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HIGHLIGHTS

Highlights of mainstream solar cell efficiencies in 2024

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2024 was an exciting year that all the single-junction silicon, perovskite solar cells, and the perovskite/silicon tandem solar cells have broken their world record power conversion efficiencies. This paper continues our highlights on the yearly highest independently confirmed mainstream (silicon, perovskite and organic) solar cell efficiencies and analyzes the progress of each cell technology. We are also happy to see that the passivating contact solar cells have been dominated the photovoltaic (PV) market and the production capacity of the perovskite solar cells has been reached to several hundred-megawatt scale in 2024.

Silicon solar cells

Although the mainstream product of the photovoltaic (PV) market in 2023 was still the p-type passivated emitter and rear cells (PERC) with the annual production of ~350 GW, the higher-efficient n-type silicon tunnel oxide passivated contact (TOPCon) solar cells stand out with the annual production from ~110 GW in 2023 to ~350 GW in 2024. In contrast, the PERC solar cells phase out and rapidly decrease to less than 100 GW in 2024 and there will be only ~5% market share in 2025. We have witnessed that the n-type silicon passivating contact solar cells have dominated the PV market in 2024, though 2022 was the first year of appreciable n-type silicon solar cell technology. This significant change originates from the TOPCon's advantages of full-area passivation contact and compatibility with high-temperature sintering process for existing PERC production lines [1]. Nevertheless, another higher-efficient passivating contact cell structure of n-type silicon heterojunction (SHJ) solar cells develops not as expected with an annual production scale of ~10 GW due to the immature ecosystem of the SHJ industrial chain. Another phenomenon in the PV market of 2024 is that the silicon back-contact (BC) solar cells having not made significant progress in scale for a long time cut a striking figure with the all-year production of ~25 GW due to the investment of China's leading PV enterprises. Table 1 lists the achievements of the TOPCon, SHJ and xBC solar cell efficiencies during 2024. The research and development in n-TOPCon has been focused from laser enhanced contact optimization (LECO) to local SiO_x/poly-Si application of the metal contact zone on the front-side (i.e., poly-finger technology), companied with the credibly independent confirmed conversion efficiency from 25.5% to 26.5%. The further optimization of absorption and passivation in the n-SHJ solar cells has pushed the cell efficiency to 27% level. Particularly the fusion of these n-type silicon passivating contact solar cells with BC electrodes (we call xBC, such as HBC for heterojunction BC, TBC for TOPCon BC and THBC for TOPCon/heterojunction hybrid BC) has yielded the highest efficiency of 27.4% in single-junction silicon solar cells [2].

In 2024, TOPCon achieved substantial advancements in cell conversion efficiency, particularly with the full introduction of LECO technology, which significantly enhanced cell performance. JA Solar and Trina Solar leveraged these advancements to achieve a record-breaking 25.6% and 25.9% conversion efficiency, respectively, for TOPCon cells in the industry [2]. However, efficiency gaps remain, primarily originating from the boron-doped p^+ emitter region on the front surface. Quantitative analysis indicates a cumulative loss of 1.19 mW/cm^2 in this area, constituting 63% of total

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Table 1 Summary of the achievements of TOPCon, SHJ and xBC solar cells in 2024

Solar cell type	PCE/%	Area/cm^2	V_{OC}/mV	J_{SC}/(mA·cm^{-2})	FF/%	Test center	Report date	Description
n-TOPCon	25.6	330.3	741.8	41.4	83.5	ISFH	Mar.	JA Solar LECO
n-TOPCon	25.9	350.5	738.3	41.7	84.1	ISFH	Oct.	Trina Solar LECO
n-TOPCon	26.07	330.1	748.6	41.55	83.82	ISFH	Nov.	JA Solar Poly-finger
n-TOPCon	26.58	350.2	744.6	42.10	84.83	ISFH	Nov.	Trina Solar Poly-finger
n-SHJ	27.08	220.5	–	–	–	ISFH	Dec.	Trina Solar Optimization
n-HBC	27.30	243.1	743.4	42.60	86.19	ISFH	May	LONGi SHJ BC
n-TBC	27.0	350.0	744.7	42.3	85.8	ISFH	Aug.	LONGi TOPCon BC
n-THBC	27.4	165.7	745.6	42.4	86.7	ISFH	Sept.	LONGi TOPCon/SHJ hybrid BC

