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Energy Efficiency of Transparent Solar Cell-Based Sustainable Architecture in Arid and Semi-Arid Climates

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Abstract. As global urbanization accelerates, the demand for sustainable building envelopes has led to the emergence of Transparent Solar Cells (TSCs) as a cornerstone of Building-Integrated Photovoltaics (BIPV). The integration of TSCs into building envelopes presents a promising pathway toward energy-efficient and sustainable architecture, particularly in regions with high solar irradiance. This paper presents an assessment of the energy, environmental, and economic benefits of deploying transparent photovoltaic glazing for sustainable buildings in warm regions. A practical case of installed TSCs in New Borg El-Arab City, Alexandria, Egypt is considered. Situated at the northeastern edge of the Sahara Desert, the site presents a dual-challenge: extreme solar irradiance and high cooling demand. Energy benefits are quantified from two complementary aspects: on-site electrical generation and reduction of cooling demand due to partial reflection and absorption of solar radiation. A detailed economic analysis, including capital costs, operational savings, and payback period, is presented and compared with conventional facade alternatives. A carbon dioxide emissions reduction assessment is also performed. Results demonstrate that transparent solar cells can significantly enhance building energy performance while offering attractive long-term economic and environmental benefits for sustainable urban development in arid and semi-arid climates. TSC facades were estimated to reduce total building energy consumption by 30–40%, with simple payback periods of 6–9 years under current local electricity prices.

Key words. Transparent solar cells, building-integrated photovoltaics, energy efficiency, HVAC.

1. Introduction

The building sector is currently responsible for approximately 30% of global energy consumption and 26% of energy-related greenhouse gas emissions, with space cooling being the primary driver of peak demand in warmer regions [1]. In rapidly developing nations, the push for "New Cities" has created an architectural trend dominated by glass-curtain walls. While aesthetically pleasing, these structures often function as "urban greenhouses," trapping solar radiation and necessitating massive energy expenditures for cooling. The thermal gradient across a standard glass facade results in a heat flux that can account for up to 60% of the total HVAC load. An example for such new cities is New Borg El-Arab City, a strategic industrial hub located at 30.9°N near Alexandria, Egypt that operates under extreme climatic stress. Positioned on the northeastern fringe of the Sahara Desert, the city experiences a hot semi-arid climate characterized by intense solar radiation and high ambient temperatures. Summer temperatures frequently exceed $38°C$, and the area receives an annual global horizontal irradiation (GHI) exceeding 2200 kWh/m^2. Conventional clear glazing in modern high-rise architecture acts as a thermal trap, necessitating massive HVAC intervention to maintain a standard indoor comfort temperature of $20°C$. The resulting energy consumption leads to high operational costs and significant carbon footprints. These environmental characteristics increase cooling loads in buildings and intensify the demand for electricity, thereby motivating the exploration of building envelope technologies that can both generate energy and mitigate thermal gains.

In response to these challenges, building-integrated photovoltaics (BIPV) have emerged as an effective solution to improve building energy efficiency while utilizing available facade and window areas [2]. BIPV offer an effective pathway toward reducing building energy demand and associated emissions. Conventional opaque photovoltaic panels, however, are often unsuitable for extensive facade integration due to aesthetic constraints and the need for daylighting [3]. The discussed environmental conditions made the area an ideal location for BIPV solutions.Transparent and semi-transparent solar cells have recently gained attention as they enable electricity generation while maintaining visual transparency and indoor daylight quality [4]. Transparent solar cells (TSCs) represent a new class of BIPV technology capable of generating electricity while maintaining visible transparency. Unlike conventional rooftop PV systems, TSCs can be integrated directly into windows and facades, offering dual functionality. TSCs can simultaneously provide daylighting, shading, and power generation [5].

