Optimizing the Artificial Lighting in a Smart and Green Glass Building-integrated Semi-Transparent Photovoltaics: A Multifaceted Case Study in Egypt

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Abstract: - Numerous increases in CO_2 emissions are recognizable nowadays. Consequently, building integrated photovoltaics (BIPV) glows up as a trendy future solution. BIPVs are introduced by substituting one of the building components with a green energy harvesting source seeking for sustainability. Herein, we propose a BIPV techno-economic feasibility by utilizing in-Lab fabricated semi-transparent solar cells as a glass interface. Three alternatives have been taken into consideration with proposing on-roof Photovoltaic (PV) system (alternative #1) and semi-transparent solar cells working as glass interfaces (alternative #2) while keeping the governmental grid as a reference alternative (alternative #3). Daylight simulations and electric lighting loads optimization are investigated showing an overall energy budget per alternative. An optimum alternative with an overall excess energy of around 88 MWh as annual energy production was reached, while satisfying 100% of the targeted electrical loads. Levelized cost of energy (LCOE) is demonstrated as an economic parameter to evaluate the three proposed alternatives.

Key-Words: - Energy management, Load management, Lighting, Optoelectronic devices, Photovoltaic cells, Solar energy.

1 Introduction

The need for alternative energy sources is a global urgent issue, where energy consumption, based on fossil fuels, is increasing worldwide, leading for more CO_2 emissions [1]. Egypt's electricity generation depends mainly on natural gas and oil [2, 3]. In 2018, Egypt produced 0.71% of the world's CO_2 emissions, making it the 23rd source of carbon emissions worldwide. Consequently, research community in Egypt focused on allocating the energy consumption distribution among various sectors, seeking for green alternatives. In [4], it was estimated that over 55% of Egypt's energy consumption can be attributed to buildings (Commercial, industrial, and residential). Furthermore, lighting load constitutes an estimated 28-30% of the total Egyptian power consumptions [5, 6]. Thus, studies have risen to inspect alternative energy sources, in the Egyptian context, to meet the increasing energy consumption, and green energy needs, through techno-economic feasibilities [6-10].
Building-integrated Photovoltaics (BIPV) has been introduced in literature as a booming solution towards green, smart and sustainable buildings [11-14]. BIPVs are technologies that replace conventional building components with components that harness solar energy [15]. One of these components can be glass windows, to be replaced by semi-transparent solar cells to provide a new range of possibilities in terms of smart building sustainability. Semi-transparent solar cells have been studied as a possible green energy source in various contexts [16, 17]. The variables that seem critical to the studies in the technical aspect were window to wall coverage ratios (WWR), orientation of building walls, transparency, and surface area/volume ratio of rooms [18]. While this work targets artificial lighting loads as its main optimization goal, other studies have targeted

heating [19-21], ventilation [22], and air conditioning loads [23, 24] in BIPVs.

The semi-transparent PV technology has the potential to significantly reduce CO_2 emissions and fossil fuel consumptions by using alternative sources of green energy such as solar energy [17]. A window replacement option in terms of energy saving in multiple conditions and factors has been investigated in [25], through studying the WWR and window orientations impacts. Additionally, a new figure of merit was introduced in [26], called the NEB (Net Energy/Electrical Benefit), with considering heat loss and artificial lighting as a key evaluating parameters. Using NEB, various semi-transparent PVs were tested where a 70% WWR semi-transparent PV solutions showed the most energy saving option [25]. Another study by Peng et. al in [18] used a c-Si based laminate semi-transparent PVs in constructing a window where electrical power, thermal energy, and daylighting performance were investigated. The window was 1.4 x 1.7 m^2 and produced 1940 Wh/day. The proposed window in [18] was then integrated in a BIPV with artificial lighting loads of 431 Wh/day per room making the net energy production 1509 Wh/day [18, 27].

Another critical parameter in fabricating semi-transparent PVs is the PV transparency as it enables a trade-off between PV efficiency and daylight utilization [28, 29]. Dingming et. al in [17] performed an in-depth analysis of the daylight aspect of semi-transparent PV windows. The study highlighted Cadmium telluride (CdTe) PV window daylight performance in terms of quality of light and color. It was shown that the windows provided acceptable lighting at a 60% WWR; however, the authors didn't provide any analysis concerning the extracted electrical power [17].

