Published by Avanti Publishers

Journal of Chemical Engineering Research Updates

ISSN (online): 2409-983X

A Comprehensive Review on Third-Generation Photovoltaic Technologies

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ARTICLE INFO

Article Type: Research Article

Academic Editor: Anjan Banerjee

Keywords:
Stability
Perovskite cell
Dye-sensitized
Organic solar cells
Third-generation photovoltaics

Timeline:
Received: July 06, 2023
Accepted: September 04, 2023
Published: October 09, 2023

Citation: De A, Bhattacharjee J, Chowdhury SR, Roy S. A comprehensive review on third-generation photovoltaic technologies. J Chem Eng Res Updates. 2023; 10: 1-17.

DOI: https://doi.org/10.15377/2409-983X.2023.10.1

ABSTRACT

The renewable energy industry has revolutionized due to photovoltaic (PV) technologies, which offer a clean and sustainable alternative to conventional energy sources. Third-generation photovoltaic technologies refer to a group of emerging PV technologies aiming to surpass the efficiency and cost-effectiveness of traditional silicon-based solar cells. Different ceramic materials have also been investigated for use in these advanced PV technologies. This review examines the science, current state, and advancements of third-generation PV systems for wide-scale implementation. The first section of this study provides an overview of the development of PV technologies from the first to the third generation, highlighting the most significant novel developments made at each step. Organic photovoltaic (OPV) cells, dye-sensitized solar cells (DSSCs), and perovskite solar cells (PSCs) are discussed here as a few new technologies that constitute the third generation, also known as the next generation of advanced PV. This review presents how these devices can be used in specialized settings, including indoor and low-light environments, thereby expanding the range of energy harvesting potential. The brief history of these emerging technologies, their current status, future developments, and key challenges are discussed in this review paper.

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1. Introduction

The massive growth in the global population and the advent of modern technologies have skyrocketed our global energy consumption levels [1], resulting in an accelerated depletion of fossil fuel reserves. Furthermore, with climate change being a serious concern, more research efforts are being directed toward the widespread usage of renewable energy sources like wind, solar, hydroelectric, and geothermal. Out of these, solar power has seen tremendous growth in commercial usage due to the rapid improvements in power conversion efficiencies (PCE) in first-generation photovoltaic devices, especially silicon-based solar cells [2]. However, Si-based solar cells are both expensive and complex to manufacture. This is why the third generation of photovoltaic technologies like perovskite, organic, and dye-sensitized solar cells and their power conversion efficiencies have been intensely researched over the past two decades due to their low cost, ease of manufacturing, and flexibility in usage.

Perovskite solar cells generate photoelectric current through their light-harvesting perovskite layer, which is typically made of compounds that are a mix of organic and inorganic materials like methylammonium lead halide or entirely an inorganic material like cesium lead halide [3]. PSCs have been hailed as one of the most prospective alternative PV technologies owing to their high PCEs, even compared to traditional Si-based solar cells [4].

Organic photovoltaic cells convert sunlight into energy using organic components like polymers or tiny molecules. They have the potential for flexible, lightweight, and inexpensive production [5]. Their versatility with various substrates opens up opportunities for integration into various applications, including portable electronics, wearable technology, windows, and building-integrated photovoltaics (BIPV) [6].

On the other hand, dye-sensitized solar cells use a photosensitive dye that can absorb light energy to generate photoelectricity. The efficiency of such cells depends primarily on the type and sensitivity of the dye in use [7].

Third-generation photovoltaic technologies show enormous potential, but several issues must be resolved before they are widely used. These difficulties include stability problems, manufacturing process scalability, long-term performance dependability, and the requirement for additional efficiency and durability enhancements. This paper highlights some ways to overcome these challenges and realize the full potential of these technologies.

2. The Emergence of Alternate Photovoltaic Technologies

2.1. Perovskite Solar Cells

Perovskite compounds have been known for a long time, but Tsutomu Miyasaka *et al*. were the first to disclose their application in solar cells in 2009 [8]. Based on the design of a dye-sensitized solar cell, a thin layer of perovskite was constructed over mesoporous TiO_2 that operated as an electronic collector. This generated a power conversion efficiency of just 3.8%. Also, these cells utilized liquid corrosive electrolytes, limiting their stability to a very short time. Nam-Gyu Park *et al*. enhanced this design in 2011 using the same dye refining process and achieved a PCE of 6.5% [8-11]. In 2012, Mike Lee and Henry Snaith of Oxford University discovered that perovskites are stable when contacted with certain high-performance, solid-state hole transporter materials like spiro-OMeTAD, essentially circumventing the requirement of the porous TiO_2 layer for transporting electrons [9]. This "sensitized TiO_2" design resulted in net efficiencies of 10%. However, enhanced efficiencies beyond 10% were possible only with inert scaffolds. Using mesoporous Al_2O_3 instead of TiO_2 increased relative efficiencies by 3-5% [11]. This led to later evidence that scaffolds are not required for electron extraction [12]. Eventually, this led to the realization that perovskites could transport holes and electrons, leading to the discovery of a thin-film PSC with more than an efficiency exceeding 10% [13]. However, despite its low cost and high-efficiency ratings, the lead halide used in current photovoltaic technologies is extremely toxic. Lead-free alternatives are therefore being investigated in third-generation PSCs to improve the overall environmental sustainability of the technology [14]. These include tin-based perovskites, bismuth-based perovskites, and double perovskites. Recently, researchers in Hong Kong and China developed a quasi-2D tin halide perovskite with an efficiency exceeding 14% [15]. It is also possible that the conversion efficiencies of tin-based PSCs can be improved significantly by the treatment of $FASnI_3$ films with phenethylammonium chloride (PEACl) [16].