The transition from opaque to transparent photovoltaics has been enabled by advances in spectral selectivity. Recent studies [6] highlight the use of Organic Photovoltaics (OPV) and Perovskite Solar Cells (PSCs) that utilize multilayer Fabry-Perot electrodes to achieve viewing-angle-independent "Janus structural colors." This allows the facade to serve as a high-performance power generator without compromising the building's aesthetic identity or the occupants' visual comfort. The evolution of semitransparent and colorful solar cells (STC-SCs) has addressed the historical conflict between energy harvesting and architectural aesthetics. As highlighted by [6], traditional opaque silicon is being replaced by thin-film, organic, and perovskite materials that offer spectral selectivity. Modern research into "Janus structural colors" allows cells to exhibit viewing-angle-independent colors while maintaining high light utilization efficiency (LUE). These advanced cells utilize multilayer stacks, such as the Fabry-Perot electrode structure, to modulate the color-gamut of the facade [7]. This allows architects to replace passive building skins with active elements that provide energy, thermal shielding, and a distinct visual identity without sacrificing natural light [8].

Several studies have investigated the optical, electrical, and thermal characteristics of transparent solar technologies, highlighting their potential role in sustainable building design. Recent research has examined the impact of advanced glazing systems and semi-transparent photovoltaics on building energy consumption [9]. Prior work has shown that such systems can reduce solar heat gains, lower cooling loads, and contribute to on-site renewable energy generation [10]. Other studies have focused on economic feasibility, life-cycle assessment, and environmental impacts, emphasizing the importance of climate-specific analysis and realistic operating conditions [11]. A Hong Kong-based practical case study is presented in [12] to assess the performance of semi-transparent PV windows and compare them to conventional energy efficient windows. The impact of window glazing on load consumption from Heating, Ventilation, and Air Conditioning (HVAC) is studied in [13]. A review on advanced glazing technology and their suitability to was presented in regions with arid and semi-arid climates [14]. The factors impacting the life cycle of advanced building facades are studied in [15]. Furthermore, the impact of BIVP on visual comfort is considered in [16], [17].

Despite these advancements, limited work has addressed the combined electrical and thermal benefits of transparent solar cells in North African and Middle Eastern climates, particularly for rapidly developing urban areas such as New Borg El-Arab City. This paper evaluates the economic and energy performance of transparent solar facades compared to traditional glazing in warm regions. A multi-disciplinary assessment for a practical project in New Borg El-Arab, Egypt is presented. This work provides: (i) a mathematical model for energy generation and thermal savings based on regional solar radiation data, (ii) estimation of HVAC energy savings resulting from reduced solar heat gains while maintaining a desirable indoor temperature, (iii) a comprehensive economic analysis comparing transparent solar facades with conventional glazing and opaque photovoltaic alternatives, and (iv) an environmental impact study. A realistic case study is presented to demonstrate the potential of transparent solar cells for sustainable architecture in arid and semi-arid regions. The study focuses on installed TSC panels in New Borg El-Arab City and analysis their performance and economic benefits.

The paper is organized as follows. Section 2 presents the transparent solar cell technology and approaches for assessing its performance. Section 3 studies the energy benefits of TSCs and provides a comprehensive approach for assessing them. Section 4 provides an approach for assessing the economic and environmental impacts of TSCs. Section 5 provides a practical case study using the proposed assessment approach in Alexandria, Egypt. Finally, the conclusion of this work is provided in Section 6.

2. Transparent Solar Cell Technology

Transparent solar cells (TSCs) is an innovative advancement to building-integrated photovoltaics (BIPV). TSCs are an emerging class of photovoltaic devices designed to transmit a significant portion of visible light while converting ultraviolet and near-infrared radiation into electrical energy. Unlike conventional silicon-based photovoltaic modules, transparent solar cells employ advanced materials such as organic photovoltaics, perovskites, dye-sensitized cells, and luminescent solar concentrators. TSC materials are categorize based on their suitability for a high-UV environment as follows.