Notes: All measured under the global AM1.5 spectrum (1000 W/m^2) at 25 °C. –: Not yet disclosed. ISFH: Institut fur Solarenergieforschung Hameln, Germany.

losses [3]. Optimizing the front surface contact structure is essential for advancing TOPCon cells toward their theoretical efficiency limit of 28.7%, which is predicated on a double-sided passivated contact structure. To address the insufficient passivated contact in the p$^+$ emitter region, the industry has shifted focus to implementing double-sided passivated contact designs. As the introduction of a polysilicon layer on the entire front surface would result in relatively high parasitic current losses, a locally passivated contact structure, poly-finger, was suggested. Dasgupta et al. [4], have simulated the short-circuit current density (J_{SC}) loss due to parasitic absorption of different polysilicon layer thicknesses in the double-sided passivated contact structure. Using selective area techniques, J_{SC} loss from a 100 nm polysilicon layer was reduced to 0.2 mA/cm^2, compared to approximately 3.2 mA/cm^2 for a full-area counterpart. Similarly, Rohatgi et al. [5], have investigated bifacial passivated contact structures, identifying the backside junction as optimal and emphasizing the importance of pairing such designs with high-lifetime wafers. While the poly-finger approach improves passivation levels, its implementation faces challenges. Upgrading existing TOPCon cell production lines require laser patterning with masks, a process complicated by the precision required in p-polysilicon preparation and laser accuracy. Moreover, developing metallization techniques compatible with boron-doped polysilicon contacts on the front surface while minimizing costly Ag consumption is a notable challenge. Electroplating technology offers a promising solution by reducing front-surface grid shading, improving cell efficiency and cutting costs [6]. The choice of metallization scheme is crucial and must align with the doping level and thickness of the polysilicon layer, allowing for adjustments based on the selected metallization techniques and specific requirements. Based on the poly-finger design, JA Solar and Trina Solar further set efficiency records of 26.07% [7] and 26.58% [8] this year, respectively. Up to now, many first-tier enterprises in the PV industry have layout this technology and realize the middle batch test verification.

To address optical losses in double-sided passivated contacts, greater emphasis has also been placed on the xBC technology in 2024. By integrating double-sided polysilicon passivation with BC, TBC technology has been developed. This scheme relocates all positive and negative electrodes to the rear side, eliminating front-side shading and significantly reducing optical losses. This configuration necessitates wafers with a high carrier lifetime to enable efficient photogenerated carrier transport across the entire substrate. Detailed simulations reveals that the theoretical efficiency limit of TBC cells reaches 27.99% [9], and LONGi has achieved a record conversion efficiency of 27.0% for TBC cells in 2024 [2], underscoring their potential for high-efficiency applications. With limited dividend for further enhancing the conversion efficiency of existing TOPCon cell technology, many manufacturers have shifted their focus toward TBC. Despite this interest, the complexity and high production costs associated with TBC technology have hindered its widespread industrial adoption.

In addition to advancements in cell conversion efficiency, one of the most critical developments for TOPCon technology in 2024 was addressing reliability issues associated with ultraviolet (UV)-induced degradation (UVID). The Renewable Energy Test Center (RETC), in its “Photovoltaic Module Index Report,” highlighted that 40% of the tested PV module samples exhibited red-light warning signals. Some mass-produced and commercialized modules showed power losses in the double digits, with degradation rates ranging from 10% to 16% within the first three years of operation. These losses significantly exceeded the terms outlined in module warranties and the power guarantees of PV systems. By this time, UVID has become a pressing concern for the solar industry, raising alarms regarding the long-term reliability of PV systems. This prompted a strong call for more rigorous testing protocols and technological innovations to mitigate the effects of UV irradiation. Shen et al. [10], analyzed the phenomenon and mechanism of UVID occurrence in TOPCon cells and gave solutions from the cell process section and encapsulation materials, respectively, in which the optimization of passivation film layer can reduce UVID to a certain degree, and the employment of light conversion film in encapsulation materials can control UVID at a very low level. Notably, although TOPCon modules exhibited substantial degradation during power testing, their actual performance in outdoor power generation was less affected. The real-world power levels of modules experiencing UVID in standard outdoor operation were found to be higher than those measured in laboratory tests. This discrepancy suggests that the observed power degradation in static tests reflects a "metastable" phenomenon. During actual operation, degradation appears to recover partially, likely due to light exposure and other environmental factors. The specific physical mechanism of recovery needs to be further explored.

