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THE NEXT GENERATION OF PHOTOVOLTAICS: A COMPREHENSIVE REVIEW OF EMERGING MATERIALS, PROSPECTS, AND CHALLENGES

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Abstract: This paper reviews the evolution of photovoltaic (PV) technologies, beginning with the commercialization of first- and second-generation PV technologies. Introducing their characteristics, market share, and current limitations, respectively. Then, bring in the main focus of the paper — the third generation PV technologies — copper zinc tin sulfide, perovskite solar cells, organic photovoltaics, quantum dot solar cells, and dye sensitized solar cells — were analyzed in terms of their characteristics, design, power conversion efficiency, and scalability. The analysis underscores the importance of current third-generation PV technologies innovation, highlighting the strong potential of third-generation PV technology to overcome the technology bottleneck of first and second-generation PV technologies and establish a solid ground for assuming a leading role in the global sustainable energy market.

Keywords: Copper zinc tin sulfide; Perovskite solar cells; Organic photovoltaics; Quantum dot solar cells; Dye sensitized solar cells; Photovoltaic technologies

1 INTRODUCTION

Every hour, the sun delivers more energy to Earth than what people on Earth consume in an entire year, yet it is deeply overvalued until the oil crisis in the 1970s kicks in. Fossil fuel is by far the most prominent energy source of the globe; for instance, it accounted for 84% of the total U.S. energy production in 2023 [1]. However, fossil fuels have significant environmental externalities: air pollution, producing hazardous air pollutants, include sulfur dioxide, nitrogen oxides which are calculated to cause 8.7 million deaths globally in 2018[2]; water pollution, each fracking well consume water range between 1.5 million to 16 million gallons of water[3], and the resulting wastewater could contaminated drinking water, brought potential health risk for the local ecosystem or neighborhood; oil spill, result inhabitate destruction, erode shorelines, fishery closure, 2010 BP Deepwater Horizon spill which cost $65 billion in penalties and cleanup cost [4]. The environmental destruction caused by fossil fuels makes it urgent that future energy look beyond oil, coal, and gas. Fittingly, photovoltaic (PV) energy offers a renewable source that offers clean, renewable electricity that is environmentally friendly, emits zero greenhouse gas, and safeguards our future energy resilience, such as the ground-mounted PV system shown in Figure 1.

Figure 1 Solar PV-System
Figure reprinted from International Energy Agency. Solar PV. 2025. Available at: httpss://www.iea.org/energy-system/renewables/solar-pv accessed on October 16, 2025

In 2024, PV broke the previous record, accounting for over 10% of the global electricity consumption; 2246 GW were installed globally by the end of 2024; 34 countries installed more than 1 GW of new capacity in 2024, with 23 countries now exceeding 10 GW in total installed capacity [5]. With surging market size and capacity, PV is becoming one of the most promising sources of reliable, clean power.

So, what is Photovoltaic technology and how does it work? The quintessential mechanism of photovoltaic technology is the process of converting incident sunlight into electricity using semiconductor materials. Those incident photons excite the electrons, leaving behind a positively charged hole. Together, the electron-hole pair will be separated by a junction, inducing an electric field. Once connected with external circuits, it generates a direct current (DC) of electricity. The whole process has no gas emission, requires no fuel combustion, and consumes minimal water resources, making PV one of the cleanest and most sustainable energy resources. To delve deeper into photovoltaic technologies with different PV materials and working mechanisms, this paper will begin by introducing the core principles of PV technology, including photoelectric and photovoltaic effects. There are three generations of PV technologies in total, including the first generation PV technology, crystalline silicon solar cells, the second generation PV technology, thin-film solar cells, and lastly, the third generation PV technology, comprising a broad category of emerging solar technologies. The first- and second-generation PV technologies are those PV technologies that have already been commercialized and widely deployed in the PV market: first-generation PV is the most mature and long lifetime, while second-generation PV offers lighter and cheaper designs. Despite their prominent deployment and technological maturity, the first and second generation PVs are constrained by the theoretical power conversion efficiency(PCE) limit, material scarcity, material footprint, etc. Third-generation PV technologies are designed to surmount those bottlenecks with new designs and absorbers that aim for higher efficiencies, lower manufacturing costs, and complexities. This paper will be mainly focused on the innovation of third-generation PV technologies, including Copper zinc tin sulfide, perovskite solar cells, organic photovoltaics(OPVs), quantum dot solar cells, and dye-sensitized solar cells(DSSCs), preceded by a general introduction to the photovoltaic effect, photoelectric effect, and development of first and second-generation PV technologies, like thin-film and Wafer-based Crystalline Silicon PVs.