The sensitized and planar designs both saw design improvements in 2013. For the sensitized design, Burschka *et al*. demonstrated a two-step solution processing deposition approach with a 15% efficiency rate [17]. Using thermal co-evaporation, Olga Malinkiewicz *et al*. and Liu *et al*. simultaneously demonstrated how to make planar solar cells with efficiency values of more than 12% and 15% in p-i-n and n-i-p architectures, respectively [17, 18].

Additionally, Docampo *et al*. showed that the conventional "organic solar cell" architecture, where the hole transporter is positioned below and the electron collector above the perovskite planar layer, may be employed to construct perovskite solar cells [19].

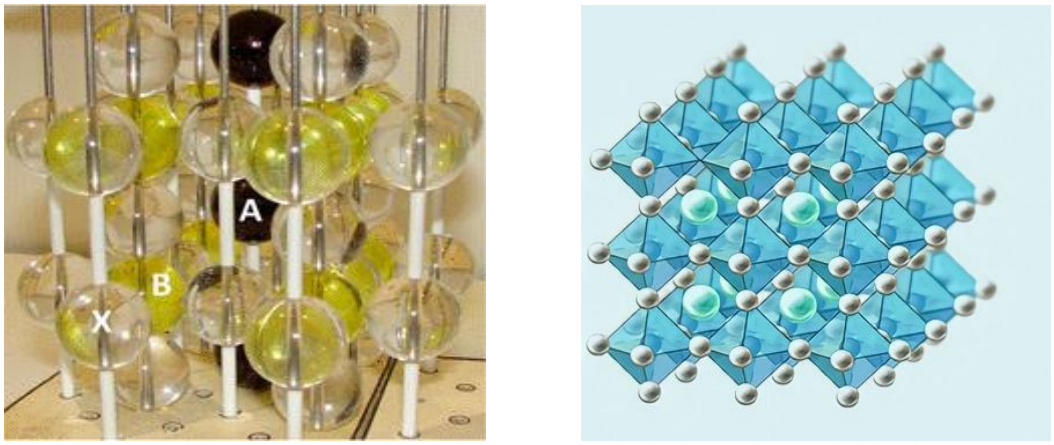
Several novel deposition techniques with significantly higher efficiency were reported in 2014. Researchers from the University of California at Los Angeles and the Hong Kong Polytechnic University reported a 19.3% efficiency for the planar thin-film design [20, 21]. In November 2014, a device created by Korean Research Institute of Chemical Technology (KRICT) researchers broke a record when it was confirmed to have a non-stabilized efficiency of 20.1%. Starting from 2015, the research conducted by KRICT and the Ulsan National Institute of Science & Technology (UNIST) has consistently exceeded the prior achievement in efficiency for single-junction perovskite solar cells [22]. The most recent record, held by researchers from UNIST, has an efficiency rate of 25.7% [23].

Since at least 2016 [24], the criteria for tandem perovskite-silicon solar cells have continuously been higher than those for single-junction cells. Since 2018, researchers from Oxford Photovoltaics and the Helmholtz-Zentrum Berlin have alternately broken records. In 2022, the former achieved the highest efficiency yet: 32.5% [25].

2.1.1. Principle and Design of Perovskite Solar Cells

The structure of a perovskite solar cell comprises five primary components: the photoanode (FTO/ITO conductive glass), electron transport layer (ETL), perovskite photoactive layer, hole transport layer (HTL), and metal back electrodes (Au, Ag, Al). In perovskite solar cells, the perovskite layer, which functions as the light-absorbing layer, absorbs photons with energies exceeding the forbidden band gap (Fig. **1**).

The energy from these photons triggers the excitation of electrons previously bound to the nucleus, resulting in the formation of excitons, essentially electron-hole pairs. The exciton binding energy in perovskite materials is relatively low, facilitating the separation of free carriers (electrons and holes) from them even at room temperature. Subsequently, these excitons disassociate into separate electrons and holes. These charge carriers then travel towards the cathode and anode of the solar cell. The electrons move toward the cathode, while the holes move towards the anode. Eventually, these charge carriers transition from the perovskite material to the electron transport material (ETM).



(a) (b)

Figure 1: (a) Representation of a perovskite solar cell, illustrating a 12-fold coordination site occupied by A-cation [26] (Reprint with permission). **(b)** Basic structure of a perovskite material (drawn in Vesta).

2.2. Organic Solar Cells (OSC)

Organic solar cells (OSC) appear to have lost ground in recent years, with research on alternative photovoltaic technologies focusing mostly on perovskite solar cells. However, because of the abundance of affordable, easily processed, and non-toxic raw materials that may be used in the photovoltaic active layer of these devices, OSCs have the potential to be among the cheapest sources of electricity in the world. The first findings of photoconductivity in organic compounds were published by Alfredo Pochettino (1906) and Melvin Kelvin and David Kearns (1958), which sparked the concept that photoelectricity may be produced if a suitable organic compound was sandwiched between low and high-work-function metals [27]. Various organic compounds were used in the 1970s and 1980s to construct organic photovoltaic (OPV) devices. Still, most of them only had power conversion efficiencies (PCE) of around 10^{-6} to 1%, insufficient to cover production and manufacturing expenses and allow commercial use [28].

