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Quantum Dots and Next-Gen Solar Cells: Evaluating the Physics and Sustainability Potential of Emerging Photovoltaics

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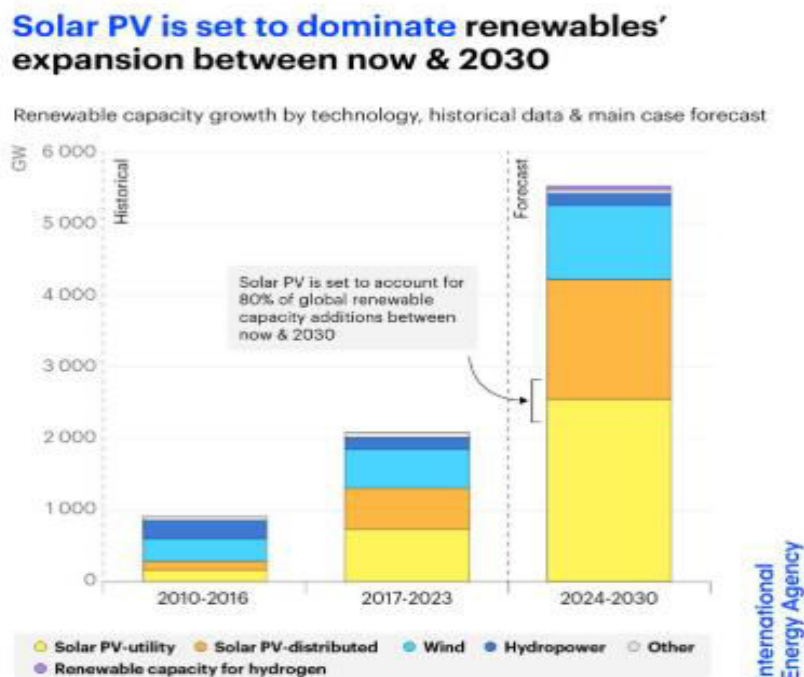
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ABSTRACT: This paper explores the physics, performance, and sustainability potential of quantum dot solar cells (QDSCs), a leading candidate for next-generation photovoltaics. Drawing on current data and literature, it examines quantum confinement effects, material innovations, device architectures, and environmental trade-offs. Key themes include advances in power conversion efficiency now exceeding 18% as well as efforts to mitigate toxicity through cadmium- and lead-free alternatives. The study also highlights fabrication scalability and the integration of QDSCs into flexible, transparent devices. Despite challenges in stability and mass production, QDSCs offer a promising route toward high-efficiency, low-impact solar energy for future applications.

KEYWORDS: Quantum Dot Solar Cells, Next-Generation Photovoltaics, Sustainable Energy Materials

I. INTRODUCTION

As global energy demands soar, solar photovoltaic (PV) technology is at the forefront of the transition to renewable energy. In 2023, solar PV accounted for nearly 6% of global electricity generation, and installations surpassed 1,400 GW of total capacity worldwide (IEA, 2023).



Source: (IEA, 2023)

Yet, conventional silicon-based solar cells, which dominate the market, face physical and economic efficiency limits, most notably the Shockley–Queisser limit of about 33% for single-junction cells. This has driven intense research into next-generation materials such as quantum dots (QDs), which promise tunable electronic properties, solution-processable manufacturing, and high theoretical efficiencies exceeding 40% when integrated into multi-junction cells (Bechu and Liao, 2021).

Quantum dots, semiconductor nanocrystals typically 2–10 nm in size, enable quantum confinement effects that allow precise control of band gaps through size variation. This property makes QDs ideal for capturing a broader spectrum of sunlight, including infrared. Current research has shown power conversion efficiencies (PCE) to reach 18.1 % in QD solar cells (IEA, 2023). In addition to this, their printable and low-temperature fabrication processes promise a way to flexible and cost-efficient solar modules. The paper critically analyses the implications of quantum dot photovoltaic on physics, performance, and sustainability, making them one of the main contenders in the development of solar energy products (Gómez, 2025).