In 1905, Maxwell proposed the classical wave theory, confirming the wave nature of light, which states that the energy of light is spread out continuously over the wavefront, and the energy delivered depends on the intensity. However, the discrepancies between the experiment and classical wave theory imply the absence of some parameter, specifically the particle nature of light. In 1905, Albert Einstein introduced that light energy is localized, and the energy behaves as if it were made up of quanta of size $E = h\nu$. When the light hits matter, electrons absorb a quantum one at a time; a set portion of the energy from the photon ϕ is used to liberate the electron from the metal's surface. Thus, the liberating electron will carry the kinetic energy $K_{max} = h\nu - \phi$. The frequency of incident light determines the kinetic energy of the ejected photoelectrons, and increasing the intensity of light only affects the number of electrons emitted per unit time instead of changing the energy of the individual electrons [6].

2 PHOTOVOLTAIC EFFECTS

The photoelectric effect is applied to many aspects of our lives, including low-light imaging devices, photoelectron spectroscopy(PES), photoelectric photometry, etc. Among them, solar photovoltaics (PV) are the most pervasive solar technology today. Deploying the photovoltaic effect, a special engineered case of the photoelectric effect that occurs inside a semiconductor. It is often called the Internal Photoelectric Effect. When the photons strike semiconductor material near the p-n junction, if the photon carries enough energy to create an electron-hole pair, it will free an electron and create a positive hole pair. The electric field inside the cell will then drive the electrons toward the cathode (the n-type side) and holes toward the anode (the p-type side), producing a direct-current electric current in Figure 2.

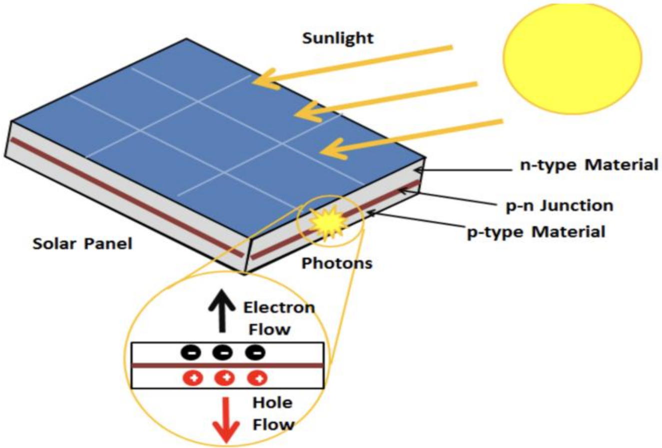

Figure 2 Photovoltaic Effect Animation

This figure is reprinted from Energy Education. (n.d.). Photovoltaic effect. University of Calgary. https://energyeducation.ca/encyclopedia/Photovoltaic_effect

3 FIRST AND SECOND GENERATION

Nowadays, the commercial solar industry is dominated by first- and second-generation photovoltaic technologies. In the past decades, the first-generation PV technology took up around 98% of the global module market share, with the thin-film PV holding around 2% of the market share alone [7]. Remarkably, U.S. PV capacity has expanded from less than 1,000MW to more than 18,000MW in the past decades [8]. On the contrary, the emerging or Third-generation PVs currently hold little market share to date, due to the hurdles on performance scalability, manufacturing scalability, bankability, etc.

This section of the paper will give a concise introduction to the development and categories of commercialized PVs. With one of the most mature technologies, consistent performance over 30 or more years of use, and established cost-efficiency manufacturing processes, Wafer-based Crystalline Silicon is composed of various advantages, consolidating its unshakable position in the PV market. However, it also faces many challenges, such as a high requirement of the energy input for wafer production and a theoretical Power conversion efficiency bottleneck. Another type of commercialized PVs is Thin-Film PV, including ones made of Cadmium Telluride(CdTe) and the other one made of CopperIndium Gallium Diselenide(CIGS). The CdTe Pvs held the largest tin-film market share. This accounts for about 3% of the global PV market [9]. CdTe has a lower material cost per watt compared to Wafer-based Crystalline Silicon, a higher light absorption coefficient due to a thinner active layer. Despite being the best performing and most reliable in large-scale production thin-film PVs, CdTe is facing restrictions from Cadmium toxicity, tellurium scarcity, and lower long-term efficiency compared to Wafer-based Crystalline Silicon. Copper Indium Gallium Diselenide(CIGS) is one of the leading thin-film technologies with the achieved record PCE of 23.64%[10]. CIGS has great tunability that helps achieve the bandgap from about 1.0eV to 1.7eV[11]. With the flexible substrate options such as polyamide, plastic films, metal foils, and flexible glass, CIGS yields lightweight and flexible modules beyond what can be achieved by Crystalline Silicon. However, it also faced hurdles regarding material scarcity and increased complexity in the manufacturing process control. Amorphous Silicon(a-Si) in turn shares a relatively smaller fraction of the thin-film market. Amorphous Silicon has no toxic heavy metals and also has flexible substrates similar to CIGS. Yet, Amorphous Silicon yields lower efficiency at about 6-10% PCE[12], and light-induced degradation in its solar cell's output.