- **Organic Photovoltaics (OPV):** High flexibility and tunable color, but require robust encapsulation to prevent degradation from warmer weather and direct sun.
- **Perovskite Solar Cells:** Offer the highest potential PCE but currently suffer from stability issues under high heat and moisture (coastal humidity).
- **Dye-Sensitized Solar Cells (DSSC):** Known for excellent performance under diffuse light and aesthetic "colorful" options, ideal for urban canyons.

The operating principle of transparent solar cells relies on selective spectral absorption. The fundamental advantage of TSCs over traditional PV is spectral selectivity. A TSC is designed to be transparent to the human eye by allowing wavelengths between 400 nm and 700 nm to pass. Visible wavelengths required for daylighting are largely transmitted through the glazing, whereas non-visible wavelengths are absorbed or redirected toward photovoltaic elements. This spectral selectivity, shown in Fig. 1, enables the dual functionality of electricity generation and daylight provision, making transparent solar cells particularly suitable

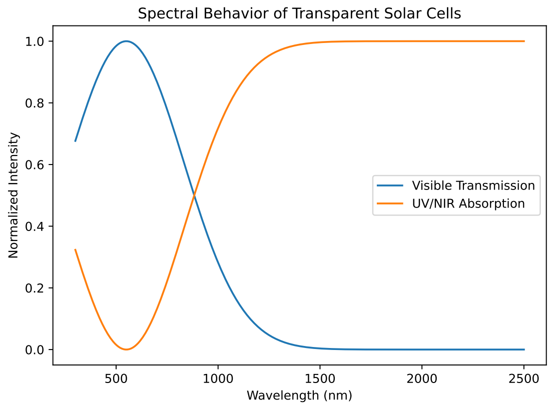

Fig. 1. Spectral behavior of TSC

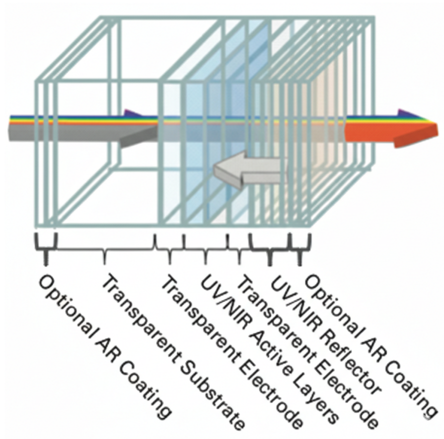

Fig. 2. Internal structure of TSC [19]

for windows, skylights, and curtain walls. Transparent solar cells selectively absorb non-visible portions of the solar spectrum, particularly ultraviolet (UV) and near-infrared (NIR) radiation, while transmitting visible light. Electrical energy is generated from the absorbed spectrum, while the reduction in transmitted infrared radiation directly lowers indoor heat gain. The integration of colorful solar cells is essential for architectural diversity. Solution-processed perovskite cells can be tuned to specific color gamuts as follows [18].

1) **Thickness Modulation:** Adjusting the active layer thickness to create interference patterns.
2) **Structural Coloration:** Utilizing photonic crystals to reflect specific wavelengths.

From an architectural perspective, transparent solar cells can be seamlessly integrated into building envelopes without compromising aesthetics or occupant comfort. Internal structure of TSCs is shown in Fig. 2. Their transparency level can be tailored to specific design requirements, typically ranging from 20% to 60%. Electrical efficiencies are lower than those of opaque photovoltaic modules; however, the large available facade area and the additional thermal benefits often compensate for the reduced conversion efficiency. The primary performance metric is the Light Utilization Efficiency (LUE), defined as:

$$LUE = PCE \cdot VLT \tag{1}$$

where PCE is the power conversion efficiency and VLT is the visible light transmittance. While opaque silicon panels reach 20% efficiency, high-performance TSCs aim for an LUE above 3-4% to ensure architectural viability. Typical performance metrics of transparent solar glazing include visible light transmittance (VLT), power conversion efficiency (PCE), and solar heat gain coefficient (SHGC). Current commercial and near-commercial systems achieve VLT values of 40–70% with PCE values ranging from 5–15%. Although lower than conventional silicon PV modules, these efficiencies are sufficient when deployed over large facade areas. In the Sahara, UV levels are high enough to degrade organic active layers. Future research must focus on inorganic-organic hybrid encapsulants to extend the lifespan of TSCs to match the 30-year lifecycle of standard facades.