In this study, three techno-economic feasibilities are proposed with enabling on-roof PV system (alternative #1) as well as semi-transparent solar cells (alternative #2), while considering the conventional grid supply scenario as a reference alternative (alternative #3). The study demonstrates the utilization of both sunlight and indoor lighting through bifacial solar cell harvesters. Three fabricated prototypes are tested, with demonstrating a complete integration process to provide larger area semi-transparent solar cells. Daylighting is simulated at various windows transparency levels, seeking for an optimum artificial lighting load for a seven floor office building in Egypt. Technical as well as economic parameters for each alternative are simulated and the overall systems performances are evaluated.

2 System Under feasibility Study

The proposed BIPV, under investigation, is chosen to be localized in New Cairo, Egypt (long 31°29'35.47"E, latitude 30° 1'33.91"N) as shown in Fig.1-a. The building footprint is about 1150 m² with 64 m length along the north axis; its area is 3928 m² with 10 meters Setbacks from all sides. The building consists of a ground floor, 6 typical floors and roof, each floor has 3.25 meters height. Consequently, the total building height is around 23 meters. All data related to the chosen BIPV are listed in Table 1. Another adjacent building (26 m height) locates beside the office building and casts a shadow over the project from the eastern direction as shown in Fig. 1-b. An overview of the building with its southeast and southwest views is presented in Fig. 1-c and Fig. 1-d. BIPV under feasibility consists of a photovoltaic on-roof array (alternative #1) and/or semi-transparent photovoltaic (PV) system (alternative #2) connected to a maximum power point tracking system (MPPT), utility grid, DC-AC inverter and net metering. In this study, three alternatives are investigated; a normal concrete building with lighting loads fed from the grid is studied as the reference case (alternative #3). Another alternative utilizes normal commercial Si-based PV system on-roof (alternative #1). The final alternative (alternative #2) utilizes double glazing semi-transparent bifacial PVs for light harvesting and daylight utilization as well as keeping the on-roof PV modules.

2.1. Load Topology

The electric loads in the building understudy can be represented by lighting loads, normal sockets, power sockets, air conditioners and light current systems such as fire alarm systems. The current feasibility integrates the lighting load and the fire alarm system to be supplied from BIPV renewable resources.

Luminaire LEDs type 33 watts manufactured by PHILIPS Company have been used in this study. The specification of the luminaire presented in Table 2. The consumption of lighting load has been calculated for one year based on 20 days per month and 10 hours per day. A simulation has been implemented using DIALUX program to ensure an average of 300 lux for the overall building according to the Egyptian and British codes.

The DIALUX simulation has been implemented in a room 12 m x 14 m to be generalized for the buildings, as shown in Fig. 2. The minimum luminance has been reached is 280 lux at corners and maximum 360 lux in the center. The total luminaires that satisfied the required luminance are