For SHJ solar cells, the combination of triple-layer structure of intrinsic hydrogenated amorphous silicon (a-Si:H(i)) with good passivation, n-type oxygen-alloyed hydrogenated nanocrystalline silicon (nc-SiO$_x$:H(n)) as a window layer, p-type hydrogenated nanocrystalline silicon (nc-Si:H(p)) as an emitter and contact layer, and the improved performance of transparent conducting oxides (TCOs) as well as fine screen-printing grids, had led to a high efficiency of 26.81% in 2022 [11]. After that, there is no further efficiency improvement based on the bifacial passivated contacting SHJ structure in two years. Until the end of 2024, Trina Solar reported an efficiency as high as 27.08% based on n-type full passivated contacting SHJ solar cell [12], which is the first time of bifacial passivated contacting solar cell efficiency exceeding 27%. The phosphorus doped Czochralski n-type silicon wafer with size of 210 mm × 105 mm is used for the SHJ solar cell. Besides the excellent passivation of a-Si:H(i) films, the key points for improvement of optical and electrical properties of SHJ solar cell include: ① the optimization of back passivated contacting, ② depositing of doped nanocrystalline silicon by PECVD (plasma enhanced chemical vapor deposition) generated by radio frequency (RF) technique with multi-frequencies to control the structure and growth rate of doped nc-Si:H, and ③ ultra-fine screen-printing grids.

Except of high efficiency, another interesting topic is flexible and thin SHJ solar cells [13,14]. The wafer thinning not only lowers the weight and cost, but also facilitates the charge migration and separation. High-performance SHJ solar cells of various thicknesses (55–130 μm) have been fabricated, all with certified efficiencies of more than 26%. Especially, the 57 μm flexible and thin SHJ solar cell shows the highest power-to-weight ratio (1.9 W/g) and an extremely high open-circuit voltage (V_{OC}) of 761 mV compared to the thick ones [14]. A two-stage composite gradient passivation of oxygen-containing hydrogenated amorphous silicon subnanolayers (a-SiO$_x$:H) is ascribed to the high V_{OC} [14]. In the first stage, a 2–3 atomic layer of a-SiO$_x$:H (i_1) (< 0.5 nm; x ≈ 10 at%, at% is atomic percentage) prevents the periodicity of the crystal arrangement of crystalline Si from continuing outwards, while minimizing the impact of oxygen doping on the electrical properties of the passivation contacts. In the second stage, an epitaxy-free a-Si:H (i_2) passivation layer with a thickness of about 4.5 nm was intentionally coated on a-SiO$_x$:H (i_1) to strengthen the passivation effect and isolate the subsequent doping layers. Additionally, a low-damage PECVD passivation process is used to make a-Si:H(i_2) be continuously grown on a-SiO$_x$:H (i_1) while guaranteeing the integrity of the epitaxy-preventing a-SiO$_x$:H (i_1) and the optimal passivation effect be obtained [14]. This flexible SHJ technological progress provides a practical basis for the commercialization of flexible, lightweight, low-cost and highly efficient solar cells, and the ability to bend or roll up crystalline silicon solar cells for travel is anticipated.