RATIONALE AND OBJECTIVE

In the face of the growing necessity to decrease the level of carbon emissions and move towards the example of sustainable energy, the innovation of photovoltaic (PV) technologies is an international concern. Silicon-based solar cells have been a commercial success, but they are experiencing a tradeoff between efficiencies and scalability (Gómez, 2024). Quantum dot solar cells (QDSCs) are a good alternate option, providing the theoretical high efficiencies, tunable bandgaps and low-cost manufacturability. Due to the fast-developing nature of research into QDs, an evaluation of both the scientific basis and the environmental and economic viability of QD technology is necessary to evaluate the feasibility of QDs in the real world and the broader effects it would have on future renewable energy systems (Pimpang et al., 2025).

Objectives:

1. To see how the physics of quantum dot operation in solar cells (such as quantum confinement, bandgap tuning and operations of the charge carriers, etc.) works.
2. To review the present-day performance parameters of QDs solar cells, laying emphasis on power conversion efficiencies, material compositions, as well as scalability issues guided by more current empirical findings.
3. To provide a critical evaluation of both the environmental and sustainability legacy of QD-based solar technologies, such as urgent analysis, resource consumption, toxicity issues, and the possibility of a low-carbon footprint relative to traditional PV infrastructures.

II. METHODOLOGY

The methodology used in the given research paper is qualitative, based on secondary data, which was developed by using an extensive review of available literature sources in the sphere of academics and scientific fields. Information and statistics were obtained on the basis of reputable and peer-reviewed sources available in Google Scholar that gave access to the better quality of journals, conference papers, and academic thesis in relation to the quantum dots and photovoltaic technologies (Singh, L., 2025). Furthermore, official sources were consulted (sites of the International Energy Agency (IEA), National Renewable Energy Laboratory (NREL), and other organizations which conduct research in the sphere of energy sources) to get the latest statistical data and technical background concerning the realization of solar energy and new technologies.

The analysis was based on an evaluation of the research that addresses the physics of a quantum dot, the application of quantum dots in solar cells, and the sustainability and environmental effects of using quantum dots. A need-based comparative review of the existing levels of efficiencies, material specifications, and production methodologies was also provided to provide a balanced perception (Ravindra, Lin and Singh, 2025). Data obtained after 2015 was only used so that the results would be based on the most current changes in the world of technology. This paper seeks to give an evidence-based, factual assessment of the possible use of quantum dot solar cells as a solution towards the generation of renewable energy in the next generation, by synthesising the findings of various sources of reference.

III. LITERATURE REVIEW

1. Emergence and Evolution of Quantum Dot Solar Cells

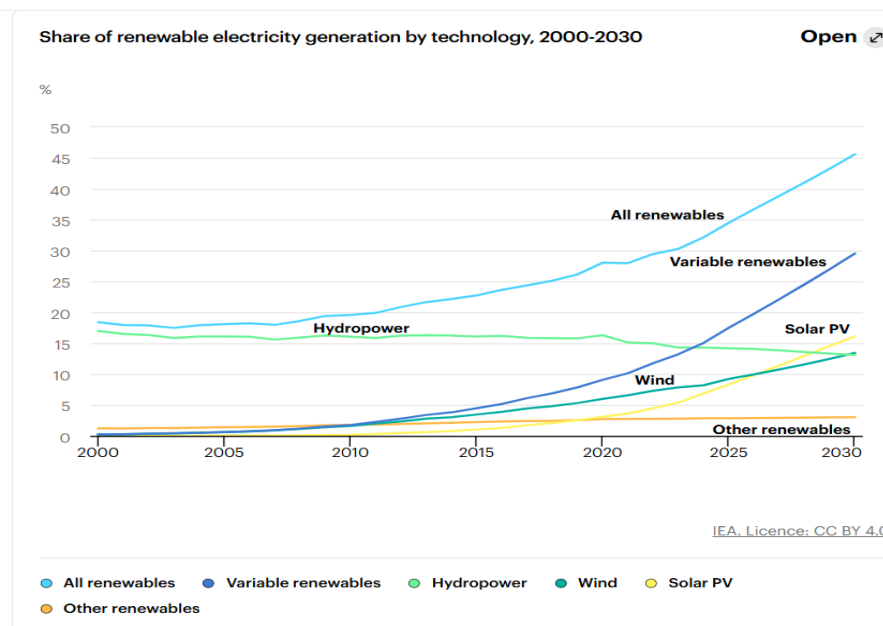
Quantum dot solar cells (QDSCs) have also become an active area of research into the next generation of solar cells, which can be used in a much more flexible manner than silicon solar cells, and where the quantum effects under which a QDSC operates afford greater efficiency. First, QDSCs reported very low efficiencies of below 1 per cent when they were first developed in the early 2000s (Chang et al., 2022). But lately, the advancement in nanomaterials science has brought forth a lot of improvements. These advances in photoanode design, quantum dot sensitization and electrolyte optimization had led to cadmium-based designs having exceeded 5 per cent (PCE) power conversion efficiency as of the year 2010.

