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Emerging photovoltaic technologies: a review of organic, dye-sensitized, and novel solar cell concepts

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ABSTRACT

Emerging photovoltaic technologies have attracted considerable research interest because they offer alternative approaches to solar energy conversion beyond conventional crystalline silicon and established thin-film devices. Organic photovoltaic (OPV) cells, dye-sensitized solar cells (DSSCs), quantum-dot solar cells, and organic–inorganic perovskite solar cells use different mechanisms and materials to absorb sunlight and generate electrical current. Their potential advantages include low-temperature processing, lightweight and flexible structures, tunable optical properties, and the possibility of lower-cost manufacturing. However, these technologies also face challenges involving conversion efficiency, charge-carrier recombination, material stability, toxic constituents, and large-area fabrication. This review examines their operating principles, materials, device architectures, performance characteristics, and engineering limitations based on research published through 2014. It highlights the rapid progress of perovskite solar cells while emphasizing that long-term reliability and scalable manufacturing remain essential requirements for commercial development.

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1. INTRODUCTION

Emerging photovoltaic technologies have been developed to address limitations associated with conventional solar-cell materials and manufacturing approaches. Unlike traditional crystalline silicon devices, several emerging technologies use molecular, nanostructured, or hybrid semiconductor materials that can be processed through solution-based or relatively low-temperature techniques. These characteristics create opportunities for lightweight, flexible, semi-transparent, and potentially low-cost photovoltaic applications [1]–[4].

Among the most extensively investigated concepts are organic photovoltaics, dye-sensitized solar cells, and quantum-dot solar cells. Organic–inorganic halide perovskite solar cells also experienced exceptionally rapid development during 2012–2014, becoming one of the most promising emerging photovoltaic approaches [5], [6]. This review discusses these technologies, focusing on their operating mechanisms, device structures, performance, and engineering challenges, with all references limited to publications available by 31 December 2014.

2. ORGANIC PHOTOVOLTAIC CELLS

2.1. Materials and operating principles

Organic photovoltaic cells convert sunlight into electricity using organic semiconductors, typically conjugated polymers or small organic molecules. Their operation involves photon absorption, exciton formation, exciton dissociation, and charge transport toward the electrical contacts. Because excitons in organic semiconductors are strongly bound, an interface between electron-donor and electron-acceptor materials is generally required to separate the photogenerated charges [3], [4].

A widely used architecture is the bulk heterojunction (BHJ), in which donor and acceptor materials are blended within the active layer. Common donor materials include conjugated polymers such as poly(3-hexylthiophene) (P3HT), while fullerene derivatives such as PCBM have frequently served as electron acceptors. The nanoscale morphology of the blend is important because it determines the interfacial area for exciton dissociation and the pathways available for charge transport [3], [4].

2.2 Device structures and advantages

Organic solar cells can be fabricated in conventional or inverted configurations using transparent electrodes, charge-selective interlayers, an organic active layer, and a counter-electrode. Solution processing, including spin coating and printing techniques, offers the possibility of producing large-area devices on flexible substrates. Their lightweight construction and potential for semi-transparent designs make OPVs attractive for applications such as portable electronics, building-integrated photovoltaics, and flexible energy-harvesting surfaces [3], [4].

2.3 Limitations

Despite significant improvements in efficiency, organic solar cells face limitations related to relatively short exciton diffusion lengths, charge recombination, and sensitivity to environmental exposure. Oxygen, moisture, ultraviolet radiation, and thermal stress can degrade active materials and interfaces, reducing operational lifetime. In addition, controlling the donor–acceptor morphology over large areas remains a significant challenge for reproducible manufacturing [3], [4].

3. DYE-SENSITIZED SOLAR CELLS

3.1. Materials and operating principles

Dye-sensitized solar cells use a light-absorbing dye attached to a porous semiconductor, commonly nanocrystalline titanium dioxide (TiO_2), to convert sunlight into electrical energy. Unlike conventional semiconductor solar cells, light absorption and charge transport are performed by different components: the dye absorbs photons and injects electrons into the semiconductor, while the electrolyte or solid-state hole conductor regenerates the oxidized dye. This separation of functions allows DSSCs to use relatively inexpensive semiconductor materials and a variety of molecular sensitizers [1], [2].