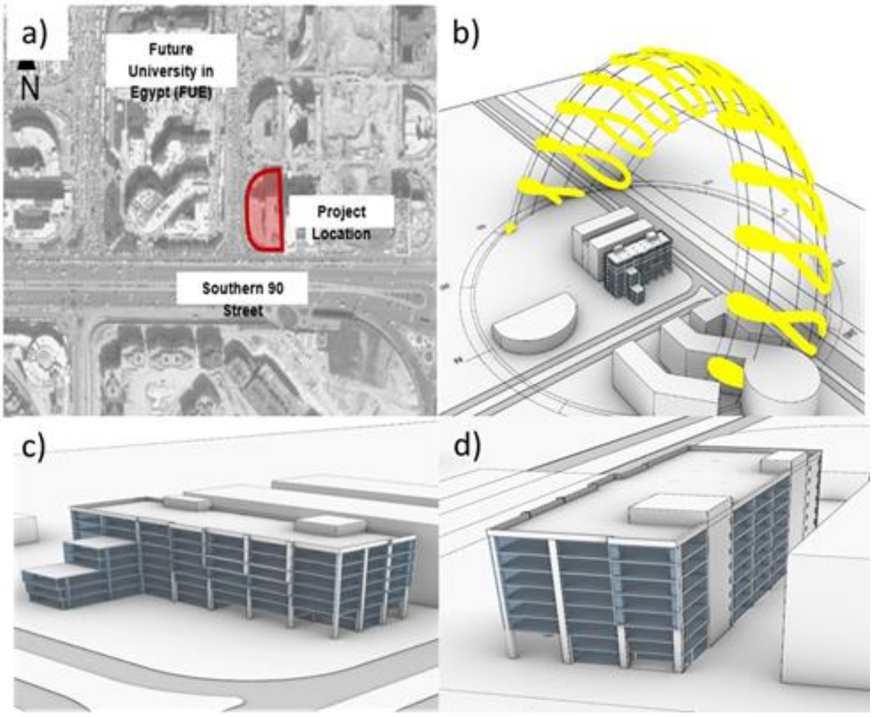


Fig. 1. a) Project location and surroundings, b) Aerial view showing surroundings and solar path over the year, c) Southwest view of the building and d) Southeast view of the building.

20 luminaires and the distances between each two LEDs were ensured according to the British and Egyptian standards.

An estimation of the total number of luminaires of the ground floor has been calculated to reach 144 LED luminaires. Consequently, the overall required lighting luminaires for the building are estimated to be 1099 luminaires (cf. Fig. 3). Therefore, the total power consumed yearly by lighting loads and fire alarm systems is 87.6 MWh/Year as listed in Table 3. Additionally, a rough estimation for the overall energy consumption of the building, based on the Egyptian code, was estimated, excluding lighting and fire alarms, to be 5705 MWh/Year, as listed in Table 3 under other loads. Following the reference alternative (alternative #3), where a conventional concrete building is supplied through the grid, and the electrical tariff for 1 kWh is 1.45 EGP. Consequently, the cost per month estimated to be 10,593 EGP/Month for 7.3 MWh/Month. This cost with the associated levelized cost of energy (LCOE) of 1.45 EGP will be considered as the reference to evaluate the other two proposed alternatives.

Table 1. Proposed BIPV under feasibility study

Site Name	Office Building in Cairo.
Roof area	983 m^2
Number of Floors	7
South Side Area	243 m^2
North Side Area	382 m^2
East Side Area	818 m^2
West Side Area	287 m^2

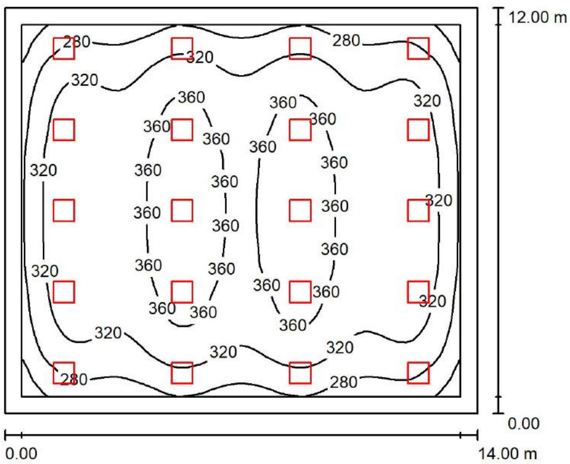


Fig. 2. Distribution of luminaires in the proposed room

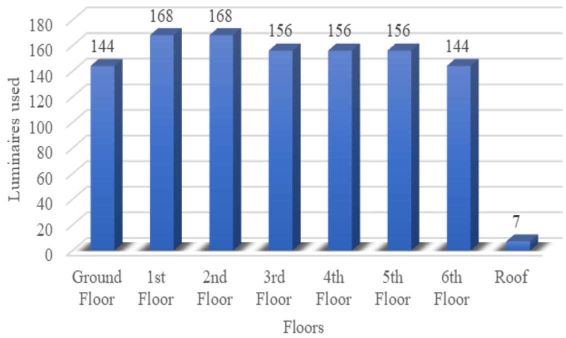


Fig. 3. Number of Luminaires on each floor

2.2. Semi-transparent Solar Cells

The utilization of glass building in embedding semi-transparent solar cells is considered as one of the key challenges in the current study. Herein, mesostructured-based solar cells (MSSCs) have been used to demonstrate the semi-transparent solar cell concept. MSSCs, first introduced in our previous work [30], includes solar cells with mesoporous TiO_2 layer acting either as an active layer or as an electron transport layer. The current feasibility introduces both dye sensitized solar cells (DSSCs) and Perovskites solar cells (PSCs) as semi-transparent solar cells for BIPV application.