The fundamental advantage of quantum dots is that their bandgap can be size-tuned, thus enabling the quantum dots to absorb a wider range of sunlight. This tunability arises from quantum confinement effects, enabling precise control over absorption from ultraviolet to near-infrared wavelengths (Mochan et al., 2024). Core/shell quantum dots, such as CdSe/ZnS and PbS/CdS, further improved efficiency and stability.

In the 2020s, efficiencies saw even sharper increases. By 2023, lead-based perovskite quantum dot solar cells achieved a record certified PCE of 18.1%, closing in on commercial-grade silicon cell performance (Ganesan, Houtepen and Crisp, 2018). Furthermore, environmentally friendlier alternatives like copper indium sulfide (CuInS₂) quantum dots have achieved efficiencies up to 7.04% in cadmium-free designs.

Technological integration has also advanced. Quantum dots can now be incorporated into flexible substrates, transparent devices, and multijunction cells, making them suitable for building-integrated photovoltaics and wearable electronics. Their compatibility with low-temperature, solution-based processing techniques makes QDSCs ideal for roll-to-roll manufacturing, further reducing production costs (Yeboah et al., 2024).

These developments underscore the evolution of QDSCs from lab experiments into scalable, competitive photovoltaic systems. With continued innovation in materials science, device architecture, and manufacturing, quantum dots are positioned to play a major role in the future of clean energy.



Source: (IEA, 2023)

2. Physical Principles and Performance Mechanisms

The outstanding attributes of quantum dot solar cells (QDSCs) depend on the wonder of the quantum confinement effect, which occurs during the reduction of semiconductor crystals to nanometer sizes, approximately existing between 2 and 10 nanometers. The details of the charge carrier motion are at this scale confined, leading to size-dependent band gaps and discrete energy levels. A wider bandgap is present on the smaller quantum dots, and a longer wavelength is absorbed on the larger quantum dots (Saadi and Nazari, 2019). This causes the QDs to be tunable as sunlight of many different wavelengths can be harnessed as when it incident on the QDs; this greatly increases the ability to absorb solar energy compared to using a fixed-bandgap material such as crystalline silicon.

An illustration of one of the most groundbreaking ideas in QDSC physics is Multiple Exciton Generation (MEG). In contrast to traditional solar cells that normally generate one electron-hole pair with each photon, MEG can enable two or more excitons to be made with a single high-energy photon. Conceptually, MEG might allow driving theoretical efficiency as high as 66% (or even up to 87% in certain quantum mechanical models). Conversely, the Shockley-Queisser limit of silicon cells with one junction would be about 33.7% efficiency (Gidwani et al., 2021).

Despite its promise, MEG's practical impact remains limited due to challenges such as ultrafast exciton recombination and inefficient charge separation. Real-world QDSCs currently demonstrate MEG-related efficiency gains only under specific conditions using high-energy photons and carefully engineered materials (Kastuar and Ekuma, 2024).

