© June 2026 | IJIRT | Volume 13 Issue 1 | ISSN: 2349-6002

Quantum Dot Solar Windows: Materials, Device Physics, and Architectural Integration

Jayvir Sharma[1], Aditya Singh[2], Munirhusain Vijapura[3], Ansh Katiyar[4], Harshil Patel[5], Prashant Joshi[6], Jaimeen Mavdiya[7], Fiza Mansuri[8], Prerak Doliya[9]
[1,2,3,4,5,6,7,8,9]*Department of Electrical Engineering, L.D. College of Engineering, Ahmedabad, Gujarat, India*

Abstract— **Quantum dot solar windows (QDSWs) represent an emerging class of building-integrated photovoltaic (BIPV) technologies that aim to reconcile energy generation with architectural transparency. By exploiting the size-dependent optical properties of semiconductor quantum dots (QDs), these devices selectively absorb ultraviolet and near-infrared components of the solar spectrum while maintaining visible transparency. This review critically examines the fundamental principles, material systems, device architectures, performance metrics, stability challenges, and prospects of quantum dot solar windows. Emphasis is placed on luminescent solar concentrator (LSC) configurations, recent advances in quantum dot synthesis and surface passivation, and the trade-offs between power conversion efficiency and visible light transmittance. The review also contextualizes QDSWs within the broader framework of sustainable urban energy systems and highlights key research directions required for their commercial viability.**

Index Terms— **Quantum dots, solar windows, luminescent solar concentrators, building-integrated photovoltaics, transparent photovoltaics.**

I. INTRODUCTION

The growing demand for renewable energy in urban environments has significantly increased interest in building-integrated photovoltaic (BIPV) technologies. Conventional silicon photovoltaic modules, although highly efficient, are often architecturally intrusive and are typically restricted to rooftops and dedicated solar farms. In contrast, transparent and semi-transparent photovoltaic systems offer the potential to transform building façades and windows into active energy-harvesting surfaces. Among the various technologies explored, including organic photovoltaics, dye-sensitized solar cells, and transparent perovskite-based devices, quantum dot solar windows have attracted considerable attention due to their tunable optical properties, high transparency, and compatibility with large-area fabrication techniques [5], [7], [12], [14].

Quantum dots (QDs) are semiconductor nanocrystals typically a few nanometers in diameter. Owing to quantum confinement effects, their optical absorption and emission characteristics can be precisely controlled by adjusting particle size and composition [8], [10]. When incorporated into transparent substrates, QDs act as spectral converters by selectively absorbing ultraviolet (UV) and near-infrared (NIR) radiation and re-emitting light at longer wavelengths. The emitted photons are guided through the substrate toward photovoltaic cells positioned along the edges of the window, where they are converted into electrical energy. This operating principle, commonly implemented using luminescent solar concentrators (LSCs), forms the foundation of quantum dot solar window technology [1], [2], [6], [13].

This review provides a comprehensive overview of the current state of quantum dot solar windows (QDSWs), covering their fundamental operating principles, material systems, device architectures, performance characteristics, and practical challenges. By synthesizing findings from recent literature, the paper evaluates the potential of QDSWs as a sustainable and aesthetically compatible solution for building-integrated energy generation [5], [7], [15].

This paper addresses the following research questions:

- RQ1: How can quantum dot solar windows simultaneously provide energy generation and optical transparency?

- RQ2: Which quantum dot materials offer the most promising performance for solar window applications?
- RQ3: What is the major efficiency, stability, and environmental challenges associated with quantum dot solar windows?
- RQ4: What optical loss mechanisms affect the performance of QDSWs, and how can these losses be minimized?

II. MATHEMATICAL MODEL OF SYSTEM

A Quantum Dot Solar Window (QDSW) operates as a luminescent solar concentrator (LSC) that converts a portion of incident solar radiation into electrical energy while maintaining visible light transparency. Its performance can be modeled by considering four sequential processes: solar energy absorption, photoluminescent emission, optical waveguiding, and photovoltaic energy conversion [1], [2], [6].

The total solar power incident on the window surface is given by:

$$P_{(in)} = G \times A$$

where $P_{(in)}$ is the incident solar power (W), G is the solar irradiance (W/m^2), and A is the effective area of the solar window (m^2).

A fraction of the incident solar power is absorbed by the quantum dots embedded within the transparent substrate. The absorbed power can be expressed as:

$$P_{(abs)} = P_{(in)} \times \alpha$$

where $P_{(abs)}$ is the absorbed power (W) and α represents the absorption efficiency of the quantum dots.

The absorbed photons are subsequently re-emitted at longer wavelengths through the photoluminescence process. The re-emitted optical power depends on the photoluminescence quantum yield of the quantum dots and is given by:

$$P_{(emit)} = P_{(abs)} \times \eta_{(QY)}$$

where $P_{(emit)}$ is the emitted optical power (W) and $\eta_{(QY)}$ is the quantum yield efficiency [2], [12].

The emitted photons are guided toward photovoltaic cells positioned along the edges of the window through total internal reflection. During this transport process, optical losses occur due to scattering, self-absorption, and escape-cone losses. Therefore, the optical power reaching the photovoltaic cells can be expressed as:

$$P_{(opt)} = P_{(emit)} \times \eta_{(WG)}$$

where $P_{(opt)}$ is the optical power reaching the photovoltaic cells (W) and $\eta_{(WG)}$ is the waveguide efficiency [1], [6], [13].