The HBC solar cell continues to be drawn much attention in 2024 in pursuit of ultimate silicon solar cell efficiency. An HBC solar cell with certified efficiency of 27.30% was reported by LONGi [15]. A high J_{SC} of 42.60 mA/cm^2 and a fill factor (FF) of 86.19% were attained in the record HBC cell. To be addressed, a dense passivating contact, which differs from conventional technology practice, was developed to make the process temperature arrive 240 °C. Pulsed picosecond lasers operating at different wavelengths are used to create the BC patterns. To meet the terawatt demand, they developed indium-less cells at 26.5% efficiency and precious silver-free cells at 26.2% efficiency [15]. The integration of all-laser patterning processes for BC electrodes, less indium TCO and silver free metallization, is poised to expand with these technological advances.

However, the costly use of parallel-plate PECVD limits the spreading and expansion of SHJ and HBC solar cells. Nowadays, TOPCon solar cells are being developed to bifacial passivated contact (application of SiO$_x$/poly-Si on the front-side, i.e., poly-finger technology) and TBC. The poly-finger and TBC employ boron-doped polycrystalline silicon (poly-Si(p$^+$)) as passivated contacting layer. The deposition of poly-Si(p$^+$) is not easy and the passivation of poly-Si(p$^+$) is not very effective, while the a-Si:H(p) or nc-Si:H(p) in SHJ and HBC solar cells have showed good passivation and technological feasibility. Thus, a structure of merging HBC and TBC (we call THBC), which combines a-Si:H(i)/a-Si:H(p) or a-Si:H(i)/nc-Si:H(p) with SiO$_x$/poly-Si(n$^+$) as p-contact and n-contact, respectively, has rapidly experimented in 2024. The hybrid THBC solar cell gives a limiting efficiency of 28.9% [16], which showing potential in future. A THBC solar cell with a size of 182 mm × 91 mm has already achieved the highest efficiency of 27.4% in single-junction silicon solar cells so far (even surpassing the 27.30% HBC cells) [2], demonstrating substantial potential for improving conversion efficiency.

Finally, as the Si single-junction solar cell efficiency is approaching the theoretical limit of 29.4%, the perovskite/SHJ tandem solar cell is the choice for efficiency over 30%. As listed in Table 2 and discussed in detail below, after the recording efficiency of 33.9% [17], LONGi has pushed the tandem solar cell efficiency to 34.6% in 2024 [2,18], and 30.1% efficiency tandem cell with a M6 size (166 mm × 166 mm) [2,19], which makes the tandem solar cells step into commercialization soon.

Perovskite solar cells

Metal halide perovskite solar cells (PSCs) have achieved remarkable progress over the past decade, offering an exceptional power conversion efficiency (PCE) [20]. With their potential to enhance traditional silicon-based solar cells, PSCs represent promising candidates for practical applications. In 2024, significant advancements were reported in both single-junction and multi-junction PSCs, as summarized in Table 2. These improvements were driven by a deeper understanding of interfacial defects and corresponding passivation strategies, alongside manipulation of homogeneous crystallization processes. Increasing research attention has been directed toward overcoming challenges in scalable and intelligent fabrication techniques. Enhanced scalability, reproducibility and processing speed are facilitating the transition of PSCs from laboratory research to industrial production. Additionally, several noteworthy developments have emerged within the perovskite research community in 2024. For instance, all-inorganic perovskite tandem cells have achieved a certified PCE of 21.92% [21], while perovskite/perovskite/silicon and all-perovskite triple-junction cells have demonstrated a certified PCE of 27.1% [22] and 27.28% [23], respectively. The integration of high-throughput experimental platforms with machine learning has proven to be a powerful approach for screening organic hole transport materials, enabling the development of devices with a PCE of 26.2% (certified 25.9%) [24]. These studies could offer valuable insights and pave the new avenues for the future development of PSCs.