2.2.1. Design and Working Principle of Organic Solar Cells

Two organic components, either organized as distinct layers or as a homogeneous combination, make up the fundamental structure of OPVs. The materials employed should possess a connected electron structure, where the semiconductor physics' band gap aligns with the energy disparity between the highest filled molecular orbital (HOMO) and the lowest vacant molecular orbital (LUMO). The HOMO functions as the conduction band, while the LUMO is the valence band in analogy to inorganic semiconductors [29]. However, because minor Van der Waal forces are present, these conduction and valence bands are substantially narrower. In contrast to inorganic semiconductors, conjugated/polymer chains or localized states with substantially lower charge mobility are where most charge transport happens.

Organic semiconductors can produce excitons or an electron-hole pair bound by Coulombic forces when they absorb photon energy. Due to their brief lifespans (in the order of 10^{-12} seconds), these excitons have very little mobility. While intermolecular exciton diffusion occurs via the previously discussed hopping process, intermolecular exciton diffusion happens through polymer chains. The exciton diffusion length sometimes called the exciton mobility range, is a crucial design factor for OSVs and is typically in the range of 10^{-8} m [30]. The excitons are split into free charges at the donor-acceptor junctions, which could either be:

- Single-layer: The semiconductor is placed between an ohmic contact and a rectifying contact electrode. Single-layer OPVs have very low PCEs.
- Bi-layer: Similar to single-later OPVs but with two semiconducting organic materials placed between the two electrodes, as shown in Fig. (**2**).
- Bulk-heterojunctions: Here, the donor and the acceptor materials are mixed, effectively resulting in a large interface area for the excitons to reach and separate into their charges. Fig. (**3**) demonstrates the fundamental difference between bilayer and bulk heterojunction (BHJ) devices.

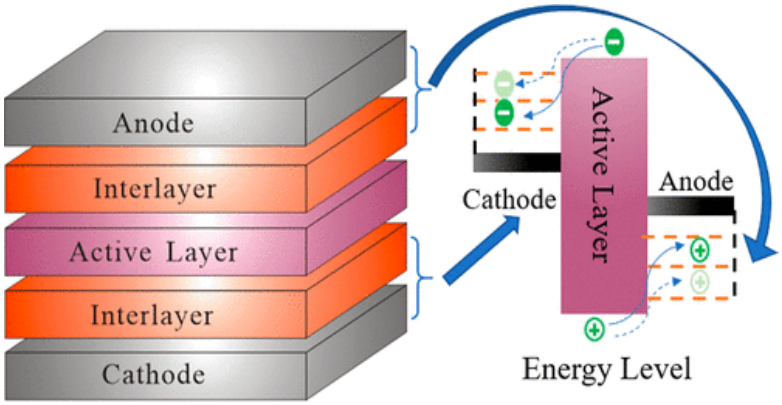


Figure 2: Schematic representation of interfacial bilayer heterojunction design of organic solar cells [31]. (Reprint with permission).

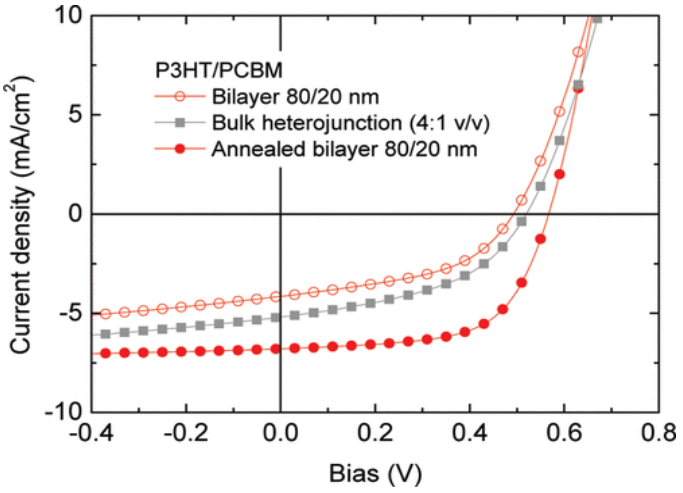


Figure 3: Illustration of a bilayer heterojunction device [32]. (Reprint with permission).

To achieve effective charge separation, the LUMO energy levels of the donor and acceptor materials must exhibit a more significant difference than the exciton binding energy. Subsequently, the charges are transported to the electrodes, and the efficiency of this transport relies on various properties of the organic materials, such as impedance and electrical conductivity.

The search for suitable materials that can serve as electron donors and electron acceptors has been a prominent focus in developing OSC technology. Typically, p-type polymers like poly(p-phenylenevinylene) (PPV) and poly(3-hexylthiophene) (P3HT) are utilized as electron donor materials [32, 33]. Electron acceptor materials, on the other hand, are commonly composed of fullerenes (n-type organic semiconductors). Nonetheless, ongoing research is being conducted to explore the potential of non-fullerene-based OSCs for achieving high performance [34].

2.3. Dye-sensitized Solar Cells

Dye-sensitized solar cells, called Grätzel cells, have emerged as a technically and economically viable substitute for p-n junction photovoltaic systems. DSSCs are thin-film photovoltaic devices designed to transform light into electrical energy. These solar cells have garnered attention owing to their uncomplicated manufacturing procedure and cost-effective production, positioning them as a promising potential option instead of conventional silicon-based solar cells [35].

Recent research describes an enhanced low-temperature hybrid dye-titania nanoparticle-based DSSC with an efficiency of 8.75%. Typically, silicon (Si) is a photoelectron source and an electric field to separate the charges and produce a current in a solar cell. But in DSSCs, most semiconductors are only used as a charge carrier and photosensitive dyes supply the photoelectrons. Since the power conversion efficiency (PCE) of DSSCs was near as predicted by theory, extensive research has been conducted on them over time to increase efficiency and promote commercialization [36, 37].