Following our previous investigation in [28, 30-33], it can be concluded that DSSCs are capable of acting as semi-transparent solar cells with tunable transparency/efficiency with respect to the mesoporous active layer thickness (cf. Fig 4-a). 5 cm × 5 cm DSSCs are fabricated with 11 mm FTO coated glass electrodes, acting as a double glazing window. N719 standard dye is used where a complete recipe can be found in [28]. Three fabricated and characterized prototypes have been examined with various efficiencies as well as transparencies; see Fig 4-b and Table 4. Additionally, as the counter electrode of the cell is fabricated using FTO coated glass; the cell has been designed to harvest indoor lighting as well. The complete bifacial cells parameters are listed in table 4.

To feasibly assemble a system that can be integrated into a large building, the construction of a window for a single area of coverage is considered. The window fabrication process could undergo two possible routes, the enlargement of the individual cell, and the construction of windows through using current produced samples. The approach of choice was the latter option. The proposed design integrates the fabricated cell as a unit in an array of connected cells (cf. Fig. 5). The proposed window is connected using transparent adhesive to decrease loss of transmittance.

Table 2. Specification of Luminaire LED

Luminaires LED type	PHILIPS RC133V W62L62 LED36S/840 OC
Luminous flux (Luminaire)	3600 lm
Luminaire Wattage	33.0 W
Luminaire classification according to CIE	100
Fitting	LED36S/840/- (Correction Factor 1.000)

Table 3. Loads calculation

	W	# of units	W/h	MWh /y
LED	33	1099	36267	87.0408
Fire Alarm	110	1	110	0.6336
Total lighting loads and fire alarm loads per year				87.6
Other loads per year				5705

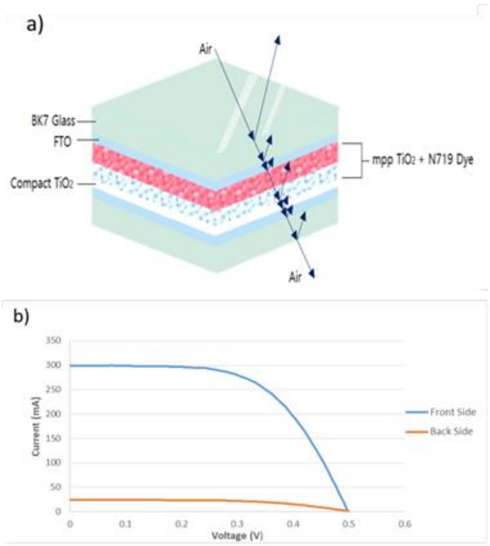


Fig. 4. (a) a schematic for MSSC used as a semi-transparent solar cell. (b) I-V curve for front and back contact harvesting using 43% transparent solar cell.

Table 4. Semi-transparent MSSCs parameters

Cell #	MSSC-1	MSSC-2	MSSC-3
T (%)	33%	43%	53%
Direct light eff. (%)	3.12%	2.52%	1.78%
Diffused light eff. (%)	0.98%	0.51%	0.43%
Indoor light eff. (%)	0.21%	0.19%	0.08%
Glazing	Double		
Thickness (mm)	22.54	22.32	22.15