3. Energy Generation and Load Reduction Benefits

The utilization of TSC in building facades offers the opportunity to harvest energy benefits from two aspects. The first aspect is the direct power generation which is a shared benefit with conventional rooftop PV systems. The other energy benefit is the decrease in the electrical load of Heating, Ventilation, and Air Conditioning (HVAC) which is the largest electrical load in residential and non-industrial business buildings. While glazed glass facades also can decrease the electrical load of HVAC systems, TSCs are generally more efficient as they absorb energy for electric power generation in addition to the glazing effect. Moreover, TSCs offer the unique capability of combining both benefits without the need for dedicated land area as in the case of conventional PV systems. This section provides an approach for comprehensive estimation of energy benefits of TSC to enable accurate assessment of the overall TSC-benefits.

A. Electrical Energy Generation

Power generation (P_t) from TSCs is a function of the incidence angle θ and the spectral response of the TSC and can be formulates as follows.

$$P(t) = \int_{\lambda_{UV}}^{\lambda_{IR}} G(\lambda,t) \cdot \eta(\lambda) \cdot A \cdot \cos(\theta) d\lambda \tag{2}$$

where A is the facade area, $G(\lambda,t)$ is the instantaneous solar irradiance within the spectrum λ of the TSC at time t, and $\eta(\lambda)$ is the efficiency of the TSC. The active electrical power output (P_{out}) can then be estimated as a function of the incident irradiance on the vertical plane (G_v) and the ambient temperature as follows.

$$P_{out}(t) = A \cdot G_v(t) \cdot \eta_{ef}[1 - \beta(T_c(t) - T_0)] \tag{3}$$

where $G_v(t)$ is the irradiance within TSC spectrum, η_{ef} is the effective efficiency for the targeted TSC spectrum, $T_c(t)$ is the ambient temperature at time t, T_0 is the reference ambient temperature, and β is a factor representing the change of TSC's efficiency with ambient temperature.

The annual electrical energy generated by a transparent solar facade can then be estimated as follows.

$$E_{\text{PV}} = A \cdot \eta \cdot G \tag{4}$$

where A is the facade area, η is the power conversion efficiency, and G is the total annual solar irradiation.

B. Reduction in Cooling Energy Demand

In addition to electricity generation, transparent solar cells reduce solar heat gains by partially absorbing and reflecting incident radiation. This reduction directly lowers cooling loads, which dominate building energy consumption in the studied climate. Environmentally, the combined reduction in grid electricity consumption and associated greenhouse gas emissions contributes to improved sustainability. Over the system lifetime, transparent solar facades can offset several hundred tons of CO_2 emissions. By absorbing and reflecting infrared radiation, transparent solar glazing reduces solar heat gain through the building envelope. Experimental and simulation studies report cooling energy reductions of 20–30% compared with conventional clear or double-pane glass, which directly translates into lower HVAC power consumption and peak demand [20]. This reduction lowers both annual energy consumption and peak cooling demand, which is particularly valuable in regions with constrained electrical infrastructure. Passive savings are calculated by comparing the TSC facade to a standard double-glazed reference (U-value and SHGC).