A conventional DSSC consists of a transparent conducting substrate, a mesoporous TiO_2 photoelectrode, a sensitizing dye, a redox electrolyte, and a counter-electrode, commonly coated with platinum. Ruthenium-based dyes have been widely investigated because of their broad visible-light absorption and favorable charge-transfer properties. Organic dyes and alternative redox couples have also been developed to improve light harvesting, reduce material costs, and increase device voltage [2], [7].

3.2. Advantages and development

DSSCs offer several advantages, including good performance under diffuse illumination, potentially low-cost processing, and opportunities for colored or semi-transparent photovoltaic products. Improvements in dye molecular design, electrolyte composition, and interfacial engineering contributed to substantial efficiency gains before 2014. Solid-state DSSCs, which replace liquid electrolytes with solid hole-transport materials, were also investigated to address leakage and sealing problems associated with liquid-based devices [2], [7].

3.3. Limitations

The principal engineering challenge for conventional DSSCs is long-term stability, particularly when liquid electrolytes are used. Electrolyte leakage, solvent evaporation, corrosion of cell components, and degradation of dyes can reduce device performance during prolonged operation. Solid-state configurations can reduce some of these problems, but charge recombination, incomplete pore filling, and the cost or processing requirements of hole-transport materials remain important limitations [7], [8].

4. NOVEL PHOTOVOLTAIC CONCEPTS

4.1. Quantum-dot solar cells

Quantum-dot solar cells use semiconductor nanocrystals whose optical and electronic properties can be adjusted by changing particle size, composition, and surface chemistry. Materials such as lead sulfide (PbS), cadmium sulfide (CdS), and cadmium selenide (CdSe) have been investigated as light absorbers or sensitizers in different device configurations. Quantum confinement provides the possibility of tuning

absorption across a broad spectral range, while multiple-exciton generation has been explored as a potential mechanism for improving solar-energy conversion [9].

Quantum-dot devices can use a sensitized architecture similar to DSSCs or a solid-state heterojunction structure in which quantum-dot films are integrated with electron- and hole-selective contacts. Their potential advantages include tunable bandgaps, solution-based fabrication, and compatibility with thin-film processing. Nevertheless, surface defects, charge trapping, ligand-related transport barriers, and the use of toxic elements such as cadmium and lead present significant challenges [9].

4.2. Organic–inorganic perovskite solar cells

Organic–inorganic halide perovskites emerged as a particularly promising class of photovoltaic absorbers during 2012–2014. Materials such as methylammonium lead iodide exhibit strong visible-light absorption and favorable charge-transport properties, enabling high conversion efficiencies in relatively thin absorber layers. Their compatibility with solution-based processing and different device configurations contributed to the rapid development of this technology [5], [6].

Early perovskite solar cells were developed from sensitized mesoscopic structures, but subsequent research demonstrated both mesoscopic and planar architectures. These devices typically incorporate electron- and hole-transport layers around the perovskite absorber to facilitate charge extraction. By 2014, independently confirmed research-cell efficiency had reached 17.9%, illustrating the unusually rapid progress of this emerging technology [5], [6], [10].

4.3. Remaining challenges

Perovskite solar cells still faced substantial challenges in operational stability and manufacturing reliability by the end of 2014. Moisture and heat could accelerate material degradation, while device hysteresis and sensitivity to fabrication conditions complicated performance assessment and reproducibility. The use of lead also raised environmental concerns, making encapsulation, material substitution, and end-of-life management important research priorities [5], [6].

5. COMPARATIVE PERFORMANCE AND ENGINEERING CHALLENGES

Emerging photovoltaic technologies differ in their light-absorption mechanisms, device structures, processing requirements, and levels of technological maturity. OPVs and DSSCs offer opportunities for flexible or semi-transparent devices, while quantum dots provide tunable optical properties and perovskites demonstrated exceptionally rapid efficiency improvement. However, laboratory efficiency alone does not determine commercial viability because stability, manufacturing yield, material availability, and module-scale performance are equally important [3], [5], [7], [9]. The main characteristics, device structures, advantages, and limitations of these emerging photovoltaic technologies are summarized in Table 1.