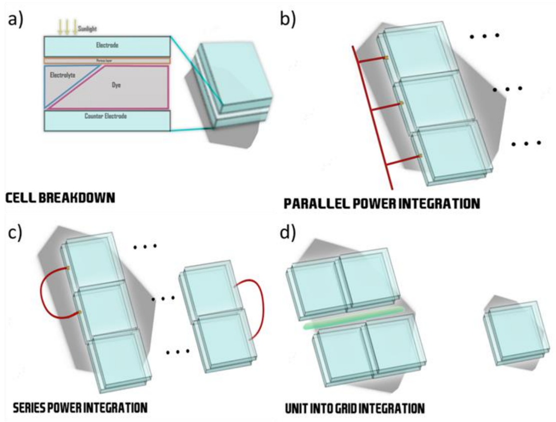


Fig. 5. Cell to window integration procedure

3. Technical Results

Looking forward to providing several ways to generate energy for building and saving cost, two alternatives for the solar system integration in the proposed BIPV were investigated. One of the alternatives is using the ordinary Si-based PV system to cover the roof of office building (alternative #1), with estimated space up to 983 m^2. In the other alternative, semi-transparent solar cells have been utilized with enabling the day-lighting privileges on one hand and harvesting both sunlight as well as artificial lighting through the proposed bifacial solar cells from the other hand (alternative #2). While alternative three is kept as a reference case where the lighting and fire alarms loads are supplied from the grid as indicated earlier.

3.1 Alternative #1: Si=based PVs On-roof

As mentioned earlier in the introduction, the target of this study is to minimize the consumption cost of the artificial lighting loads in the proposed BIPV. Consequently, the current alternative introduces the utilization of the roof area to implement a number of solar panels to supply the targeted load seeking for low cost and low CO_2 emissions. A complete sizing process has been implemented using an online PV sizing tool developed by our group and can be accessed through [34]. In this case, the building is assumed to be with concrete solid faces with no sunlight entering the building. By utilizing the roof area of 983 m^2, 174 units of PV panels, each with 335 W have been sized. As indicated in the exported report presented in Fig. 6, the data of each month have been observed to determine the annual produced energy by 99.1 MWh/Year. Moreover, Table 5 shows the data information and results from implemented PV panels on the roof, including the power inverter and the specific power required from each cell to covering the total consumption. It can be observed from this alternative that 100% of the targeted load will be supplied by the on-roof PV system. Additionally, excess annual energy production of 11.5 MWh/Year will be supplied to the grid through the net metering system. This provides around 0.2% of the overall system consumptions excluding the target loads.

Month	GlobHor (kWh/m²)	E_Grid kWh
January	144	6,133.72
February	169	7,198.61
March	195	8,306.09
April	218	9,285.78
May	223	9,498.75
June	216	9,200.59
July	225	9,583.95
August	224	9,541.35
September	208	8,859.82
October	199	8,476.47
November	158	6,730.06
December	148	6,304.11
Year	2,327	99,119.29

FIG. 6. A detailed sizing report from PV CELT

Table 5. Alternative #1: PV on-roof Technical Analysis

Average Monthly Consumption	7.306 MWh
Power required for covering the consumption	58.25 kWp
Number of Modules (Using Jinko – 335 W)	174 Units
Power of Inverter	48.54 kW-AC
Annual Produced Energy	99.119 MWh
The tilt angle of the PV Panels	28 Degree
Circuit breaker Capacity	125 A
Covering the Percentage of total power	100%

3.2 Alternative #2: Glass Building with Semi-transparent Solar Cells

In this alternative glass BIPV is proposed with integrating semi-transparent solar cells as a decorative glass interface for the BIPV four faces. The suggested design enables the utilization of day-lighting in optimizing the artificial lighting loads used in the current feasibility. Moreover, the integrated semi-transparent cells harvest the sunlight, direct and diffused, as well as artificial indoor lighting in a bifacial manner. According to the Illuminating Engineering Society (IES), two methods are approved for the daylighting calculations: Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) [35]. In the coming paragraphs, both methods will be illustrated.

Spatial Daylight Autonomy is a measure of daylight luminance sufficiency for a given area, reporting a percentage of floor area that exceeds a specified luminance (e.g., 300 lux) for a specified percentage of the analysis period [35]. Accordingly, it examines whether a space receives enough daylight during standard operating hours (8 a.m. to 6 p.m.) on an annual basis using hourly luminance grids on the horizontal work plane.

The sDA of the building has been proposed in Fig. 7. Acceptance Criteria in the case of LEED v4, sDA300/50% indicates that a certain present of area must meet or exceed 300 lux for at least 50% of the working hours per year. The proposed simulation has been conducted for 43% transparency double glazing glass, as described in section 2.2 (MSSC-2).

