. The window under test which is mounted on the South wall for office 1 and mounted on the West wall for office 2 is the only surface of the room that was exposed to exterior environments while the other surfaces of the room were assumed to be adiabatic to avoid heat transfer in between so that the prototype office can be correctly analyzed.

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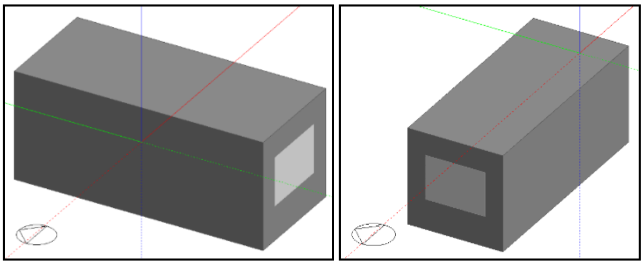

Fig. 4. The 3D prototype office 1&2 as modelled in DesignBuilder.

These rooms are to be used as assistants' offices in Horus University, Egypt. Each for three people from 9:30 to 4:00 Five-day week with two days off (Friday and Saturday). An illuminance level threshold of 500 lux is used as the lower limit for lighting. The internal heat gains and building construction details are shown in Table 2 and Table 3, respectively. The construction details values used in simulation follow the Egyptian Specifications for Thermal Insulation Work Items [24]. A split with no fresh air-cooling system is chosen for the offices under test.

Table 2. HVAC and occupancy parameters for DesignBuilder simulations.

Workday	9.30 - 16.00
Work week	Sun -Thurs
Occupancy density (people/m^2)	(3 persons) 0.11 person/m^2
Heating setpoint temperature [°C]	22
Lighting density	6.4 W/m2 (by using 4 lamps each lamp consumes 40 watt/hour)
Cooling setpoint temperature [°C]	24
Illuminance set point	500 lux
Orientation	South & West
Total simulated area	3.5*8=28m^2
Clear height	3.5m
Window – to – wall ratio (WWR)	30%
Transmittance degree	40%
Equipment	Non

Table 3. Construction details of office room used in simulation [21].

Layers (outer to inner)	Thermal conductivity W/(m□K)	Density kg/m^3	Specific heat J/(kg□K)	Thickness cm
Exterior walls Cement mortar	0.88	2800	896	2
Solid brick	1	1950	826	25
Cement mortar	0.88	2800	896	2
Interior walls	assumed to be adiabatic			
Floor	assumed to be adiabatic			
Ceiling	assumed to be adiabatic			

IV. RESULTS AND DISCUSSION

IV.I. Energy Performance Due to Heating, Lighting and Cooling

Initially, we study the impact of STPV window in a passive state, without generating power, on the building's energy consumption. The energy consumption is expressed in terms of kWh per year and they are further divided into heating, cooling and lighting energy consumption.

Table 4. Comparison of electricity consumptions due to heating, cooling, and lighting under the different configurations analyzed.

Electricity consumption [kWh/year]	**Heating electricity consumption**	**Cooling electricity consumption**	**Lighting electricity consumption**	**Overall variable electricity consumption**	**savings achieved in %**
Sgl Clr (South)	15.20	1567.50	31.11	1613.81	
PV (South)	135.24	968.73	72.63	1176.6	27%
Sgl Clr (West)	140	1745.27	38.22	1923.49	
PV (West)	317.24	1130.22	112.67	1560.13	19%

The thermal simulations for the selected offices (Table 4) showed that, one of the important results observed in the two cases is that the heating demand can be considered negligible because of the obtained heating loads are hardly observable. the integrated semi-transparent a-si PV glazing result in fewer accessible daylight and increased lighting energy consumption. It can be obviously noticed that the case of using single clear glass has the lowest artificial lighting loads due to having the maximum transmittance degree. In the meantime, PV glazing will also decrease the transmitted solar heat gain, which lead to fewer cooling load in summer and more heating load in winter. It is interesting to illustrate that the use of a-si PV glazing significantly decrease the amount of solar gains due to external window into the building compared to clear glass as shown in Table 5.

Table 5. Comparison of yearly incident radiation on windows surfaces and corresponding transmitted values for the glazing types.

	South	West
CG, Solar gains exterior window [kwh/year]	2227.22	2100.36%
PV, Solar gains exterior window [kwh/year]	899.69	862.27
Fraction	40%	41%

IV.II. Energy produced by BIPV window

We now explore the additional benefit of the STPV windows in generating power. As shown in Table 6, the use of STPV window in South orientation (an area of about 3.5 m^2) returned in total 128.48 kWh/year of electricity. This corresponds to 11% of the overall electricity demand. However, in case of the West orientation STPV window returned in total 126.544 kWh/year of electricity, which corresponds to approximately 8% of the overall electricity demand.

Table 6. Annual electricity yield [kWh/year] due to a-si PV integrated glazing.

	South	West
Total generation power [kWh/ year]	128.48	120.22

V. CONCLUSION

Energy crisis Egypt facing today is becoming more critical besides the high level of pollution and harmful emissions. Cooling loads are particularly dominant in Egypt because of the high solar heat gains nearly during the whole year. The effect of using semi-transparent photovoltaic (STPV) in office building facades on building energy performance and indoor environment quality is evaluated through combined optical, electrical and energy model in Egypt's climate with considering the effect of using the artificial lighting control system. using DesignBuilder software as a graphical interface with EnergyPlus as a simulation engine have been used to exploring the performance of semi-transparent a-si PV glazing with 40% transparency and 30% Window to wall ratio (WWR) on building heating, lighting and cooling energy consumption. Compared to single clear glass, this study found that although the presence of a-si PV glazing increases the heating and lighting load, at the same time it reduces the cooling demands significantly. The balance between the generated electrical powers, reduced cooling loads and increased heating and lighting loads produces a significant energy preservation potential. In South orientation an area of a-si PV about 3.5 m^2 caused an overall electricity consumption drop from 1613.81 to 1176.6 KWh/year and returned in energy generation of 128.48 KWh/year which, corresponds to about 11% of the overall electricity demand. However, in case of the West orientation a-si PV window caused an overall electricity consumption drop from 1923.49 to 1560.13 KWh/year and returned in energy generation of 120.22 KWh/year which, corresponds to around 8% of the overall electricity demand. These results are promising, mainly for buildings with large window-to-wall ratios. In conclusion, windows with integrated semi-transparent a-si PV glazing offers a variety of benefits for energy preservation and carbon footprint of the buildings. This paper aims to elaborate a process for developing a representative model to assist in future policy. The work presented is mainly for office buildings but also, proposed to be widely replicable targeting to serve as an easy mechanism to implement example for large-scale activities.

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