Table 1. Comparison of emerging photovoltaic technologies

Technology	Main light absorber	Typical device structure	Main advantages	Major limitations
Organic PV	Conjugated polymers or small organic molecules	Donor–acceptor bulk heterojunction	Lightweight; flexible; solution-processable	Morphology control; environmental degradation; recombination
Dye-sensitized PV	Dye molecules on mesoporous TiO_2	Dye/TiO_2/electrolyte/counter-electrode	Good diffuse-light response; tunable color; relatively simple processing	Electrolyte leakage; sealing; long-term stability
Quantum-dot PV	Semiconductor nanocrystals, e.g., PbS or CdSe	Quantum-dot sensitized or solid-state heterojunction	Tunable bandgap; solution processing; broad spectral absorption	Surface traps; charge transport; toxic constituents
Perovskite PV	Organic–inorganic metal-halide perovskite	Planar or mesoscopic absorber with selective contacts	Strong absorption; rapid efficiency progress; low-temperature processing potential	Moisture and thermal instability; lead content; reproducibility

Note: Structures are representative examples; individual devices may use different materials and layer arrangements.

By 2014, independently confirmed research-cell efficiencies demonstrated that several emerging technologies had achieved meaningful photovoltaic performance. The values in Table 2 are laboratory cell records reported in the 2014 efficiency tables and should not be interpreted as typical commercial module efficiencies. Differences in device area, measurement conditions, and stability testing also need to be considered when comparing technologies [10].

Table 2. Selected independently confirmed research-cell efficiencies reported by 2014

Technology	Efficiency	Record context
Perovskite solar cell	17.9%	KRICT; confirmed in April 2014
Organic thin-film solar cell	11.1%	Mitsubishi Chemical; confirmed record listed in 2014
Dye-sensitized solar cell	11.9%	Sharp; confirmed record listed in 2014

Source: Green *et al*., "Solar cell efficiency tables (version 44)," 2014 [10]. Values refer to research cells, not commercial modules.

The main engineering challenge shared by emerging photovoltaic technologies is maintaining high performance while improving operational lifetime and production scalability. OPVs require precise control of active-layer morphology, DSSCs need stable electrolytes and durable seals, quantum-dot cells require effective surface passivation and charge transport, and perovskite devices need improved resistance to moisture and heat. These challenges indicate that material innovation must be accompanied by interface engineering, encapsulation, process optimization, and standardized reliability testing [3], [7]–[9].

6. DEVELOPMENT PERSPECTIVES

Future development of emerging photovoltaic technologies should focus on combining improved conversion efficiency with stable operation and reproducible manufacturing. For OPVs, research priorities include new donor–acceptor materials, optimized bulk-heterojunction morphology, and improved barrier layers. For DSSCs, more stable redox systems, durable sensitizers, and solid-state charge-transport materials are important directions for reducing degradation and improving device integration [3], [7], [8].

Quantum-dot solar cells may benefit from improved nanocrystal synthesis, surface passivation, and ligand engineering to facilitate charge transport. Perovskite solar cells require further progress in moisture-resistant compositions, stable interfaces, encapsulation, and lead-management strategies. Across all emerging technologies, the development of scalable deposition methods and reliable module designs will be necessary to translate laboratory advances into practical photovoltaic products [5], [6], [9].

7. CONCLUSION

Organic, dye-sensitized, quantum-dot, and perovskite solar cells represent diverse approaches to photovoltaic energy conversion beyond conventional silicon technologies. Their distinctive material properties and device architectures provide opportunities for lightweight, flexible, semi-transparent, and potentially low-cost solar applications. By 2014, perovskite solar cells had demonstrated particularly rapid efficiency improvements, while OPVs and DSSCs had established important research and development foundations. Nevertheless, all these technologies faced challenges involving operational stability, charge-carrier losses, material toxicity, and large-area manufacturing. Future progress will depend on improving absorber materials, interfaces, encapsulation, and fabrication reproducibility while considering environmental impacts throughout the device life cycle. Their long-term contribution to the photovoltaic industry will therefore depend not only on laboratory efficiency but also on durability, scalable production, and practical application requirements.

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