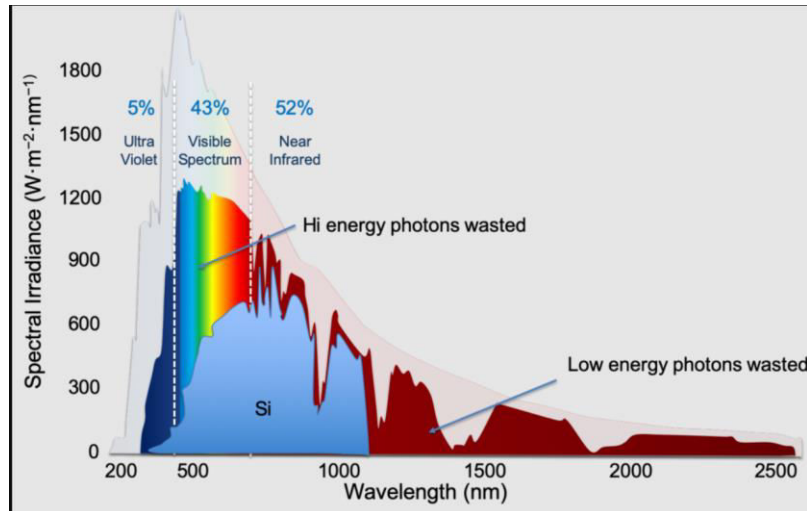
Another critical factor is carrier mobility, which influences how efficiently charge carriers move through the QD layer. Experimental studies have reported mobilities ranging from 10^{-2} to $1 \text{ cm}^2/\text{V}\cdot\text{s}$, depending on dot size, surface ligands, and film thickness. Enhancing surface passivation and minimizing trap state densities (on the order of 10^{14} – 10^{15} cm^{-3}) are essential to limit recombination losses and maximize charge collection (Giannikou, 2024). Together, these physical mechanisms distinguish QDs as versatile, next-generation photovoltaic materials with extraordinary theoretical potential.

3. Material Composition and Environmental Considerations

The material composition of quantum dots (QDs) is central to both their photovoltaic performance and environmental footprint (Rafiq et al., 2018). Historically, some of the most efficient quantum dot solar cells (QDSCs) have utilized heavy metal-based compounds such as cadmium selenide (CdSe), cadmium telluride (CdTe), lead sulfide (PbS), and lead selenide (PbSe). These materials exhibit excellent optical properties, including strong absorption coefficients ($>10^5 \text{ cm}^{-1}$), tunable bandgaps, and high photoluminescence quantum yields. As a result, they have enabled certified power conversion efficiencies exceeding 13–18% in experimental settings (Harris and Kim, 2024).

Nonetheless, cadmium and lead are harmful elements, which are dangerous in terms of manufacturing, use and disposal. Some consumer-facing solar technologies have faced regulatory constraints e.g. EU Restriction of Hazardous Substances (RoHS) directive, which has created questions regarding the future feasibility of these materials in the longer term.

To check these risks, development has been focused on cadmium and lead-free quantum dots. Such materials as copper indium sulfide (CuInS_2) and silver bismuth sulfide (AgBiS_2) are less toxic and environmentally less harmful. Such eco-friendly QDs continue to afford high light absorption through the visible and near-infrared range and are reported to have solar cell efficiencies of 6.66–7.04% at laboratory scale (SAYAN, 2025).



Source: ((Son et al., 2022)

The role of surface passivation in enhancing the stability and the toxicity profile of QDs cannot be overemphasized. Surrounding the quantum dot core with shells of zinc sulfide (ZnS) decreases the number of surfaces defects and avoids leaching of poisonous ions, and preserves high photoluminescence efficiency up to 80% at times (Ikeri, Onyia and Adokor, 2021). Simultaneously, developments of green synthesis techniques, including aqueous-phase green synthesis or alcoholic organic synthesis, minimized the use of toxic organic solvents.

The main challenge is the formulation of non-toxic, stable, and scalable quantum dot materials that will be adopted in a mainstream scenario. The performance of environmentally responsible QDs, besides satisfying the requirements of a next-gen solar application, also follows the global sustainability and safety standards.

4. Device Architectures and Fabrication Techniques

The structure of quantum dot solar cells (QDSCs) is possible through a set of device architectures, each of which has its own benefits in the respective fields- light gathering, charge direction, and scalability. The most popular variants of constructing describe Schottky junctions, p-n heterojunctions, depleted heterojunctions, and quantum dot-sensitized solar cells (QDSSCs). Schottkey junction devices have a metal contact which junctions with the quantum dot layer and in p n heterojunctions different n p type layers which enable separation of charge. The most popular are depleted heterojunctions which generally have relatively high efficiency and are generally based on dishes of TiO₂ and PbS QDs (Jayraj, 2024).

Among these, QDSSCs have gained traction due to their structural similarity with dye-sensitized solar cells. They rely on a photoanode (e.g., TiO₂) sensitized with quantum dots and paired with a suitable redox electrolyte and counter electrode. Early QDSSCs achieved efficiencies of around 5–6%, but with improved interface engineering and optimized materials, efficiencies have climbed to 12–13% in some lab-scale devices (XRAY, 2025).