On the other hand, Annual Sun Exposure (ASE) measures the percentage of floor area that receives more than 1000 lux of direct sunlight for more than 250 occupied hours per year (c.f. Fig8). As such, this study begins by calculating only the direct sun falling on a horizontal outdoor surface. This is then multiplied by window transmittance and used to select sun positions that only have values above the 100 lux threshold. The resulting sun vectors are then used in a "sunlight hours" calculation to determine the floor area that exceeds 250 hours per year. The result of the ASE Analysis showed that the ASE is almost equal in all floors. 33% of each floor area receives more than 1000 lux of direct sun for more than 250 occupied hours per year as illustrated in in Fig. 8.

According to [36] daylight glare evaluation has been the recent focus of research on visual comfort since newer office buildings have large glass facades offering daylight provision and outdoor views. Available glare indices are related to source luminance size and location, view direction and background luminance.

Following the daylighting analysis implemented above, simulations have been used to reduce the total power by a specific percentage based on the sunlight over the office building. Therefore, the percentage of reducing the total power for each floor has been calculated according to the intensity of the sun on each side of the building. The daylight coverage percentage for each floor is illustrated in Fig. 7. Consequently, the needed artificial lighting loads have been recalculated to be 55.69 MWh/Year with average reduction reaches 36% with respect to the model proposed in alternative #1 (see fig. 9). In the current alternative, MSSC-2 with 43% transparency is utilized in implementing the BIPV understudy. Semi-transparent solar cell is crucial technology for providing huge support to cover the energy consumption from loads. By optical modeling and simulations, the total power observation from transparent windows solar cells has been estimated by 44.5 MWh/Year, following the data provided in section 2.2. The calculations have been estimated assuming the south side is directed to direct.

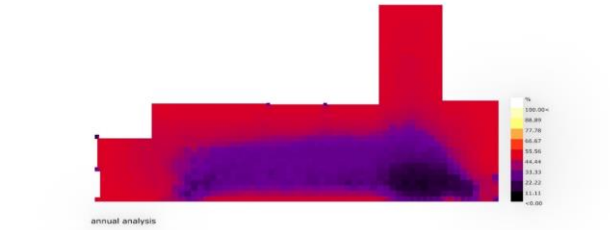
Finally, in the current alternative, MSSC-2 with 43% transparency is utilized in implementing the BIPV understudy. Semi-transparent solar cell is crucial technology for providing huge support to cover the energy consumption from loads. By optical modeling and simulations, the total power observation from transparent windows solar cells has been estimated by 44.5 MWh/Year, following the data provided in section 2-2. The calculations have been estimated assuming the south side is directed to direct sunlight, while the north side is directed to diffused sunlight. Both east and west sides are treated as 50% of the time directed to direct sunlight and another 50% to diffused sunlight. On the other hand, indoor harvesting is simulated assuming 200 lux artificial lighting with considering the associated spectral mismatching. The overall energy budget of alternative #2 is listed in Table 6. It can be observed from this alternative that still 100% of the lighting and fire alarm load is satisfied. However, more excess energy, 87.91 MWh/Year, is now supplied to the grid per year. Herein, 1.54% of the overall energy turns to be green. This is approximately eight times the excess energy demonstrated in alternative #1.

Table 6. Alternative #3 Energy Budget

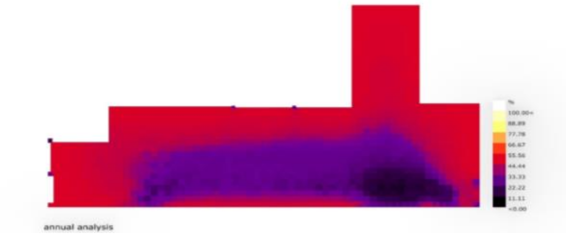
Consumed or supplied energy	Energy in MWh/Year
Lighting loads and fire alarms with including daylight effect	55.69
On-roof PV system annual production	99.1
Semi-transparent (43%) glass sides annual production	44.5
Excess energy directed to the grid	87.91