The thermal performance of transparent facades is primarily evaluated using two metrics: the U-Factor and the Solar Heat Gain Coefficient (SHGC). The U-Factor quantifies thermal insulation; while values vary, typical window ratings fall between 0.20 and 1.20, with lower figures indicating superior insulating properties. Conversely, the SHGC, which ranges from 0 to 1, measures the fraction of incident solar radiation transmitted through the glazing. A lower SHGC value correlates with reduced solar heat gain. [21]. Total building heat gain (Q_{total}) from transparent facades is defined as follows.

$$Q_{total} = A \cdot [U(T_{out} - T_{in}) + SHGC \cdot G] \tag{5}$$

Where Q_{total} is the total heat gain, A is the area of the facade, U is the U-Factor of the facade, T_{out} is the outside temperature, T_{in} is the temperature inside the building, $SHGC$ is the solar heat gain coefficient, and G is the total annual solar irradiation, for a Q_{total} estimation of one year.

4. Economic and Environmental Analysis

While the evaluation of energy benefits of TSCs is discussed in Section 3, financial costs and environmental impact are also essential aspects to consider when comparing facade alternatives. This section provides an assessment framework of the economic and environmental benefits to compare TSCs with other facade options. The economic feasibility of transparent solar cells is evaluated by comparing initial investment costs, annual energy savings, and payback period against alternative facade solutions. While the upfront cost of transparent solar glazing is higher than that of conventional glass, the additional cost is partially offset by reduced HVAC system sizing and operational savings.

A. Facade Cost and Payback Comparison

Transparent solar glass currently exhibits higher upfront costs than traditional glazing. Typical installed costs are summarized in Table I.

TABLE I. Installed Cost Comparison of Facade Materials

Material	Cost ($/m^2)	Primary Function
Conventional glass	80–150	Daylighting
Low-E double glazing	120–180	Thermal control
Transparent solar glass	250–500	PV + glazing

A comparative cost analysis is performed for three options: conventional double glazing, double glazing with external shading, and transparent solar cell glazing. Results show that transparent solar cells achieve payback periods between 8 and 12 years under current electricity tariffs in Egypt, with shorter periods expected as technology costs decline. The simple payback period is calculated as:

$$T_{\text{PB}} = \frac{C_{\text{TPC}} - C_{\text{glass}}}{S_{\text{PV}} + S_{\text{cool}}} \tag{6}$$

where C_{TPC} and C_{glass} are the installed costs of transparent solar glazing and conventional glass, respectively. S_{PV} represents annual savings from electricity generation, and S_{cool} represents savings due to reduced cooling energy consumption.

B. CO_2 Emissions Reduction Analysis

Electricity generation in Egypt is predominantly based on natural gas, with an average emissions factor of approximately 0.45 kg CO_2/kWh. The reduction of 74 metric tons of CO_2 per year is equivalent to planting approximately 3,400 trees annually [22]. This makes TSCs a vital tool for commitment to the environmental agreements and emission reduction. The annual emissions reduction achieved through transparent solar facades can be estimated as:

$$\Delta CO_2 = (E_{\text{PV}} + E_{\text{cool}}) \cdot \gamma \tag{7}$$

where γ is the grid emissions factor. For combined savings of 165 MWh/year, annual emissions reductions exceed 74 metric tons of CO_2. Although transparent solar glass has a higher initial cost, it replaces both window glazing and energy generation systems. In high-irradiance regions, the payback period is estimated between 5–9 years depending on electricity pricing and cooling load reduction.

Fig. 3. Layout of the installed TSC in campus

5. Case Study: Transparent Solar Cells in Semi-Arid Climates

This paper provides a practical case study for the TSC installed in a university campus in New Borg El-Arab, Alexandria, Egypt as shown in Fig. 3. The region receives an average global horizontal irradiance of 5.2–6.0 kWh/m^2/day, corresponding to an annual solar resource of approximately 1900–2200 kWh/m^2. These conditions make facade-based solar energy harvesting particularly attractive. In New Borg El-Arab, the high ambient temperatures lead to cell temperatures (T_c) exceeding 60$^\circ C$, making the thermal management of the facade (e.g., ventilated double-skin facades) essential to prevent PCE drops. The area exhibits a hot semi-arid climate with average summer daytime temperatures exceeding 38°C. Given a south-facing facade with optimal tilt operating at 10% efficiency and an average annual solar irradiation of 2,200 kWh/m^2, the expected annual generation ranges from 14 to 18 MWh/100 m^2/year.