A major advancement has been the shift to low-temperature, solution-based processing. Quantum dots, synthesized in colloidal solutions, can be deposited using spin-coating, spray-coating, inkjet printing, or roll-to-roll printing (SAYAN, 2025). These methods reduce manufacturing costs and enable fabrication on flexible substrates like PET or aluminum foil, expanding the use of QDSCs in wearable and portable electronics. This contrasts with high-temperature vacuum processing used for silicon PVs, which increases cost and complexity.

Film uniformity, charge mobility and interdot coupling have also been enhanced due to surface ligand engineering to replace long insulating organic ligands with short, conductive ligands. The efficiencies have risen to more than 19.1 percent with the incorporation of perovskite QDs and hybrid nanostructures and are close to the commercial standards (Mahapatra et al., 2022).

These technologies in devices structure and fabrication taken together constitute a big step toward realization of high-efficiency, economic, and scalable solar technologies based on quantum dots.

5. Stability, Scalability, and Sustainability Challenges

Although quantum dot solar cells (QDSCs) exhibit high use performance and versatile structure, there are significant impediments to their efforts on operation reliability, cost-effective volume manufacturing, and sustainability. Amongst the most important challenges lies the environmental sensitivity (Goyal et al., 2025). Quantum dots are sensitive under the effects of oxygen, moisture, UV light, and high temperatures and may undergo degradation, frequently via oxidation, chelating ligand separation, and surface fissures. Without protection, performance will start degrading in tens of days and eventually significant power conversion efficiency (PCE) will be lost.

To improve stability, researchers have developed core/shell quantum dot structures (e.g., PbS/CdS, CdSe/ZnS) that shield the photoactive core from external stresses. Halide ligands, such as iodide and bromide, provide better electronic coupling and resist desorption compared to traditional organic ligands (Sharma et al., 2025). Encapsulation techniques using glass barriers, polymer overcoats, and atomic layer deposition (ALD) have extended device lifetimes to over 1,000 hours under continuous illumination, but this is still below the 25-year standard of commercial silicon panels.

Scalability presents additional complexity. Producing uniform, monodisperse quantum dots at industrial scale requires precise control of synthesis parameters. Batch-to-batch inconsistencies in dot size, composition, or surface chemistry can lead to unpredictable device performance. Advanced continuous-flow reactors and scalable synthesis routes are being explored to meet growing demand. Currently, manufacturers like UbiQD and Avantama have scaled production to tens of metric tons per year, but widespread module-level deployment remains limited (Wang and Tian, 2016).

Sustainability is also a concern, especially regarding the toxicity of cadmium and lead-based QDs. Regulatory pressures in the EU and US restrict their commercial use. As a solution, non-toxic alternatives like CuInS₂, AgBiS₂, and ZnSe are being adopted, with efficiencies up to 7% and potential for safer deployment in consumer products (Sk, Islam and Burman, 2025).

Quantum dots' compatibility with flexible, transparent substrates offers applications in windows, vehicles, wearables, and smart infrastructure, supporting both urban integration and sustainable design.

IV. CONCLUSION

Quantum dot solar cells (QDSCs) represent one of the most promising frontiers in next-generation photovoltaics due to their unique physical properties, tunable bandgaps, and potential for high power conversion efficiencies. The literature highlights a steady evolution in performance, with efficiencies rising from below 1% in early prototypes to over 18% in current advanced architectures. The fundamental principles of quantum confinement and multiple exciton generation distinguish QDSCs from traditional semiconductors, offering theoretical efficiency limits far beyond those of conventional silicon-based cells.

Some of the major concerns regarding sustainability have been resolved with material innovations, more specifically, surface passivation and environmentally friendly quantum dots, but the use of toxic heavy metals cadmium and lead remains a limitation to their massive implementation. Innovations in manufacturing technologies, like solution processing and roll-to-roll printing, exist that open avenues to low-cost, big scale manufacturing. Nevertheless, there are remaining problems with longer-term process resilience, environmental friendliness and reproducibility of batches in synthesis on larger scales.

Nevertheless, these challenges do not mean that QDSCs cannot be implemented into buildings, mobile devices, and cars due to their flexibility, transparency, and being lightweight materials. Since their disadvantages are still in the process of being overcome, QDSCs are poised to become a complementing (or even superior) already established solar technology, becoming a potential sustainable and energy-efficient alternative to the overall energy mix in the future.

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