4. Economic Analysis

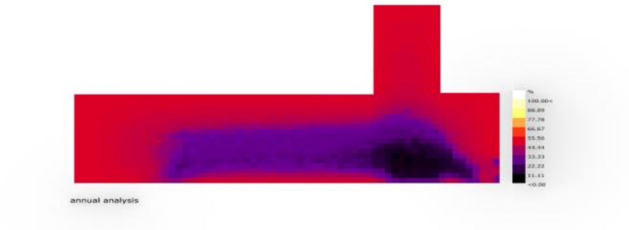
The second portion of this study investigates the economic analysis for the proposed three alternatives. In alternative #3, as the governmental grid is used as the main source of energy, the LCOE can be taken directly as the electricity tariff (1.45 EGP/kWh for 2020). Assuming a project lifetime of 20 years, with inflation rate of 10.4%, an average LCOE for alternative #3 can be calculated to be 5.2 EGP/kWh. In alternative #1, all the economic analysis have been implemented using the PV-ON online tool [34], showing an average LCOE of 0.92 EGP/kWh across the same lifetime of the project.



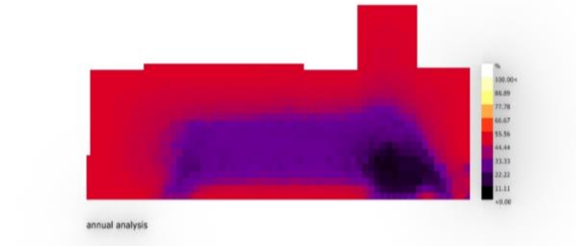
(a) Diagram shows sDA study on the G floor which has area = 32% covered with Daylight



(b) Diagram shows sDA study on the 1st floor which has area = 35% covered with Daylight



(c) Diagram shows sDA study on the 2nd floor which has area = 36.6% covered with Daylight



(d) Diagram shows sDA study on the 3rd floor which has area = 35% covered with Daylight

(e) Diagram shows sDA study on the 4th floor which has area = 36% covered with Daylight

(f) Diagram shows sDA study on the 5th floor which has area = 40.2% covered with Daylight

(g) Diagram shows sDA study on the 6th floor which has area = 41.5% covered with Daylight

Fig. 7. sDA analysis of each floor in the proposed building.

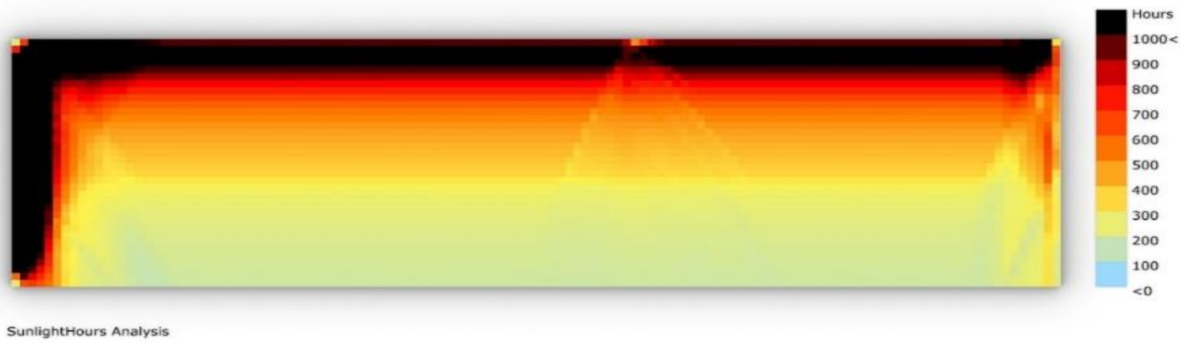


Fig. 8. ASE study on the 5th floor which has area = 33% receives more than 1000 lux of DIRECT SUN ONLY for more than 250 occupied hours per year.