For the Sahara region, the reduction in near-infrared (NIR) transmission is the primary driver of savings. Maintaining an indoor temperature of 20 °C, the decrease in cooling energy demand can be quantified using standard heat balance equations. By absorbing or reflecting the NIR portion of the spectrum, results indicate HVAC energy savings of 15–25% compared to conventional clear glazing. The TSC reduces the Solar Heat Gain Coefficient (SHGC) from 0.8 to 0.25. Hence, with an indoor setpoint of 20$^\circ C$, the heat flux (Q) reduction is significant.

For commercial buildings in Egypt, average electricity tariffs range from 0.08–0.12 USD/kWh. Assuming a tariff of 0.10 USD/kWh, annual PV generation of 90 MWh yields approximately 9,000 USD in direct savings. Additional cooling energy savings of 75 MWh correspond to a further 7,500 USD annually. Under these conditions, the simple payback period is estimated to be between 6 and 9 years. The "Green Premium" for TSCs is evaluated against the lifecycle savings. Table II demonstrates that under Egyptian commercial tariffs, the ROI is accelerated by the high cooling energy prices. Since the "green premium" is

TABLE II. 25-Year Lifecycle Cost Comparison

Parameter	Conventional Glass	TSC System
Initial CAPEX	$21,000	$124,500
Annual Energy Bill	$28,000	$11,500
Maintenance Cost (25y)	$5,000	$18,000
Net Total Cost	**$726,000**	**$430,000**

$103,500, the annual savings from electricity generation (90 MWh) and cooling reduction (75 MWh) at $0.10/kWh amount to $16,500. This results in a simple payback period of 6.27 years. Over a 25-year facade lifespan, the net present value (NPV) is strongly positive, confirming economic feasibility. Simulation results demonstrate substantial combined energy savings from on-site generation and reduced cooling demand. The case study confirms the suitability of transparent solar cells for large-scale facade applications in arid and semi-arid climatic conditions.

6. Conclusion

The combined electrical and thermal benefits of transparent solar cell (TSC) facades distinguish them from conventional Building-Integrated Photovoltaics (BIPV) solutions. While efficiency remains lower than rooftop PV, the utilization of otherwise passive building surfaces and the reduction in cooling loads significantly enhance overall system value in warm climates. This paper has presented a comprehensive assessment of the energy efficiency, environmental impact, and economic viability of transparent solar cells integrated into building facades. By leveraging high solar irradiance levels and combining electricity generation with Heating, Ventilation, and Air Conditioning (HVAC) load reduction, transparent solar cells offer a compelling solution for sustainable architecture in arid and semi-arid regions. By addressing the dual needs of power generation and cooling load reduction, TSCs provide a pathway toward net-zero energy buildings. Transparent solar cells offer a multi-functional solution for the challenges of desert urbanism. This study has demonstrated that in New Borg El-Arab, Egypt, a south-facing TSC facade provides substantial active and passive energy benefits. The study demonstrates that transparent solar cells offer a viable and effective solution for sustainable building facades in warm regions such as Alexandria, Egypt. When both electricity generation and cooling load reduction are considered, transparent solar facades achieve favorable economic payback periods and substantial CO_2 emissions reductions. The study establishes that Transparent Solar Cells are a technologically robust and economically sound solution for the architectural landscape of New Borg El-Arab, Egypt. The results indicate that, despite higher initial costs, transparent solar facades can deliver significant long-term benefits, supporting national and global sustainability objectives. Continued improvements in efficiency and manufacturing cost are expected to further enhance their attractiveness.

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