Extensive research has been conducted on a specific category of coumarin-based dyes for their potential application in dye-sensitive solar cells (DSSCs). These dyes combine the acceptor -CNCHCOOH, thiophene bridge (Th-) units, and coumarin donor (D) moiety (A). The investigation aimed to assess the performance of these dyes in DSSCs and examine their optical and electrochemical properties. Furthermore, density functional theory (DFT) optimization simulations were carried out to explore the diverse geometries of coumarin dyes featuring different Th-bridge units [38].

2.3.1. Design and Working Principle of Dye-sensitized Solar Cells

Light absorption, electron injection, carrier transportation, and current gathering are the four primary functions of DSSCs. The subsequent actions are a part of how photons are changed into the current. A

photosensitizer must first take in the incident light (photon) before it can promote electrons from the ground state (S+/S) to its excited state (S+/S*) of dye. For most of the dye, this corresponds to an absorption range of 700 nm or a photon energy of nearly 1.72 eV [39].

$$S+/S+hv \rightarrow S+/S* \backslash s S+/S* \rightarrow S+/S+e-(TiO_2) \quad \text{(i)}$$

These injected electrons moved between the TiO_2 nanoparticles and toward the back contact (transparent conducting oxide, TCO). The external circuit delivers electrons to the counter electrode. When the electrons at the counter electrode decrease, the acceptance of electrons from the Ion Redox Mediator causes I^{-1} to be oxidized to I^{-3}. Thus, dye regeneration or the ground state occurs (oxidized state) of dye. Again, the oxidized mediator (I^{-3}) diffuses in the direction of the counter electrode before being reduced to I ion, as shown in equation (ii) [40].

$$I^{-3}+2e- \rightarrow 3\ I^{-1} \quad \text{(ii)}$$

4. Challenges

4.1. Toxicity, Stability, Material Degradation of Perovskite Solar Cells

Perovskite solar cells (PSCs) adhering to the ABX_3 structure have exhibited rapid advancements in power conversion efficiency (PCE) within a compact timeframe. In this context, A, B, and X represent a monovalent cation, divalent cation, and monovalent anion, respectively [41]. The heightened efficiency of perovskite solar cells can be attributed to their exceptional material characteristics [42]. These characteristics encompass notable traits such as elevated optical absorption cross-sections [43], low binding energies of excitons, long-range charge carrier diffusion lengths [42-44], and facile tuning of the band gaps [44] through uncomplicated alterations of the precursor components.

Perovskite solar cells have also garnered attention as a prospective substitute for silicon-based solar cells due to their economical production cost and remarkable device efficiency. However, several substantial challenges need to be surmounted before widespread commercialization becomes feasible. These obstacles encompass material toxicity, device hysteresis, instability (caused by chemical, thermal, atmospheric moisture, and excessive UV exposure), and sealing concerns related to perovskite materials [45, 46]. Lead in perovskite raises environmental apprehensions, prompting the exploration of alternative, non-toxic materials [47].

Another crucial obstacle preventing perovskite solar cells from reaching their full potential is the lack of long-term module stability and reliable outdoor operation [48]. There is a need for consensus within the perovskite photovoltaic community regarding stability measurement methodologies and the establishment of standardized testing procedures. Novel approaches must be developed to accelerate the aging process, enabling accurate predictions of the lifespan of perovskite solar cells in operational conditions. While suitable encapsulation can mitigate degradation caused by moisture or oxygen in the ambient air, efforts should focus on designing stable materials and interfaces to address performance decay resulting from illumination and heat [49]. Table **1** highlights some of the latest strategies in the stability enhancement of various PSCs based on their structures and controlled test parameters. Here, PCE/PCE_0 denotes the percentage retention of the power conversion efficiency of the specific PSC before and after the stability test.

The presence of moisture in the air can greatly affect the performance of perovskite solar cells that combine organic and inorganic materials. So, the stability of various compositions of these cells is evaluated by exposing them to humidity, in a Humidity Soaking Test. Among the different compositions, the perovskite-based solar cell with resistance to humidity was selected to achieve a heightened rate of photocurrent generation [58].

High temperatures, particularly those above 90°C, can cause perovskite materials to decompose. Another challenge associated with perovskite solar cells is a phenomenon called hysteresis, which has been extensively studied. Researchers have explored various techniques to reduce hysteresis in these devices. These techniques include using low-temperature thermal annealing of SnO_2 layers for electrical selectivity, adjusting the composition of the perovskite materials, adding certain substances, optimizing the structure of grain boundaries, and improving the interfaces between different layers [59].

Table 1: Stability enhancement strategies against various Perovskite Solar Cell structures.