Overall, crystalline silicon and thin-films are two PV technologies currently dominating the market. Together, they yielded low-cost, reliable, and mature renewable energy for the global market. Nevertheless, those commercialized PV technologies are potentially confined to their theoretical PCE limit and the scarcity of some thin-film materials. To overcome those setbacks and limits of commercialized PVs, researchers are developing a class of emerging "third generation" technologies, some especially promising ones, including Copper zinc tin sulfide, perovskite solar cells, organic photovoltaics(OPVs), quantum dot solar cells, and dye-sensitized solar cells(DSSCs), which will be discussed in the next section.

4 THIRD GENERATION MATERIAL

Besides the First-generation and Second-generation photovoltaic Materials, the Third-Generation Solar Materials are generally defined as the new and emerging solar cell materials, including Copper zinc tin sulfide, perovskite solar cells, organic photovoltaics(OPVs), quantum dot solar cells, and dye-sensitized solar cells(DSSCs). The Third-generation materials are considered materials that offer the potential for higher efficiency compared to the efficiency of the first-generation Crystalline Silicon(c-Si) cells and second-generation Thin-Film Solar cells. In addition to the power conversion efficiency advantage, the Third Generation Material is also set to acquire technology innovation to help achieve large-scale manufacturing at lower cost, achieve lower material use, such as over 99% material use reduction of Quantum Dot PV compare to crystalline silicon and 80% material use reduction in thin-film visualized in figure 3, and reduce manufacturing complexity and cost than traditional methods. Thus, the Third-generation materials often have higher material complexity; once synthesized, they can be deposited as thin films quickly and easily. Third-generation material has many unique characteristics with higher material complexity: the majority of the Third-generation material has reduced material use and cell weight due to decreased absorber thickness; employing separate active material synthesis and deposition processes, the Third-generation material often consists of lightweight substrates, enabling high weight-specific power; High complexities have higher tolerance for impurity of the cells.