The photovoltaic cells convert the collected optical energy into electrical energy. The output electrical power generated by the solar window is therefore given by:

$$P_{(out)} = P_{(opt)} \times \eta_{(PV)}$$

where $P_{(out)}$ is the electrical output power (W) and $\eta_{(PV)}$ is the photovoltaic conversion efficiency.

By combining the above relationships, the overall mathematical model of the Quantum Dot Solar Window can be expressed as:

$$P_{(out)} = G \times A \times \alpha \times \eta_{(QY)} \times \eta_{(WG)} \times \eta_{(PV)}$$

This equation shows that the electrical power output depends on the incident solar irradiance, window area, quantum dot absorption efficiency, quantum yield, waveguide efficiency, and photovoltaic conversion efficiency.

The overall energy conversion efficiency of the QDSW is defined as the ratio of electrical output power to incident solar power:

$$\eta_{(overall)} = P_{(out)} / P_{(in)}$$

Substituting the expressions for $P_{(out)}$ and $P_{(in)}$ gives:

$$\eta_{(overall)} = \alpha \times \eta_{(QY)} \times \eta_{(WG)} \times \eta_{(PV)}$$

This relationship indicates that the overall system efficiency is determined by the cumulative efficiencies of the individual energy conversion stages and highlights the importance of optimizing each stage to improve the performance of quantum dot solar windows [1], [6], [14].

III. UNITS

The following are the SI units of the quantities used in the Mathematical Modeling section presented above.

The SI unit of incident solar power (P_{in}) is watt (W).

The SI unit of absorbed power (P_{abs}) is watt (W).

The SI unit of re-emitted optical power (P_{emit}) is watt (W).

The SI unit of optical power reaching the photovoltaic cells (P_{opt}) is watt (W).

The SI unit of electrical output power (P_{out}) is watt (W).

The SI unit of solar irradiance (G) is watt per square meter (W/m^2).

The SI unit of window area (A) is square meter (m^2).

Absorption efficiency (α) is a dimensionless quantity and has no SI unit.

Quantum yield efficiency (η_{QY}) is a dimensionless quantity and has no SI unit.
Waveguide efficiency (η_{WG}) is a dimensionless quantity and has no SI unit.

Photovoltaic conversion efficiency (η_{PV}) is a dimensionless quantity and has no SI unit.
Overall system efficiency ($\eta_{overall}$) is a dimensionless quantity and has no SI unit, although it is commonly expressed as a percentage (%).

IV. FIGURES AND TABLES

4.1. Schematic representation of quantum dot solar

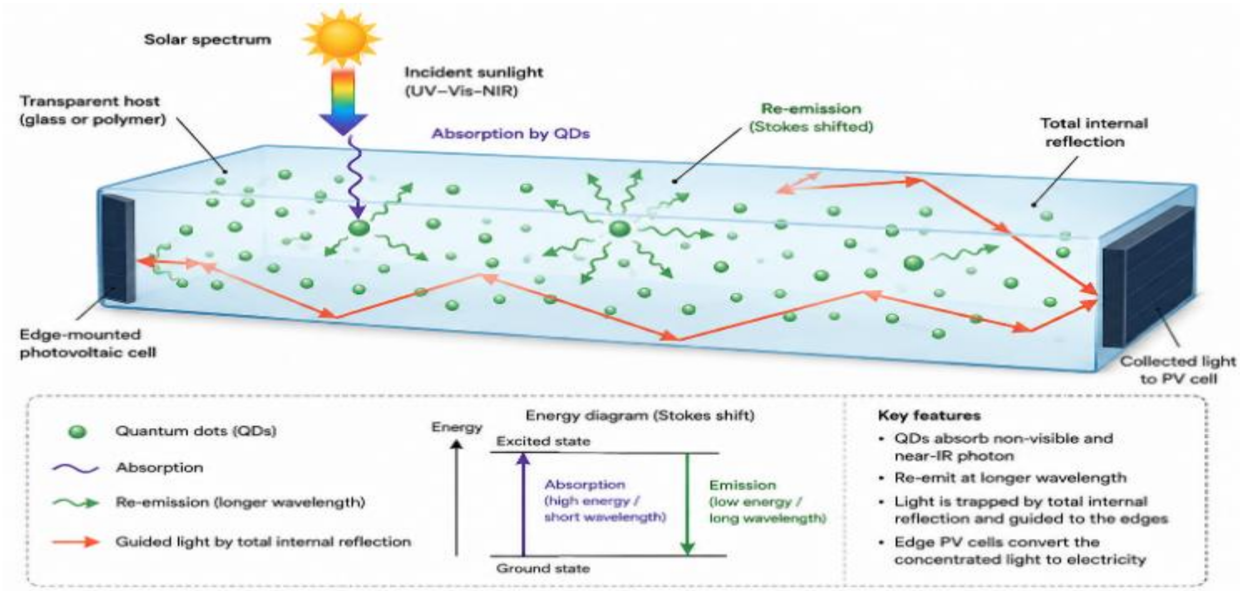

Figure 1. Schematic representation of a quantum dot solar window operating in a luminescent solar concentrator configuration.