The efficiencies of single-junction PSCs continued to improve in 2024, with many research groups achieving certified PCEs exceeding 26.0% on small-area devices (aperture area: 0.05–1 cm^2) [25–27]. University of Science and Technology of China (USTC) holds the current record at 26.7% [20]. Similar to 2023 [28], most highly efficient devices are based on the p-i-n (inverted) structure. This is due to the application of self-assembled materials (SAMs), which can act as the organic hole transport layer [26,29–31] or interface engineering on inorganic hole transport layer [27,32]. For high-performance SAM devices, post-treatment remains a prevalent strategy, involving the surface modification of as-crystallized perovskite films [33]. For instance, researchers at North-western University introduced 4-chlorobenzenesulfonate ligands to coordinate with two neighboring Pb^{2+} defects. This dual-site passivation could also facilitate the carrier extraction between perovskites and the electron transport layer (ETL) [26]. By coupling this approach with bimolecular surface passivation using 3-(methylthio)propylamine hydroiodide (3MTPAI) and propane-1,3 diammonium iodide (PDAI$_2$), the fabricated PSCs reached the certified quasi-steady-state PCEs of 26.15% (0.05 cm^2) and 24.74% (1.04 cm^2). Further improvements in champion PCEs to 26.3% were achieved by replacing ammonium-based surface passivators with amidinium iodides. This enhancement is

Table 2 Summary of achievements of perovskite-based cells and minimodules in 2024

Solar cell type	PCE/%	Area/cm^2	V_{OC}/V	J_{SC}/(mA·cm^{-2})	FF/%	Test center	Report date	Description
Perovskite	26.7	0.0519 (ap)	1.193	26.49	84.5	NPVM	Apr.	USTC
Perovskite	26.1	1.036 (ap)	1.200	26.08	83.5	NPVM	Nov.	SolaEon
Perovskite	22.6	20.25 (da)	1.169	25.00	77.4	NPVM	May	Singfilm
Perovskite	23.2	20.25 (da)	1.185	24.31	80.5	NPVM	Sept.	NUS/SERIS
Perovskite	22.4	715.1 (ap)	49.88	0.554	81.2	NPVM	Sept.	SJTU
Perovskite/Si	34.2	1.004 (da)	1.990	20.65	83.2	JRC-ESTI	Apr.	LONGi, 2-T
Perovskite/Si	34.6	1.004 (da)	1.996	20.71	83.6	JRC-ESTI	May	LONGi, 2-T
Perovskite/Si	30.1	212.1 (ap)	1.997	19.69	76.5	FhG-ISE	May	LONGi, 2-T
Perovskite/Si	26.4	17115 (t)	208.7/72.6	0.117/0.12	77.0/85.9	NIM	Apr.	GCL, 4-T
Perovskite/Si	27.3	2050 (t)	127.5/8.531	0.202/0.98	79.2/82.7	NIM	Jun.	GCL, 4-T
Perovskite/perovskite	24.8	64.98 (da)	2.134	15.32	75.9	JET	Dec. (2023)	NJU/Renshine

Notes: All measured under the global AM1.5 spectrum (1000 W/m^2) at 25 °C. da: designated illumination area; ap: aperture area; t: total area. NPVM: National Photovoltaic Industry Measurement and Testing Center, China; JRC-ESTI: European Solar Test Installation at Joint Research Centre, Italy; FhG-ISE: Fraunhofer Institute for Solar Energy Systems, Germany; NIM: National Institute of Metrology, China; JET: Japan Electrical Safety and Environment Technology Laboratories, Japan. USTC: University of Science and Technology of China; Singfilm: Singfilm Solar; NUS: National University of Singapore; SERIS: Solar Energy Research Institute of Singapore; SJTU: Shanghai Jiao Tong University; NJU: Nanjing University. 2-T: Two-terminal configuration; 4-T: Four-terminal configuration.

attributed to the synergistic effects of field-effect passivation and chemical passivation [30].