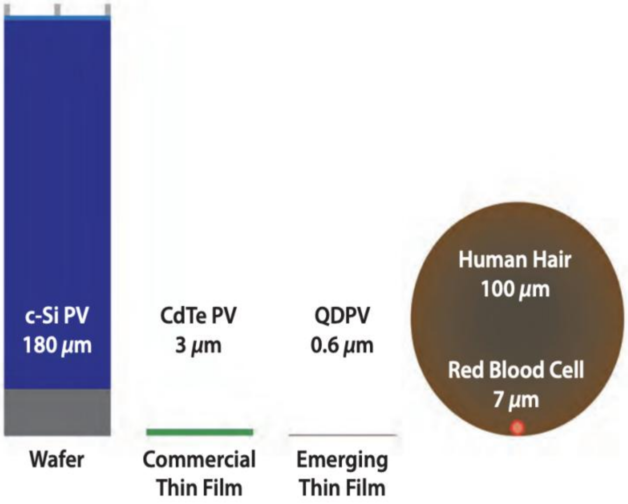

Figure 3 The Length Comparison between Three Generation PVs

Being the first pioneering emerging photovoltaic technology in the 1990s, the Dye-sensitized solar cell(DSSC) is the most mature and firmly established nanomaterial-based PV choice, which started the third generation PVs wave. Different from many other Third-generation materials, DSSC often deploys a liquid electrolyte to carry ions to the platinum counter electrode. The incident light will excite and then oxidize the dye, the free electron will transport through TiO_2(a nanoporous layer), then get collected by the FTO glass(coated with a transparent fluorine-doped tin oxide) and be conducted laterally to the external wire, producing an electric current. The oxidized dye molecules restore to their state by accepting an electron from the liquid electrolyte, which the oxidized electrolytes will diffuse through the liquid electrolyte, at the platinum counter electrode, and restore their state by the incoming electrons from the external circuit. The platinum counterelectrode with low overpotential will act as a catalyst to speed up the whole redox reaction at the counter electrode. The new cobalt-based redox couples make it possible to obtain a higher open-voltage circuit. DSSCs are now able to achieve a 13.5% PCE under standard AM1.5G illumination(100mW cm^{-2}), and 34.5% under 100 lux indoor illumination on a 2.8cm^2 cell[6]. Therefore, they are very outstanding ideal power sources as the charger for the portable consumer electronics and sensors in the future. One of the shortcomings of cobalt-based complexes is that they decrease the diffusing speed of the ions inside the electrolyte. It is also very important to balance the thickness and the combination loss of the TiO_2 layer, with a thicker layer absorbing more dye and enabling more light absorbance, but retarding the recombination of electrons TiO_2 . Other approaches have been adopted, such as introducing the organic high open-circuit voltage dye MS4 and MS5 as co-sensitizer, which significantly improves the photovoltaic performance of the DSSCs by reducing the interfacial charge recombination[6]. However, the use of liquid electrolyte in DSSCs raised concerns about its long-term stability due to the potential risk of spillage, dye breakdown, and fluid combustibility. In manufacturing complexity, DSSCs first screen-print both layers on FTO glass, then immerse the electrodes in dye solution for approximately 14 hours. After that, the electrolyte was injected into the counter electrode, preceded by UV-curable glue; lastly, the platinum solution was electropolymerized under a constant applied electrical voltage.

The emergence of dye-sensitized solar cells(DSSCs) soon inspired the innovation of Organic Photovoltaics(OPVs) in the 2000s, shifting towards more printable and flexible devices. Over the past 3 decades, the PCE of OPVs has surged from 1% to 19% as of now through donor-acceptor optimization and side-chain engineering[13]. Taking advantage of the advancing photoactive material, OPVs have evolved through polymer-fullerene blends to narrow bandgap small-molecule acceptors with wide bandgap polymer donors. Allowing the OPVs to obtain higher photocurrent and open-circuit voltage, the photoactive material in OPVs enables achievement such as high efficiency, stability, indoor performance[14], and semitransparency characteristics. Moreover, the solution processability of OPVs and the great mechanical flexibility realized by the roll-to-roll printing production significantly reduced the manufacturing cost of OPVs. Transferring from the lab-scale spin-coating to a scalable roll-to-roll compatible method, blade coating, spray coating, screen printing, slot-die coating, and inkjet printing have been applied successfully to fabricate OPV. However, the large-scale manufacturing of OPVs also faces challenges regarding morphology control and interlayer wetting. The inclusion of an additive effectively controlled the morphology of OPVs, while it also introduced many unstable factors in the process, such as inducing unstable chemical interactions on the polymer interlayer. Interlayer wettability is also crucial for the manufacturing of OPVs to obtain a uniform and complete film. Adding surfactant can effectively solve this challenge by reducing the surface tension of the solution.

Around the same time, Colloidal quantum dot photovoltaics(QDPV) were introduced, offering high tunability using quantum confinement effects. Colloidal quantum dot photovoltaics(QDPV) deploy solution-processed nanocrystals(quantum dots, QD) such as lead chalcogenide (PbS and PbSe) to absorb incident light. Due to the high tunability of QDs across IR-visible range between 0.6-1.7eV[15], QDPV can be tailored by adjusting the size and composition of solution-processed nanocrystals, such as PbS and PbSeto absorb the infrared region of the spectrum with the long-wavelength of 1100-2500 nm. The latest PCEs of PbS-based QD are approximately 14%, and 16-17% for inorganic perovskite QDs[16]. When the incident light excites the electrons in QDs, QDs have a very high surface-to-volume ratio, thus electron recombination loss and charge trapping can happen, resulting in low PCE. Nowadays, new developments of QD materials expand from inorganic nanocrystals(ex, CdSe nanorods) to CdS, CdSe, PbS, and InP to sensitize mesoporous metal oxide layers in both liquid and solid form, which is similar to the dye-sensitized solar cells [16]. Those QD materials were ascribed to high dielectric constants, which in turn help delocalize the electron carriers, improving the PCE of QDPV[17]. The similar setbacks for the previous DSSCs due to the use of the liquid electrolyte are also present for the colloidal metal halide perovskite QDs, with a required 300 °C annihilation for the lattice expansion[18], making it priced out of the economic PV applications. The innovation of the solution-phase ligand exchange, or SolEx, realized a single-step deposition of active layers from the material and time-wasting layer-by-layer process, significantly improving the scalability of QDPV on industrial production.