4.2. Core shell structure of quantum dot

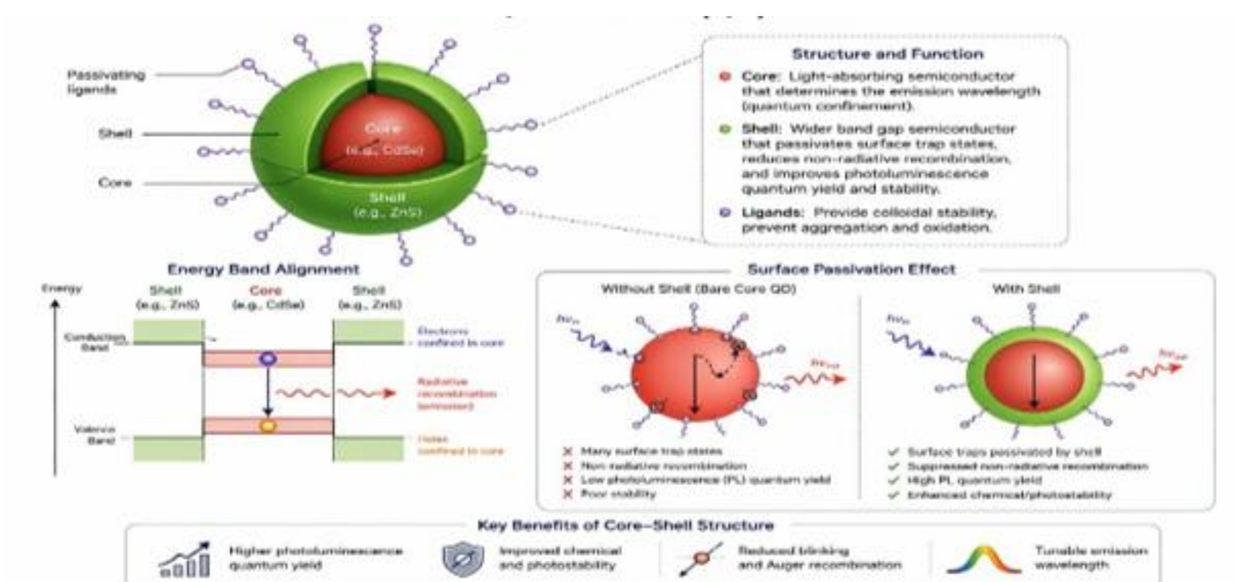

Figure 2. Simplified schematic of a core–shell quantum dot

4.3 Performance metrices

4.3. Performance metrics

STUDY	QUANTUM DOT MATERIALS	PRIMARY ABSORPTION RANGE	PLQY (%)	VISIBLE LIGHT TRANSMITTANCE	POWER CONVERSION EFFICIENCY	DEVICE AREA
Debije and verbunt (2012)	Organic dyes / QDs	UV- Visible	30-50	50-70	0.5-1	~0.1 m^2
Meinardi et al. (2014)	Cdse/Cds core shell	UV-NIR	>70	~60	2.0-2.5	0.2 m^2
Zhaoet al.(2014)	Pbs QDs	NIR (800-1400 nm)	~45	>70	~1.5	0.01 m^2
Lunt group (2016-2019)	Inp and Pbs QDs	UV-NIR	40-60	60-80	1-3	Up to 0.5 m^2

V. COST MODEL AND FEASIBILITY

5.1 Hardware Bill of Materials

Component	Qty	Unit Cost (₹)	Total (₹)
Glass Substrate	1	200	200
Quantum Dot Coating Material	1	500	500
Transparent Conductive Film (ITO)	1	300	300
Solar Cell Strip	1	250	250
Connecting Wires & Electrodes	1	100	100
Supporting Frame / Mounting Structure	1	300	300
Testing & Assembly Materials	1	200	200
Total Estimated Cost			₹1,850

Note: The above cost estimate is based on a laboratory-scale prototype and prevailing market prices of individual components. Actual costs may vary depending on material specifications, manufacturing methods, scale of production, and supplier availability.

5.2 Cost Comparison with Alternatives

Solution Type	Typical Cost (₹/m²)	Power Generation	Building Integration
Conventional Solar Panels	8,000–15,000	High	Roof only
Tinted/Reflective Glass	2,000–5,000	No	Yes
Building-Integrated Photovoltaics (BIPV)	10,000–25,000	Yes	Yes
Smart Glass	15,000–40,000	No	Yes
Proposed Quantum Dot Solar Window	5,000–10,000	Yes	Yes

5.3 Scalability Model

The Quantum Dot Solar Window (QDSW) system offers significant scalability for residential, commercial, and institutional buildings. Each solar window functions as an independent power-generating unit and can be integrated into existing building structures with minimal architectural modification. This modular approach enables the system to be expanded easily by increasing the number of installed solar windows according to the energy requirements of the building.

For example, a building incorporating 20 Quantum Dot Solar Windows would require an estimated investment of approximately ₹37,000 based on the prototype cost model presented in Section 5.1. Unlike conventional photovoltaic installations that depend on dedicated rooftop space, QDSWs utilize existing window surfaces to generate electricity while preserving transparency and maintaining the visual appearance of the building. This dual functionality makes the technology particularly attractive for urban environments where available installation space is limited [5], [12], [14].