The aforementioned PSCs utilized mixed SAMs, including the commercial [2-(9H-Carbazol-9-yl)ethyl]-phosphonic acid (2PACz) and [4-(3,6-Dimethyl-9H-carbazol-9-yl)butyl]phosphonic acid (Me-4PACz). For devices based on pure SAM, structural modification is an effective approach. For instance, employing the so-called amorphous (4-(3,6-diphenyl-9*H*-carbazol-9-yl)butyl)phosphonic acid (Ph-4PACz) could enable homogeneous growth of the perovskite, resulting in a reduced trap-assisted recombination rate (0.5×10^6 s^{-1}) compared to Me-4PACz (1.3×10^6 s^{-1}). The derived 1 cm^2 device achieved a certified PCE of 24.35% [31]. Further strategies for enhancing device performance include incorporating conjugated phenylene linker, e.g., [4-(3,6-dimethyl-9H-carbazol-9-yl)phenyl]PA (Me-Ph*p*PACz) [34] or alkyl linker, e.g., (4-(7*H*-dibenzo[*c,g*]carbazol-7-yl)phenyl)phosphonic acid (CbzNaphPPA) [35], and pyrene functional group, e.g., (2-(pyren-1-yl)ethyl)phosphonic acid (Py3) [36]. These innovations in SAM structures have all facilitated the PCEs over 26%. Based on common carbazole-phosphonic-acid SAM, e.g., 2-[2-(3,6-dimethoxy-9H-carbazol-9-yl)ethyl]phosphonic acid (MeO-2PACz), the PSCs requires meticulous optimization of various parameters, like film thickness and processing temperature, to reach efficiency of 26.1% [29].

On glass substrates, achieving a closely packed SAM remains a significant challenge. To strengthen the chemical bonding at the buried heterointerface, a metal-oxide hole transport layer is normally indispensable. Although antimony-doped tin oxides (ATO_x) exhibited good transmittance and stability without redox reactions (certified steady-state PCE of 24.0% on 1 cm^2 device) [32], NiO_x is more widely adopted thanks to its low cost and easy fabrication. Enhancing the performance of NiO_x-based PSCs can be achieved through SAM blending or doping with other small organic molecules. For example, blending Me-4PACz with a commercial SAM of [4-(3,6-dibromo9H-carbazole-9-yl) butyl] phosphonic acid (Br-4PACz) could finely tune the energy-level alignment between NiO_x and perovskite, yielding a champion PCE of 26.28% (certified 25.80%) [37]. Huazhong University of Science and Technology (HUST) reported a molecular hybrid by Me-4PACz with 4,4′,4″-nitrilotribenzoic acid (NA), which improved the wettability of Me-4PACz, contributing to the reduction of nanovoids and the residual stress in the perovskite film. Furthermore, NA could mitigate the Me-4PACz agglomerations and improve its manufacturing for large-area device. This strategy facilitated carrier extraction and suppressed non-radiative recombination between NiO_x and perovskite, leading to a certified steady-state PCE of 26.54% (0.057 cm^2) and 22.74% for mini-modules (11.1 cm^2). Additionally, material optimization, such as using ytterbium oxide (YbO_x) as the buffer layer between ETL C_{60} and metal electrode Cu [38] and small-molecule as the hole transport layer (HTL) [39], have shown potential for further performance enhancement.

In addition to advancements in the p-i-n structure, n-i-p PSCs also demonstrated significant progress in 2024. The Institute of Semiconductors, Chinese Academy of Sciences (ISCAS), developed a binary ammonium iodides for perovskite surface (e.g., 4-*tert*-butyl-benzylammonium iodide, tBBAI, and phenylpropylammonium iodide, PPAI) [25], yielding a champion PCE of 26.75% (certified 26.0%). For perovskite minimodule, employing dopant of methylammonium chloride (MACl) together with the additive of 1,3-bis(cyanomethyl)imidazolium chloride ([Bcmim]Cl) achieved a certified PCE of 23.3% (27.22 cm^2) [40]. To further optimize perovskite lattice doping, N,N-dimethylmethyleneiminium chloride ([Dmei]Cl) was added into the perovskite solution to realize *in situ* reactions, enhancing the PCE to 23.2% on the same aperture area (27.22 cm^2) [41]. Encouragingly, when the aperture area over 700 cm^2, a research group at Shanghai Jiao Tong University (SJTU) achieved a certified PCE of 22.46% [42], setting a record efficiency for perovskite submodule. This milestone was achieved by using the 2-(1-cyclohexenyl)ethyl ammonium iodide treatment, which could serve as the impurity-healing interface engineering method, converting the PbI_2 and δ-$FAPbI_3$ impurities into stable two-dimensional perovskite. Due to a wide range of operational conditions, this method is suitable for upscaling fabrication. Building on their functional molecule approach (e.g., perfluorobutanesulfonyl chloride, PFSC), the group also achieved record efficiency for inorganic minimodules, attaining a certified PCE of 18.22% (12.82 cm^2) [43].