To address material scarcity in conventional thin film, Copper Zinc Tin Sulfide(CZTS) later emerge as an earth-abundant material used in the third-generation material with potential for low-cost, high power conversion efficiency, and environmentally friendly characteristics[19]. The incident light being absorbed creates electron-hole pairs in the CZTS layer, and then the electric field within the design moves electrons. CZTS has a direct bandgap of ~1.4-1.6 eV, with a very high absorption coefficient; it can absorb most visible light[20]. Being an alternative to CIGS, CZTS is relatively less toxic with its quaternary compounds including copper, zinc, Tin, and Sulfur. CZTS has an interface trap density at the interface range from 10^{8} 10^{18} cm^{-2} [20]. The power conversion efficiency(PCE) of CZTS decreases substantially above the defect density of 10^{14} cm^{-3} , at $10^{17} cm^{-3}$, the PCE of Cu_2O -based BSF cells dropped from 18.54% to 10.24%, showing a sharp efficiency loss due to Shockley-Read-Hall recombination[5]. Under ideal back-surface field conditions with low defect densities and high shunt resistance, CZTS cells Cu_2O reach a PCE of 26.19%, the highest record simulated PCE with BSF layers[5]. Due to its material abundance, CZTS has a clear cost advantage over CIGS. CZTS has Roll-to-Roll manufacturing potential from its flexible substrates, which is more economical than rigid module production. The manufacturing of CZTS often needs substrate preparation, precursor deposition, alkali incorporation, annealing, and back contact options.

The perovskite solar cell(PSCs) is one of the most recently developed and promising emerging thin-film PV technologies. “Perovskite” specifically refers to the crystal structure of hybrid organic-inorganic lead halides. The single-junction PSCs have already achieved a PCE of 26.1% comparable to monocrystalline silicon cells[11]. In the manufacturing process, PSC films can be deposited at low temperatures via solution or vapor, which enables low-cost and scalable potential. The fine-tuning of the optical bandgap of PSCs through composition engineering of A- and X-site ions offers potential to yield high PCE for PSCs[21]. The addictive engineering of Lewis acid-base interaction can effectively passivate the uncoordinated ions, thereby minimizing the recombination losses of PSCs. The raw materials of Perovskite Solar Modules(PSM) are comparatively less expensive than traditional silicon solar cells; besides, recycling the top electrode material brought cost efficiency along the way. For those reasons, PSCs offer long carrier diffusion length, low recombination losses, low material cost, and tunable band gaps that facilitate PSCs to significant PCE gains with tremendous potential for scalable manufacturing.

Figure 4 shows the minimum and maximum bandgap range among first generation: Crystalline silicon[22]; second generation: CdTe[19], CIGS[11]; and third generation materials: CZTS[21], PSCs[22], OPV[23], QDPV[15]. Third-generation PV material genuinely offers a wider tunable bandgap range compared to first and second-generation PVs, which enable their application from ideal single-junction to tandem top cells.