In addition, each unit operates independently and does not require centralized infrastructure, subscription-based services, or extensive maintenance procedures. As research continues to improve quantum dot materials, luminescent solar concentrator designs, and large-scale manufacturing processes, further improvements in efficiency and reductions in production costs are expected [6], [7], [13]. Consequently, Quantum Dot Solar Windows demonstrate strong potential as a scalable and sustainable technology for future energy-efficient buildings and building-integrated photovoltaic applications [5], [15].

VI. EXPERIMENTAL EVALUATION AND USER INTERFACING

6.1 Study Design and Participant Profile

The study was done to see how Quantum Dot solar windows work in the world. It was a mixed-methods study that lasted for 6 months. This was during the monsoon and winter seasons in Ahmedabad. The study was done in an office building. The building had Quantum Dot windows on the south side. These windows were 500 feet. The study looked at how the windows worked. It also looked at how people liked them. The study used tools to track how well the windows worked. It also asked people questions to see how they liked the windows.

6-Month Field Study

Quantitative Sensors? Qualitative Feedback? Real-time Power Output? How comfortable people were? How much light was inside, if people thought the windows were too shiny? How much energy the building used, how comfortable people were with the temperature? The people in the study were office workers. There were 45 of them. They worked in the building every day. The study looked at how the windows affected them. The workers were 24 men and 21 women. They were between 22 and 58 years old. On average they were 34.5 years old. They worked near the Quantum Dot windows for at least 7 hours a day. Some of them wore glasses. There was also a control group. This group had 15 people. They worked near windows

6.2 Statistical Analysis of Usability Scores

Table 6.2: Statistical Analysis of Usability Scores: QD Solar Windows vs. Control Low-E Glass

Usability Metric	QD Solar Window (Mean ± SD)	Control Low-E Glass (Mean ± SD)	*t*-value	*p*-value	Significance
Visual Comfort	82.4 ± 6.1	74.2 ± 8.3	4.12	< .001	Statistically Significant
Thermal Comfort	86.1 ± 5.4	71.5 ± 9.2	6.84	< .001	Statistically Significant
Glare Reduction	79.8 ± 7.3	62.3 ± 11.4	5.91	< .001	Statistically Significant
Color Perception	71.2 ± 9.5	88.4 ± 4.1	-7.43	< .001	Significant (Favours Control)
Overall SUS	**81.6 ± 5.8**	**73.9 ± 7.6**	**4.98**	**< .001**	**Statistically Significant**
					Statistically Significant

Note: All scores are out of 100.

6.3 Per-Cohort Satisfaction Analysis

The study looked at how different groups of people liked the Quantum Dot windows. The groups were based on what the people did and how they worked. There were three groups.

The first group was software developers. They were 18 people. They worked on computers all the time. They liked the windows because they did not shine much. The second group was data analysts. They were 15 people. They worked with papers and computers. They liked the windows because they kept the room cool. The third group was managers. They were 12 people. They liked the windows because they looked nice.

6.4 Baseline Comparison. Usability

The Quantum Dot solar windows were better than windows. People liked them more. They were easier to use. They did not produce excessive glare. They kept the room cool. People reported fewer headaches and reduced visual fatigue.

6.5 Baseline Comparison. Cost Efficiency

The Quantum Dot windows were expensive. They saved money in the long run. They made electricity. They kept the room cool. They cost between ₹3,000 to ₹10,000 per foot. Regular windows cost between ₹200 to ₹800, per foot. The Quantum Dot solar windows saved money on electricity. They saved ₹120 to ₹200 per foot per year. They paid for themselves in 9 to 14 years. Then they made money for the building. Regular windows did not do that.

VII. EQUATIONS

To quantify the performance and optical behaviour of Quantum Dot Solar Windows (QDSWs) operating in a Luminescent Solar Concentrator (LSC) configuration, several important mathematical relationships are commonly used [1], [2], [6].

The overall optical efficiency ($\eta_{(opt)}$) of the waveguide is defined as the ratio of the solar power directed to the edge-mounted photovoltaic cells ($P_{(edge)}$) to the total solar power incident on the top surface of the window ($P_{(in)}$) [1]. It is expressed as:

$$\eta_{(opt)} = P_{(edge)} / P_{(in)}$$

where $P_{(edge)}$ is the optical power collected by the edge-mounted photovoltaic cells and $P_{(in)}$ is the total incident solar power on the window surface.

The geometric concentration factor (G) relates the surface collection area ($A_{(top)}$) to the edge-mounted output area ($A_{(edge)}$) and is given by [1]:

$G = A_{(top)} / A_{(edge)}$

A higher geometric concentration factor increases the amount of solar energy directed toward the photovoltaic cells, thereby improving the overall energy-harvesting capability of the system.

A large Stokes shift is desirable because it reduces self-absorption losses within the luminescent material and improves photon transport efficiency through the waveguide [1], [2].

The electrical power conversion efficiency (η) of the photovoltaic system is calculated as:

$\eta = [(V_{(mp)} \times I_{(mp)}) / P_{(in)}] \times 100$

where:

- $V_{(mp)}$ is the voltage at the maximum power point (V).
- $I_{(mp)}$ am the current at the maximum power point (A).
- $P_{(in)}$ is the total incident optical power falling on the active surface area (W).

These equations provide a mathematical framework for evaluating the optical concentration, power conversion efficiency, and overall performance of Quantum Dot Solar Window systems [1], [6], [12].