Structure	Material	Test Parameters	PCE/PCE0 (%)	References
Planar	$MAPbI_{3-x}Cl_x$(unencapsulated)	28d ageing	89.2	[50]
	SnO_2 as ETL/perovskite with inter-layer modification	500h continuous light exposure	90	[51]
HTL Free	c-TiO_2/$CH_3NH_3PbI_3$/C	72h with thermal stress of 80°C	90	[52]
	C-PSC with $PbTiO_3$	90 d in dry air with humidity around 20%	90	[53]
	ITO/perovskite/ETL/BCP/Cu. Perovskite: $Cs_{0.05}(FA_{0.92}MA_{0.08})_{0.95}Pb(I_{0.92}Br_{0.08})_3$(inverted structure)	1000h of contentious white light under N_2 ambient conditions	90	[54]
ETL Free	Fabricated glass/$CH_3NH_3PbI_3$/spiro-OMeTAD	Continuous illumination under the sun with an air mass of 1.5	80	[55]
	FTO/a-NbOH/perovskite/PTAA/Au	500h of continuous 1 sun illumination	96	[56, 86]
	TETA-GR, $MABPI_3$: GQDs, and bathocuproine (BCP)	500h of light soaking conditions in an ambient environment	83	[57]

4.2. Scalability and Stability of Organic Solar Cells

The limited scalability of traditional manufacturing techniques like spin coating poses a significant challenge to commercializing both fullerene-based and non-fullerene-based organic solar cells [60]. Although more scalable techniques such as spray coating, blade coating, and push coating are available, they come at the cost of reduced power conversion efficiencies. However, these techniques offer higher performance cost indices (PCIs) and larger coated areas, which are crucial for the large-scale manufacturing of OSCs [61].

Another crucial issue in commercializing OSCs is their stability, particularly during long-term usage under challenging environmental conditions and material degradation. Several factors contribute to the instability of OSCs:

- Intrinsic Instability: The morphology changes within the active layer of OSCs due to the structural incompatibility between the electron donor and acceptor materials and the high mobility of these materials within the bulk heterojunction [62]. The electrodes and charge carrier transport layers also exhibit high mobility, leading to intrinsic instability [63].
- Thermal Instability: The constant illumination and high operating temperatures can cause thermal instability in the active layer, altering the film morphology from its optimal condition when heated [64].
- Photodegradation: The photo-oxidation of the charge carrier transport and active layers in OSCs leads to structural changes in the donor and acceptor materials, resulting in degradation. This is particularly concerning as OSCs are primarily designed to operate under well-illuminated conditions [65].
- Atmospheric Oxygen and Water: During operation, oxygen and water from the surrounding air inevitably diffuse into OSC devices, leading to physio-chemical degradation of the active layers, charge transport carrier layers, and electrodes [66].

Intensive research is underway to enhance organic overall stability and performance of the cell, particularly in mitigating the inevitable degradation caused by external factors.

4.3. Intrinsic and Extrinsic Stability of Dye-sensitized Solar Cells

DSSCs have recently demonstrated comparable efficiency, however, due to certain of these inherent limitations of cells, they still need to be improved. According to their restrictions, stability failures can be classified into two categories: (A) limitations on internal stability and (B) restraints on extrinsic stability. A sizable amount of oxidized

dye energy is also lost during regeneration due to the energy discrepancy between an electrolyte and an oxidized dye [67].

For DSSCs to meet consumer expectations and increase their commercialization, their [68] intrinsic and extrinsic stability must be equivalent to Si-solar cells. Two examples of the sealing components used in DSSCs to enclose the cells are Surlyn and Bynel hotmelt foils. Internal pressure buildup and exposure to cyclic or regular temperature variations reduce their sealability [68]. Although they are inexpensive and simple, their use cannot be disregarded. Therefore, it is crucial to improve their adhesion to glass by giving it a metal oxide pre-treatment.

It has been thoroughly investigated how the stability of DSSCs is affected by external elements such as thermal and light soaking loads, environmental variables, and sealing-related problems. Here, losses-in-potential is measured as a limiting factor. Since the redox mediator potential (I halide) significantly affects the maximum photovoltage, the potential of the redox couple should be near the ground state of dyes [69]. This repeatable operation can be carried out with 210 mV of the driving force. Encouragement of the use of various electrode materials, such as nanotubes, carbon nanowires, and graphene, as well as different electrolytes instead of liquid ones, such as gel electrolytes and quasi-solid electrolytes, as well as different pre- and post-treatments for the working electrode, such as anodization pre-treatment and $TiCl_4$ treatment, as well as different types of CEs and the creation of hydrophobic sensitizers, can boost the performance.

Utilizing phosphorescent or luminescent compounds like rare-earth-doped oxides in Dye-Sensitized Solar Cells (DSSCs), or employing energy relay dyes (ERDs) that are either dissolved in the electrolyte or applied as a luminescent layer onto the photoanode glass [70], has raised questions about the efficiency and long-term stability of the DSSC system as it has evolved technologically. To address these concerns, numerous research initiatives have been undertaken to create devices capable of satisfying global demand for photovoltaic cells across various applications. Nevertheless, the primary challenges persist in low efficiency and stability, impeding the advancement of DSSC technology.

5. PCE and Scalability of Alternate PV Technologies

Power Conversion Efficiency and scalability are the two vital metrics for evaluating the performance of a PV technology. PCE measures the ability of a solar cell to convert sunlight into electricity, while scalability is a direct metric for assessing the potential for commercialization of that solar cell (Fig. **4**). The following section of the review delves into the issues and most recent advancements related to PCE and the scalability of third-generation solar cells, focusing on perovskite solar cells, organic solar cells, and dye-sensitized solar cells.

5.1. Perovskite Solar Cells

Perovskite solar cells have gained attention due to their potential to offer higher efficiency and lower production costs compared to traditional silicon-based solar cells. Perovskite solar cells have demonstrated rapid advancements in PCE, reaching record levels of over 25% in lab settings in 2022, from 3.8% PCE as reported in 2009. This remarkable efficiency is attributed to the unique crystal properties of perovskite materials, enabling efficient charge separation and transport. However, studies have shown that carrier traps below the energy gap in lead-based perovskites are an intrinsic property. They likely arise due to the interaction between electrons and phonons at the surfaces or interfaces of crystalline perovskite materials, are intrinsic properties of lead-based perovskite materials, and are a natural roadblock to improving PCEs beyond a certain extent [71].