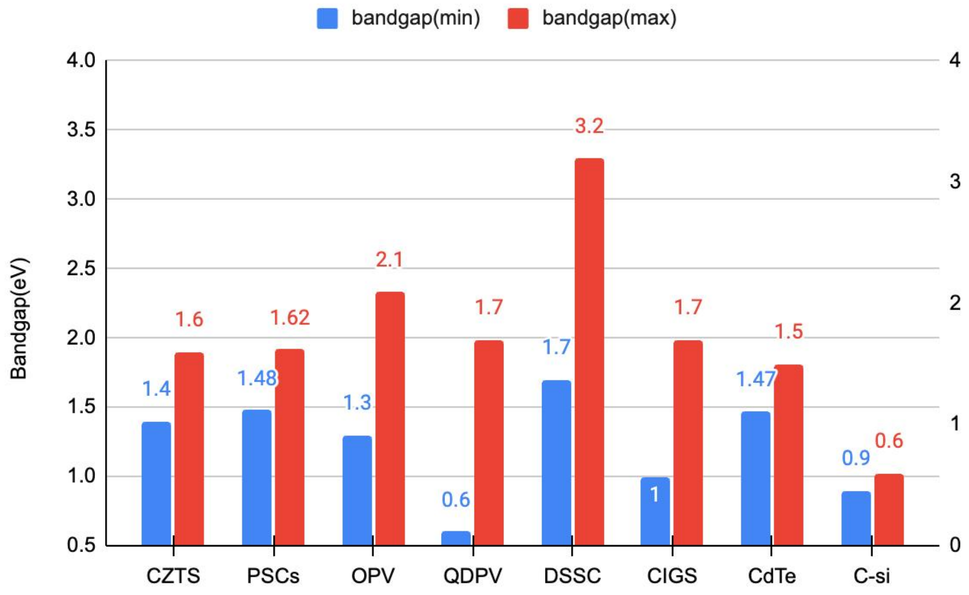

Figure 4 Bandgap range for different Photovoltaic materials

Table 1 collects data for Copper-Zinc-Tin-(Sulfide/Selenide), Organic PV, Quantum-dot solar cells(CQD), Dye-sensitized solar cells (DSSC), regarding each of the manufacturing cost, recombination loss, and the highest PCE.

Table 1 Comparison of Third-generation Photovoltaic Technologies

Technology	Manufacturing/ fabrication cost	Recombination loss(V_{oc}deficit)	PCE record
Copper-Zinc-Tin-(Sulfide/Selenide) CZTS, CZTSe	\$41-52/m^2[15]	0.55-0.75V[25] (V_{oc} deficit)	14.2%[1] (Chinese Academy of Sciences)
Perovskite(singlejunction) PSCs	\$0.38/W~\$0.57/W[24]	~0.35-0.45V[11] (V_{oc} deficit)	~27%[4]
Organic PV (OPV)	\$7.9 $\pm$/2.4/m^2[25] (legacy estimate) ~\$7.9$\pm$2.4/m^2[25](mass production)	~0.17-0.30V[28] (V_{oc} deficit)	~19.2%[4]
Quantum-dot solar cells (QDPV)	<\$6/g[9]	~0.55-0.70V[9] (V_{oc} deficit)	19.1%[4]
Dye-sensitized solar cells (DSSC)	\$22.4/m^2[26] (mfg cost) ~\$0.18/W[27] (module price)	~0.60-1.0V[6] (V_{oc} deficit)	13%[4]

Although those five emerging third-generation materials are making astonishing breakthroughs, it is still very hard to fully commercialize and achieve large-scale manufacturing for the third-generation material due to the obscure cost or performance gain present at laboratory or small-scale manufacturing. While the current mature PV module manufacturing is \$0.20/W-dc reported in 2024, higher than the most cost-effective emerging PV technology DSSC, which can achieve a module price of \$0.18/W under introduced modules[29]. However, the billion-dollar capital investment hinders the third-generation material from substantiating its evident cost and performance gain at gigawatt-scale manufacturing. Beyond the challenge of securing large-scale investment, emerging photovoltaics still need to demonstrate long-term stability, scalable manufacturing, and regulatory standardization in order to be fully on par with or exceed the commercialized thin-film and wafer-based photovoltaics. Besides obstacles towards achieving large-scale manufacturing, each third-generation photovoltaic technologies also face critical challenges itself. DSSCs suffer primarily from the instability of the liquid electrolyte and manufacturing complexity; OPVs are restrained by morphological instability, interface wettability issues, and the lack of chemical stability of solution additives during the process; QDPVs mainly faces surface recombination losses and electrolyte instability; CZTS is constrained by high defect density and unsolved uniform large-area deposition; PSCs's lead toxicity prevents long -term commercialization.

5 CONCLUSION

This paper aimed to research the up-to-date advancements in third-generation photovoltaic technologies, featuring their potential to overcome the technological limitations of the prior first- and second-generation photovoltaic technologies. The paper delves deep into the material stability, power conversion efficiency, toxicity concerns, and large-scale manufacturing obstacles faced by third-generation photovoltaic technologies, including Copper zinc tin sulfide, Perovskite solar cells, Organic photovoltaics, Quantum dot solar cells, and Dye-sensitized solar cells. The third-generation photovoltaic technologies offer higher power conversion efficiency, mitigate the concerns about material scarcity often associated with thin film PVs, tunable bandgap, and more flexible absorbers etc. Future research should focus on enhancing the long-term performance and continuing to improve the power conversion efficiency of third-generation photovoltaic technologies. Moreover, it is crucial to acknowledge that the primary obstacles preventing the third-generation photovoltaic technologies from entering the PV market are their scalability. Third-generation photovoltaic technologies still remain underdeveloped in the transition from laboratory-scale production to large-scale manufacturing. Despite the aforementioned challenges, with continued technology breakthroughs and government support, the third-generation photovoltaic technologies will offer a revolutionary path for the globe against climate change.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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