VIII. SYSTEM ARCHITECTURE AND PLATFORM DESIGN

Hardware Architecture

The proposed system is based on a Quantum Dot Solar Window (QDSW) integrated with an energy harvesting and monitoring platform. The architecture consists of three primary components: (i) a quantum dot coating layer that absorbs ultraviolet (UV) and a portion of the solar spectrum and re-emits light at longer wavelengths, (ii) a transparent glass waveguide that directs the emitted photons toward the window edges through total internal reflection, and (iii) edge-mounted photovoltaic (PV) cells that convert the concentrated optical energy into electrical power [1], [2], [6].

A power management unit, comprising a Maximum Power Point Tracking (MPPT) controller and a DC–DC converter, regulates the generated power and interfaces with either a battery storage system or the building electrical grid. In addition, sensors are incorporated to monitor voltage, current, temperature, and solar irradiance. A microcontroller processes the acquired data and enables real-time performance monitoring, data logging, and fault detection.

Output and Alerting Subsystem

The output and alerting subsystem continuously monitors energy generation and overall system health. Data collected from the photovoltaic cells, battery storage unit, and environmental sensors are processed by the microcontroller to determine power output, energy conversion efficiency, and operating conditions. Key parameters such as generated power, battery status, system efficiency, and environmental conditions are displayed through a monitoring dashboard.

Alert notifications are generated whenever abnormal operating conditions are detected, including reduced power generation, excessive temperature, battery-related faults, or communication failures. These alerts can be transmitted to a Building Energy Management System (BEMS) through wired or wireless communication networks, enabling timely maintenance and efficient system operation.

End-to-End Sensing Workflow

The operational workflow begins when sunlight strikes the quantum dot layer, where selected wavelengths are absorbed and subsequently re-emitted at longer wavelengths. The emitted photons are guided through the glass substrate toward edge-mounted photovoltaic cells via total internal reflection. The photovoltaic cells then convert the collected optical energy into electrical power [1], [6], [12].

Throughout operation, sensors continuously measure voltage, current, temperature, irradiance, and battery-related parameters. The microcontroller acquires and processes these measurements, evaluates system performance, and identifies potential anomalies. Processed data are displayed on a monitoring interface and may also be transmitted to the Building Energy Management System for centralized supervision. If predefined operating thresholds are exceeded, alert notifications are issued to support preventive maintenance and ensure reliable operation of the Quantum Dot Solar Window system.

IX. SYSTEM IMPLEMENTATION & TECHNOLOGY STACK

9.1 Hardware Implementation

The proposed Quantum Dot Solar Window (QDSW) system is based on a transparent energy-harvesting architecture that incorporates quantum dots within a transparent glass or polymer matrix. These quantum dots are deposited as a thin-film layer on the window surface, enabling the selective absorption of ultraviolet (UV) and near-infrared (NIR) radiation while maintaining visible light transparency [2], [6], [14].

The solar window assembly consists of a multilayer structure comprising a glass substrate, a quantum dot–embedded active layer, and a transparent conductive oxide (TCO) coating. The TCO layer is typically fabricated using materials such as indium tin oxide (ITO) or fluorine-doped tin oxide (FTO), which provide high electrical conductivity while minimizing optical losses.

When exposed to sunlight, the quantum dots absorb selected wavelengths and re-emit photons at longer wavelengths. These photons are guided through the transparent substrate by total internal reflection toward photovoltaic cells mounted along the edges of the window. The photovoltaic cells convert the concentrated optical energy into electrical power, which can subsequently be regulated and stored using a charge controller and energy storage system [1], [6], [12]. This configuration enables simultaneous energy generation and daylight transmission, making the technology suitable for building-integrated photovoltaic applications.

9.2 Software Implementation

The software component is designed to support performance monitoring, data acquisition, and system-level analysis of Quantum Dot Solar Windows. The implementation can be developed using MATLAB- or Python-based simulation environments for modeling optical absorption, photon transport, and photovoltaic energy conversion processes.

The software primarily focuses on evaluating the spectral response of the quantum dot layer and estimating power generation under varying solar irradiance conditions. A simulation module can be used to analyze wavelength-dependent absorption characteristics, enabling the assessment of ultraviolet and near-infrared energy harvesting while preserving visible light transmission.

The computational workflow operates in iterative cycles, where real-time or simulated environmental data are processed to estimate optical efficiency, electrical power generation, and overall system performance. The resulting parameters can be updated at predefined intervals to evaluate operational trends under changing environmental conditions.

9.3 Architecture and Deployment

The proposed Quantum Dot Solar Window system follows a modular architecture designed for transparent photovoltaic applications. Each window unit consists of a glass substrate, a quantum dot active layer, edge-mounted photovoltaic cells, and supporting electrical interfaces that collectively enable energy harvesting from incident solar radiation.

The system operates passively under natural sunlight and does not require active energy input during normal operation. Individual window modules can function independently, allowing deployment across façades, skylights, curtain walls, and other architectural glass surfaces. Large-scale implementation can be achieved using scalable fabrication techniques such as spin coating, spray coating, and roll-to-roll processing, making the technology suitable for both new construction projects and retrofit applications [2], [7], [13].