The industrial upscaling process, which is crucial for the commercialization of the technology, has also been challenging. Studies have shown that inconsistencies in film deposition, composition, and thickness can lead to variations in cell performance and efficiency [72]. Therefore, the techniques used to fabricate perovskite solar cells at a laboratory scale, like the one-step and two-step solution methods, are not easily scalable. Industrial fabrication techniques like vacuum deposition, chemical vapor deposition, blade coating, slot-die coating, and spray coating have been more efficient [73]. Moreover, since large-area PSCs will be exposed to a wider range of environmental conditions like light and moisture, the stability of laboratory-scale and industrial-grade PSCs is bound to vary [74]. Developing robust encapsulation techniques that can withstand outdoor conditions is crucial

for the long-term stability of large-scale perovskite solar arrays [75, 76]. It should be noted that the efficiency of large-scale perovskite solar cells depreciates significantly impacted by their effective area due to challenges in charge transport and recombination [77]. This makes scalability a key concern for PSCs.

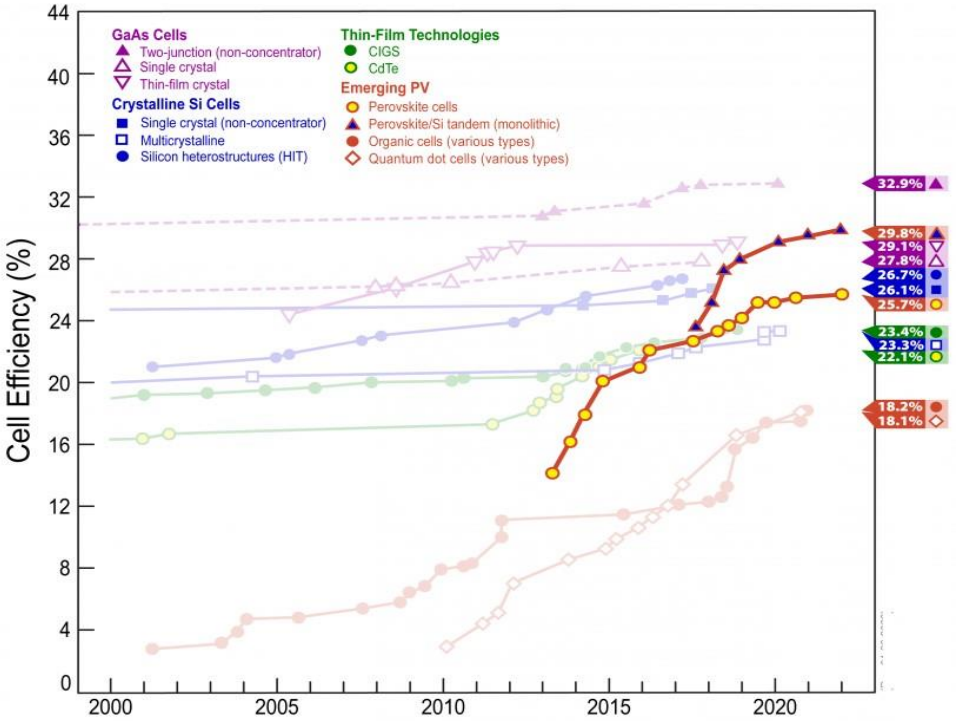


Figure 4: Illustration of chart of record performances, displaying the power conversion efficiencies for developing solar technology from 2000 to 2020 [78]. (Reprint with permission).

5.2. Organic Solar Cells

Organic Solar Cells have shown tremendous promise for specific applications due to their flexibility, lightweight design, and ease of fabrication. However, a key hindrance to their industrial acceptance has been their unimpressive PCE compared to perovskites and traditional silicon-based solar cells. The latest figures for OPV efficiencies have been reported to be around 19% [79].

Scalability is a major concern for organic solar cells due to their fabrication processes and material properties. Solution-based methods are typically employed in fabricating organic solar cells, including inkjet printing or roll-to-roll processing. However, these methods make it challenging to maintain uniform film thickness and characteristics across the entire device architecture, which inevitably leads to variations in PCE and stability [80-83]. Developing robust and automated manufacturing processes is a crucial ongoing area of research and is also vital for the long-term viability of large-area OPVs [84-86].

5.3. Dye-Sensitized Solar Cells

DSSCs were one of the first emerging PV technologies, and they present a promising avenue for solar energy conversion due to their potential for low-cost production and flexibility [87]. Nonetheless, similar to perovskite solar cells, dye-sensitized solar cells encounter limitations in their power conversion efficiency compared to conventional silicon-based photovoltaic technologies. This is primarily attributed to suboptimal charge separation dynamics and electron recombination at the dye-semiconductor interface, reducing the overall generated electrons [88]. Nevertheless, through continuous research efforts, coupled with advancements in dye sensitizers, electrolytes, and electrode materials, the efficiency has escalated from 3% to 14%. Moreover, the operational lifespan of dye-sensitized solar cells has extended from months to over a year. However, further endeavors are required to enhance their competitiveness regarding efficiency and stability [89].

The widespread commercialization of DSSCs is also severely impacted by common industrial problems. Dye-sensitizing agents, conductive materials, and electrolytes are the key elements of the manufacturing process, which must be both affordable and abundant to justify large-scale production [90]. Moreover, the manufacturing process of DSSCs involves precise layer deposition, sensitization, electrode assembly, and proper encapsulation of the device. Minor errors can impede the PCE and the long-term stability of the device to a significant extent [91].