In order to investigate alternative #2 from economic prospective, a full estimation for the cost of the MSSC semi-transparent solar cell is needed. The cost is analyzed as direct and indirect cost. Direct cost includes materials involved in the manufacturing process (see Table 7), while indirect costs includes labour cost and machines depreciation. In the current study, two types of FTO coated glass have been used; the first is commercial glass from Sigma Aldrich, while the second is in-lab fabricated using CVD techniques [37]. Logically, the in-lab fabricated FTO glass showed lower direct cost than the corresponding commercial one (52.42 EGP to 96.52 EGP per 5×5 cm^2 cell). As an overall fabrication cost the MSSC-2 cost using in-Lab FTO coated glass records 64.59 EGP/cell. Consequently, the overall LCOE for alternative #3 reached 9.85 EGP/kWh.

Table 7. MSSC COST PER LAYER

Material	Quantity	Cost in euro
TiO_2 powder	3.5 g	9.37125
Triton X	3 ml	1.9275
N719 dye	0.2 g	100.6
I_2 Iodin	0.24g	4.584
Acetonitrile	2 ml	0.8864
Ethylene glycol	5 ml	0.61
KI Potassium iodide	2.49	0.447
Graphene coated glass	2	0.1
Indium tin oxide FTO	2 g	5.04

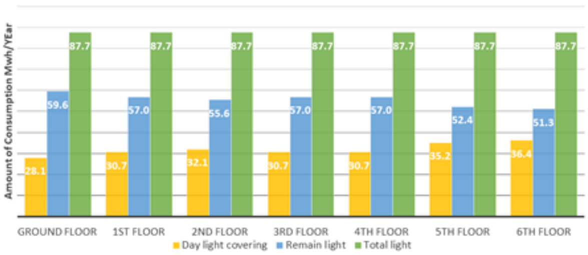


FIG. 9. Office building day-lighting analysis

Numerically, it can be noted that the LCOE for alternative #2 is nearly double that in alternative #3 and ten times the LCOE in alternative #1. However, we should consider that the calculated cost for the MSSC is an in-Lab fabrication cost, where mass production cost should totally differ. Some relevant studies can be found in [38, 39]. Moreover, the integration of new technology for semi-transparent solar cells with bifacial capabilities may be considered as a future booming technology even with relatively higher present cost, as utilizing perovskites and dyes in solar cells for window applications is collecting interests everywhere [40, 41].

5. Conclusion

43% semi-transparent solar cells are introduced in the current feasibilities to replace normal glass in an office building in Egypt. The energy budget for the system under-test has been evaluated using two various alternatives by utilizing the roof area and the glass sides for energy harvesting, while considering the running scenario with grid as the reference alternative. Lighting loads and fire alarms were considered as the targeted loads with optimizing the first through enabling daylight simulations across the year. 100% targeted load coverage has been achieved in both alternatives #1 and #2, while alternative #2 promotes eight times excess energy to the grid rather than alternative #1. From an economic perspective, alternative #1 recorded the lowest LCOE taking into consideration that the cost investigated in alternative #2 is contributed to the in-Lab fabrication cost which should show rapid minimization whenever it becomes a mass production cost.

Acknowledgment

The authors would like to acknowledge the support and contribution of the STDF in this work. As part of the STDF Project entitled, “Mesostructured Based Solar Cells for Smart Building Applications”, Project ID#33502. Additionally, the authors would like to thank the Centre for Emerging Learning Technology (CELT), directed by Prof. Hani Ghali, and Nanotechnology research centre (NTRC), directed by Dr. Amal Kassary, in The British University in Egypt for providing all the fabrication facilities needed. Finally, the authors would like to thank Dr. Frank Marllow and his team in Max-Planck-Institut für Kohlenforschung as the work presented here is considered as an extension for the cooperation and shared publications [28, 30].

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Author Contribution: The main idea and conceptualization for the current study is contributed to the last author (**Sameh O. Abdellatif**). Concerning the simulation work and feasibility study implementations, all authors contributed equally to the paper in the following manner: M. O. Ahmed, A. K. Madkor and P. Makeen contributed with the PV sizing simulations, while S. I. Betelmal, M. M. Hassan, and S. O, Abdellatif considered the semi-transparent solar cells prototyping and characterization. Mohamed M. Abdelsamee, Ahmed Ayman, Mohamad H. El-Adly tackle the economic analysis and finally, Ashraf Nessim and Sameh O. Abdullatif contributed with the sunlight simulation and the optical analysis respectively.