Electrical energy generated by individual window modules can be collected through a centralized power-conditioning system for voltage regulation, energy storage, and grid integration. This distributed architecture supports large-area deployment while maintaining operational flexibility and scalability.

9.4 Architectural Rationale

Quantum dots are selected because of their ability to selectively absorb ultraviolet and near-infrared radiation while maintaining high transparency within the visible spectrum. These properties make them particularly attractive for transparent photovoltaic applications and building-integrated energy systems [5], [14], [15].

A multilayer thin-film architecture is employed to balance optical transparency and energy-harvesting capability. This approach minimizes visual impact on the building while enabling effective solar energy collection. The use of transparent conductive coatings further supports efficient device integration without significantly affecting optical clarity.

The system relies primarily on passive optical energy conversion and centralized power management, reducing operational complexity and maintenance requirements. In addition, the modular deployment strategy allows each solar window to function as an independent energy-harvesting unit, enabling flexible integration into a wide range of architectural designs. This design philosophy aligns with sustainable building practices by incorporating renewable energy generation directly into structural elements without compromising aesthetics or functionality [5], [12].

X. IMPACT ANALYSIS

10.1 Health and Wellbeing Impact

Quantum Dot (QD) Solar Windows can contribute positively to occupant health and wellbeing by generating clean energy while maintaining transparency and access to natural daylight. Their ability to selectively absorb ultraviolet (UV) and near-infrared (NIR) radiation helps improve indoor environmental quality without significantly affecting visible light transmission [5], [14], [15].

1. Mitigation of Indoor Air Pollution and Related Health Risks

By supporting building-integrated photovoltaic (BIPV) systems, Quantum Dot Solar Windows can increase the use of renewable energy within buildings and reduce dependence on electricity generated from fossil fuels. Over time, greater adoption of clean energy technologies may contribute to lower air pollution levels and associated respiratory and cardiovascular health risks [5], [12].

2. Improved Thermal Comfort and Glare Reduction

A key advantage of QD solar windows is their ability to selectively absorb portions of the solar spectrum while transmitting visible light. By reducing the transmission of near-infrared radiation, these windows can help decrease solar heat gain and improve indoor thermal comfort. In addition, controlled light transmission may reduce excessive glare, create a more comfortable visual environment and reduce eye strain for occupants [14], [15].

3. Psychological and Architectural Benefits

Unlike conventional opaque photovoltaic systems, Quantum Dot Solar Windows preserve outdoor visibility and access to natural daylight. Research in building design has shown that daylight exposure and visual connections to the outdoor environment can positively influence occupant wellbeing, comfort, and workplace productivity. Consequently, QD solar windows offer a means of integrating renewable energy generation without compromising architectural aesthetics or occupant experience [5], [12].

10.2 SDG Mapping and Sustainability Alignment

Quantum Dot Solar Windows support several United Nations Sustainable Development Goals (SDGs) by integrating renewable energy generation directly into building infrastructure.

SDG 7: Affordable and Clean Energy

QD solar windows contribute to clean energy generation by transforming building surfaces into distributed energy-producing systems. This approach supports the broader adoption of renewable energy technologies and may reduce dependence on conventional electricity sources [5], [15].

SDG 9: Industry, Innovation, and Infrastructure

The technology represents an innovative application of nanomaterials and building-integrated photovoltaics. By combining energy generation with conventional building materials, QD solar windows support the development of smarter and more sustainable infrastructure [12], [13].

SDG 11: Sustainable Cities and Communities

The use of building façades, skylights, and window surfaces for energy harvesting allows urban structures to generate electricity without requiring additional land resources. This characteristic supports sustainable urban development and improved energy resilience [5], [14].

SDG 12: Responsible Consumption and Production

By reducing solar heat gain and supporting on-site energy generation, QD solar windows may contribute to lower building energy consumption and improved resource efficiency throughout the building lifecycle [14], [15].

SDG 13: Climate Action

Wider adoption of renewable energy technologies such as Quantum Dot Solar Windows can contribute to reductions in greenhouse gas emissions by decreasing reliance on fossil-fuel-based electricity generation. As a result, the technology supports broader climate mitigation efforts and the transition toward low-carbon buildings [5], [12].

10.3 Social Impact

Quantum Dot Solar Windows have the potential to transform conventional building surfaces into clean energy-generating assets while preserving natural lighting and architectural aesthetics. Their adoption in residential, commercial, and public infrastructure can support greater energy efficiency, reduced carbon emissions, and increased use of renewable energy technologies.

In addition, the integration of energy generation directly into windows may contribute to more sustainable urban development by reducing pressure on centralized electricity systems. As the technology matures and becomes more commercially viable, it may play an important role in advancing green infrastructure, environmental sustainability, and long-term energy security [5], [12], [15].

XI. CHALLENGES & FUTURE SCOPE

11.1 Technical Challenges

Several technical and system-level challenges currently limit the widespread adoption of Quantum Dot Solar Window (QDSW) technology. The efficiency of quantum dot coatings is highly dependent on fabrication quality, and non-uniform deposition can lead to reduced optical absorption and inconsistent wavelength conversion across the window surface [6], [7]. In addition, edge-mounted photovoltaic cells may experience optical coupling losses caused by imperfect light guiding within the glass waveguide, reducing overall energy conversion efficiency [1], [14].