6. Future Prospects and Commercialization

6.1. Perovskite Solar Cells

The successful adoption of perovskite technology relies on validation, performance testing, and bankability, which refers to the willingness of financial institutions to provide fair interest rates for financing projects or proposals. However, the lack of sufficient field data and variations in testing procedures pose challenges in comparing the performance of different perovskite devices and predicting their long-term operational behavior.

Presently available primary photovoltaic (PV) technologies, like silicon and Cd-Te solar cells, have well-established testing procedures explicitly tailored to their characteristics. These tests are conducted indoors and can reliably predict their performance outdoors. However, due to the distinct degradation patterns of perovskite technology compared to these PV technologies, the existing testing methods cannot provide reliable assessments of perovskite technology.

To promote investment in scaling up and deploying perovskite technologies, it is crucial to enhance confidence in their reliability. This necessitates the implementation of objective and trusted certification through test methods capable of effectively identifying real-world failure mechanisms. Standardized validation becomes particularly challenging and important as perovskite solar cells continuously evolve regarding materials and device compositions.

Despite achieving efficiencies exceeding 20% on a laboratory scale, it is difficult to replicate the same on a commercial scale. Before perovskites can be industrialized, they must overcome various obstacles to compete with silicon solar cells. However, perovskite solar cells are promising from a business perspective, as their expected manufacturing cost is half that of silicon solar cells.

With increasing PSC area, efficiency declines, as mentioned in the scalability section. We anticipate that with continuing research and industrial community efforts towards scaling up PSCs, the efficiency gap between lab cells and commercial modules ameliorate and eventually reach a level equivalent to that of other PV technologies. The duration and effectiveness of solar panels play a crucial role in determining the cost per kilowatt-hour. The availability of affordable raw materials and the simplicity of perovskite solar cell (PSC) manufacturing suggest the potential to lower manufacturing expenses beyond the current photovoltaic (PV) systems. As time progresses, the reduced production costs could lead to a sustained reduction in the overall module price, thereby rendering PSCs economically feasible for commercial adoption.

6.2. Organic Solar Cells

Over the last decade, extensive research has concentrated on developing organic materials with smaller bandgaps and improved solar absorption spectra. This field has recently received much attention because of the discovery of non-fullerene acceptors with increased absorption spectra and configurable electron energy levels. Power conversion efficiencies (PCEs) of chlorinated or fluorinated non-fullerene acceptors (NFAs), such as IT-4F, IEICO-4F, and BT-CIC, have exceeded 16% [92]. Furthermore, a BT-based NFA combined with P3HT, the most cost-effective p-type polymer, attained a PCE greater than 18%. Small-molecule OSVs have also been a key research area in recent years due to their higher scalability and reproducibility [93]. However, they have lagged far behind other OSCs regarding optimum PCE figures for commercial usage. The latest studies have addressed this issue to a large extent by synthesizing novel small-molecule materials. In 2019, Zhou *et al*. reported a PCE of 14.34% in an all-small molecule binary OSC [94].

Ternary organic solar cells (TOSC) have also gained widespread traction since their introduction in 2008. These solar cells incorporate a third component in the photoactive layer to achieve more efficient sunlight harvesting [95], as shown in Fig. (**5**). This ensures higher short-circuit current density while maintaining low costs. PCEs greater than 14% have already been achieved with NFA-based TOSCs.

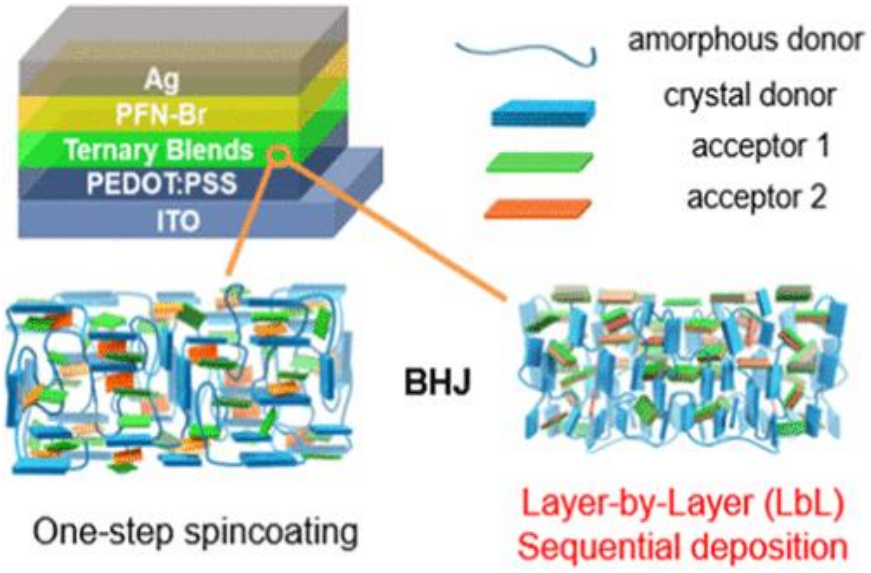


Figure 5: Schematic representation of a ternary organic solar cell with a bulk heterojunction or a layer-by-layer architecture [96]. (Reprint with permission).

While the widespread commercialization of OSCs may still be a distant goal due to their lower power conversion efficiency (PCE) compared to inorganic counterparts and even PSCs, they possess distinct properties that make them suitable for sustainable photovoltaic applications. An exciting application of OSCs involves their use in semitransparent configurations to create flexible, building-integrated power systems, achieving an average PCE of 5% [97].

OSCs, particularly those based on non-fullerene acceptors, offer the advantage of tunable absorption spectra, allowing customization for specific user requirements. This feature can be precious in indoor lighting conditions. Cui *et al*. demonstrated this by adjusting the active layers of 1 cm^2 OSC to match the emission spectra of 1000 lux LEDs, resulting in a peak PCE of 22% [98].

6.3. Dye-sensitized Solar Cells

Demand for portable, wearable, flexible, and solar-powered electronic devices is rising, according to the industry. Solar cells must be flexible, light, and reliable to meet market demand. Dye-sensitized solar cells might be an alternative to meet this demand. The maximum power conversion efficiency of DSSCs is only 14.1%. Therefore, utilizing various nanostructure designs and materials in numerous DSSC layers has tremendous potential for improving the PCE of DSSCs [99].

Due to their unique structural design and numerous hue dyes, dye-sensitized solar cells can generate power even in settings with artificial lighting. This property makes the cells translucent and colored, making them appropriate for applications in architecture, interior design, electrical devices, and portable power systems. The first commercial application of DSSCs in Hong Kong was in 2009, using bags and backpacks. These bags and backpacks include solar panels that generate electricity to charge portable devices such as cell phones, e-books, cameras, and LED lighting systems. Thin, transparent, flexible sheets of dye-coated glass can cheaply combine these modules into power-generating panels and billboards. The military has shown interest in DSSC technology for applications such as tents and fabrics that can generate up to 1 kW of power, enabling the operation of lights and laptops. Flexible solar panels can be deployed to cover tents and power more advanced machinery. Wearable

solar panels with sufficient power and weight could also recharge and power military electronics, eliminating the need for additional field battery packs or battery-filled bags [100].

Dye-sensitized solar cells offer several advantages over their competitors, making them suitable for portable devices and low-density applications. One advantage is their deep nanostructure, which enables efficient absorption of photons from sunlight. The dyes in the cells effectively convert absorbed photons into electrons. DSSCs are well-suited for low-density applications, typically achieving a peak power output efficiency of around 11%. Despite being less efficient than some top thin-film cells, DSSCs provide a favorable price-to-performance ratio compared to other thin-film solar cells.

The dye used in DSSCs can absorb both fluorescent light and scattered sunlight, allowing the cells to perform well even under low light levels and cloudy weather. Other conventional cells would struggle to generate power under such conditions. DSSCs are particularly suitable for indoor use due to their exceptionally low cut-off and ability to operate at wider angles, enabling them to absorb a significant portion of available sunlight. Furthermore, DSSCs have a longer lifespan and require less frequent replacement since they do not degrade over time in sunlight as regular thin-film cells do [101]. Additionally, their lightweight materials enhance their mechanical durability, eliminating the need for additional protection from harsh elements or objects.

7. Conclusive Remarks

- The above assessment of 'Third-Generation Photovoltaic Technologies' is aimed to provide a thorough and insightful examination of the most recent breakthroughs in the field of solar energy conversion, with a major focus on the advancement of novel materials such as perovskite solar cells, organic photovoltaics, and dye-sensitized solar cells.
- When compared to conventional silicon-based photovoltaics, these materials have the potential for improved efficiency, lower cost, and increased flexibility. The review explores the underlying concepts, fabrication techniques, and performance characteristics of these innovative materials, encouraging further research into identifying new natural sensitizers and creating solar cell components compatible with such a dye.
- While most commercial PV cells are made using silicon-based materials, researchers continuously explore alternative materials to improve efficiency, reduce costs, and increase durability.
- The feasibility review study of novel third-generation photovoltaic (PV) technologies has provided valuable insights into their potential as viable alternatives to traditional PV systems. These novel technologies offer several advantages over traditional PV systems, including higher power conversion efficiencies, lower manufacturing costs, and the potential for flexible and lightweight applications.
- This study emphasized how third-generation photovoltaic technologies have enormous potential to address the issues related to energy sustainability and environmental impact. These technologies provide a more sustainable option to conventional solar cells by utilizing available and straightforward ingredients like metal halides and carbon-based chemicals. This factor is vital to combat climate change and reduce reliance on fossil fuels.
- The study also highlighted how crucial it is to carry on with research and development to improve the functionality and stability of third-generation solar technology. Even though there has been substantial development, several issues remain to be resolved, such as enhancing long-term stability, scalability, and manufacturing procedures.
- Due to their flexibility and lightweight, they can be integrated into various surfaces and structures, including building facades, windows, and wearable gadgets. This invention can transform the urban landscape and promote the broad use of renewable energy sources.
- Investigating revolutionary third-generation photovoltaic technologies has revealed their enormous potential to alter the solar energy sector. This increased efficiency, sustainability, and integration capabilities of technologies open the path for a more sustainable and decentralized energy future.

- It is important to note that while certain ceramic materials have shown promise in research and development, their commercial viability and widespread adoption in photovoltaics are still being evaluated. Continued research efforts aim to optimize ceramic-based properties, stability, and cost-effectiveness of PV technologies to make them competitive with existing silicon-based solar cells. However, more research and development are required to address the remaining obstacles and ensure this commercial and circular economic feasibility.

Conflict of Interest

The authors declare that there is no conflict of interest.

Acknowledgment

Author (S. Roy) would also like to acknowledge “Scheme for Transformational and Advanced Research in Sciences (STARS)” (MoE-STARS/STARS-2/2023-0175) supported by Ministry of Education for promoting translational India-centric research in sciences implemented and managed by Indian Institute of Science (IISc), Bangalore, for their support.

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