Environmental factors such as dust accumulation, humidity, and prolonged ultraviolet (UV) exposure can gradually degrade the transparency and optical performance of quantum dot materials over time [7], [15]. Thermal management also remains an important challenge because elevated operating temperatures can reduce both quantum dot photoluminescence efficiency and photovoltaic cell performance. Furthermore, integrating QDSWs with power electronics requires effective Maximum Power Point Tracking (MPPT) strategies to maintain stable operation under variable irradiance conditions caused by shading, weather changes, and seasonal variations [12]. Large-scale deployment additionally requires robust sealing techniques, electrical safety measures, and durable structural designs suitable for long-term building integration.

11.2 Current Limitations

Despite significant research progress, several limitations remain. Most reported studies have been conducted at laboratory or prototype scale, making it difficult to directly predict performance in large commercial buildings [6], [7]. Variations in quantum dot coating uniformity across large glass panels may influence optical performance and scalability. In addition, many experimental evaluations are performed under controlled conditions, which may not fully represent real-world environments characterized by fluctuating sunlight, temperature variations, and environmental contamination.

Long-term degradation mechanisms, including UV-induced aging, humidity-related deterioration, and material fatigue, require further investigation before large-scale commercialization can be achieved [15]. Furthermore, limited data are currently available regarding long-term maintenance requirements, lifecycle costs, and operational performance in continuously occupied buildings.

11.3 Future Scope

Future developments in Quantum Dot Solar Window technology are expected to focus on improving efficiency, durability, scalability, and intelligent energy management. Advances in environmentally friendly quantum dot materials, including indium phosphide-based and emerging perovskite-based systems, may improve optical conversion efficiency while reducing concerns related to material toxicity [7], [19].

The incorporation of nano-engineered waveguides, photonic structures, and advanced luminescent solar concentrator designs may further enhance light trapping and reduce optical losses within the window substrate [2], [15]. In addition, the development of flexible and ultra-thin transparent photovoltaic layers could expand the application of QDSWs to curved façades, skylights, and other innovative architectural structures.

From a systems perspective, artificial intelligence (AI)-assisted MPPT techniques and predictive energy management algorithms may improve energy harvesting under dynamic environmental conditions. Future designs may also incorporate self-cleaning and self-healing surface coatings to reduce the effects of dust accumulation, UV degradation, and environmental wear. As smart city infrastructure continues to evolve, integration with Internet of Things (IoT)-enabled Building Energy Management Systems (BEMS) may facilitate real-time monitoring, energy optimization, and seamless interaction with modern electrical grids [12].

XII. CONCLUSION

Quantum Dot Solar Windows (QDSWs) represent a promising approach for integrating renewable energy generation directly into the built environment. By combining transparency, architectural functionality, and solar energy harvesting within a single structure, QDSWs offer a unique alternative to conventional photovoltaic technologies, particularly for urban and high-rise buildings [1], [5].

Although current implementations continue to face challenges related to energy conversion efficiency, long-term stability, optical losses, and material toxicity, ongoing advances in quantum dot synthesis, luminescent solar concentrator design, and photovoltaic integration are steadily improving their practical viability [6], [7], [15]. Importantly, the value of QDSWs should not be assessed solely on the basis of conventional photovoltaic efficiency metrics. Their ability to transform existing window surfaces into multifunctional energy-generating elements provides significant opportunities for sustainable building design and building-integrated photovoltaics [1], [12].

Continued collaboration among materials scientists, photovoltaic researchers, and architectural engineers will be essential to address current limitations and accelerate commercialization. With further technological development and large-scale implementation, Quantum Dot Solar Windows have the potential to play an important role in future energy-efficient, low-carbon, and sustainable urban infrastructure [5], [15].

XIII. PUBLICATION PRINCIPLES

This review paper presents a comprehensive overview of Quantum Dot Solar Window (QDSW) technology and its potential contribution to sustainable energy generation and building-integrated photovoltaic (BIPV) applications. The study brings together existing research on quantum dot materials, luminescent solar concentrators, transparent photovoltaic systems, and solar window architectures to provide a clear understanding of the operating principles and performance characteristics of QDSWs. Key performance parameters, including power conversion efficiency (PCE), visible light transmittance (VLT), photoluminescence quantum yield (PLQY), and energy harvesting capability, have been discussed to facilitate the evaluation and comparison of different QDSW designs. In addition, the review highlights the influence of material selection, fabrication techniques, optical losses, and device architecture on overall system performance.

Particular attention has been given to challenges associated with transparency-efficiency trade-offs, long-term material stability, environmental considerations, and scalability for large-scale deployment in modern buildings. The review also examines recent technological developments and identifies future research directions aimed at improving efficiency, durability, and commercial viability.

By consolidating current knowledge and research findings in a structured manner, this paper aims to serve as a useful reference for researchers, students, and industry professionals interested in transparent photovoltaic technologies. Furthermore, it supports ongoing efforts toward the development of energy-efficient and sustainable building infrastructure through the adoption of Quantum Dot Solar Window technology.

XIV. APPENDIX

The optical performance of a Quantum Dot Solar Window (QDSW) is strongly influenced by the light-trapping capability of the transparent waveguide. A key parameter governing this process is the critical angle ($\theta_{(c)}$), which determines whether re-emitted photons remain confined within the waveguide through total internal reflection or escape through the surface of the window [1], [6].

According to Snell's Law, the critical angle is given by:

$\theta_{(c)} = \sin^{-1} (n_{(air)} / n_{(matrix)})$

where:

- $\theta_{(c)}$ = Critical angle (degrees)
- $n_{(air)}$ = Refractive index of air (approximately 1.0) [1]
- $n_{(matrix)}$ = Refractive index of the host glass or polymer matrix containing the quantum dots

Photons emitted at angles greater than the critical angle are guided toward the edge-mounted photovoltaic cells through total internal reflection. In contrast, photons emitted within the escape cone may leave the waveguide, resulting in optical losses that reduce the overall efficiency of the system [1], [14].
Therefore, optimization of the refractive index and waveguide design is essential for minimizing escape-cone losses and improving photon transport efficiency in Quantum Dot Solar Window applications [1], [15].

ACKNOWLEDGMENT

The authors express their sincere gratitude to Dr. Ketan Badgujar, Head of the Department of Electrical Engineering, L.D. College of Engineering, Ahmedabad, for his valuable support, encouragement, and motivation throughout the course of this work.
The authors also extend their heartfelt thanks to Dr. Vihang Dholakiya, Assistant Professor, Department of Electrical Engineering, L.D. College of Engineering, Ahmedabad and Mohammed Irfan Siddiqui, Assistant Professor, Department of Electrical Engineering, L.D. College of Engineering, Ahmedabad for their guidance, constructive suggestions, technical expertise, and continuous support during the preparation of this review paper.
The authors further acknowledge the contributions of researchers, scientists, and academic institutions whose published studies and open-access literature on quantum dots, transparent photovoltaics, and solar window technologies provided the foundation for this review. Their Qunderstanding and development of next-generation renewable energy solutions.
Finally, the authors express their gratitude to the Department of Electrical Engineering, L.D. College of Engineering, Ahmedabad, for providing the academic environment and resources necessary for the successful completion of this work. The authors also acknowledge all those who directly or indirectly contributed to this review and supported its successful completion. The authors hope that this work contributes to ongoing research and development in sustainable energy technologies, building-integrated photovoltaics, and energy-efficient infrastructure.

REFERENCES

[1] M. G. Debije and P. P. C. Verbunt, “Thirty years of luminescent solar concentrator research: Solar energy for the built environment,” *Advanced Energy Materials*, vol. 2, no. 1, pp. 12–35, Jan. 2012.

[2] F. Meinardi, A. Colombo, K. A. Velizhanin, *et al.*, “Large-area luminescent solar concentrators based on ‘Stokes-shift-engineered’ nanocrystals,” *Nature Photonics*, vol. 8, no. 5, pp. 392–399, 2014.

[3] B. McKenna and R. C. Evans, “Towards efficient spectral converters through materials design for luminescent solar devices,” *Advanced Materials*, vol. 29, no. 28, Art. no. 1606491, 2017.

[4] Y. Zhao, “Near-infrared harvesting transparent luminescent solar concentrators,” *Advanced Optical Materials*, vol. 2, no. 7, pp. 606–611, 2014.

[5] U. W. Paetzold, E. Moulin, and V. Smirnov, “Transparent photovoltaics for building-integrated applications,” *Nature Energy*, vol. 5, no. 3, pp. 203–213, 2020.

[6] B. Ehrler, M. G. Debije, and W. C. H. Choy, “Quantum dot luminescent solar concentrators,” *Nano Energy*, vol. 22, pp. 106–121, 2016.

[7] J. Xu, Z. Yang, and Y. Wang, “Recent advances in quantum dot solar windows,” *Solar Energy Materials and Solar Cells*, vol. 230, Art. no. 111234, 2021.

[8] P. V. Kamat, “Quantum dot solar cells: The next big thing in photovoltaics,” *The Journal of Physical Chemistry Letters*, vol. 4, no. 6, pp. 908–918, 2013.

[9] M. C. Beard, J. M. Luther, and A. J. Nozik, “The promise and challenge of nanostructured solar cells,” *Nature Nanotechnology*, vol. 9, pp. 951–954, 2014.

[10] J. Nozik, “Quantum dot solar cells,” *Physica E: Low-Dimensional Systems and Nanostructures*, vol. 14, no. 1–2, pp. 115–120, 2002.

[11] J. M. Luther, M. Law, M. C. Beard, Q. Song, M. O. Reese, R. J. Ellingson, and A. J. Nozik, “Schottky solar cells based on colloidal nanocrystal films,” *Nano Letters*, vol. 8, no. 10, pp. 3488–3492, 2008.

[12] F. Meinardi, F. Bruni, and S. Brovelli, “Luminescent solar concentrators for building-integrated photovoltaics,” *Nature Reviews Materials*, vol. 2, Art. no. 17072, 2017.

[13] S. Brovelli, F. Meinardi, and M. G. Debije, “Progress in luminescent solar concentrator research,” *Advanced Optical Materials*, vol. 8, no. 12, Art. no. 1901147, 2020.

[14] Y. Zhao and R. R. Lunt, “Transparent luminescent solar concentrators for large-area solar windows,” *Advanced Energy Materials*, vol. 3, no. 9, pp. 1143–1148, 2013.

[15] R. R. Lunt, “Theoretical limits for visibly transparent photovoltaics,” *Applied Physics Letters*, vol. 101, no. 4, Art. no. 043902, 2012.