Due to the tunable bandgap, perovskites can be integrated with other PV semiconductors or with themselves to construct tandem cells, which could reduce the thermalization loss and broaden solar spectrum utilization for higher efficiency [44]. Both p-i-n and n-i-p PSCs exhibit comparable PCEs in the single-junction cells, while the former is more advantageous in tandem configuration due to its lower parasitic absorption. Amongest tandem cells, perovskite/perovskite, perovskite/organic, and perovskite/silicon experienced rapid advancements in 2024. Nanjing University (NJU) reported perovskite/perovskite (all-perovskite) tandem cells with an efficiency of 28.5% (certified 28.2% on 1.05cm^2) [45]. This approach requires mixed ammonium salts, consisting of 4-fluorophenethylammonium chloride (F-PEACl) and 4-trifluoromethyl-phenylammonium chloride (CF3-PACl), coated on the wide bandgap perovskite. For scalable deposition techniques, like blade coating, aminoacetamide hydrochloride (AAH) was added in narrow-bandgap Pb-Sn perovskite to realize a wide processing window and homogeneous crystallization, leading to a certified PCE of 24.5% (20.25 cm^2) [46].

Although perovskite/perovskite tandem cells have shown promising efficiency, the unavoidable oxidation of Sn^{2+} in narrow-bandgap perovskite poses the challenges in the practical fabrication processing. Thus, perovskite/organic tandem cells are regarded as one of the alternatives. To further suppress the phase segregation of wide-bandgap perovskite, additive engineering is a commonly used method in perovskite/organic tandem cells, such as 2-amino-4,5-imidazoledicarbonitrile (AIDCN) achieving a champion PCE of 25.13% (certified 23.40%) [47] and 2-anthraquinonesulfonate phenylammonium (AQSP) yielding a PCE of 25.22% (certified 24.27%) [48]. Further surface passivation by cyclohexane 1,4-diammonium diiodide ($CyDAI_2$) could improve the PCE up to 26.4% (certified 25.7%) [49]. However, the relatively low efficiency of the non-fullerene acceptor-based organic solar cells remains a limiting factor for further advancements of the perovskite/organic tandem cells [50].

Currently, perovskite/silicon tandem cells hold the champion PCE of 34.6% [2], in which the efficiency optimization primarily focused on the perovskite layer. Therefore, the strategies in the previously single-junction PSCs provided many insights for these tandem cells. For example, incorporating conventional oleylammonium iodide (OAmI) into the perovskite precursor could modulate the nuclei. Further vacuum and gas-quenching could help stabilize the nuclei, leading to the certified PCEs of 32.5% (1 cm^2) and 29.4% (28.8% certified in 25 cm^2) on perovskite/silicon tandem cells [51]. Other additives, such as methylenediammonium dichloride, induced *in-situ* reaction within the perovskite solution. The formed tetrahydrotriazinium ($THTZ\text{-}H^+$) could improve the crystallization quality of the perovskite film, contributing to a certified PCE of 33.7% (1 cm^2) [52]. In addition to additive engineering, a bilayer interface passivation strategy was reported to further enhance PCE. Based on the common lithium fluoride (LiF) and ethylenediammonium diiodide (EDAI), the tandem device achieved a certified PCE of 33.9% [17]. Therefore, perovskite/Si tandem cells are the most competitive candidates for market entry in the coming years.

Organic solar cells

Organic photovoltaics (OPVs) stand out as a promising option for sustainable energy due to their lightweight, flexibility, non-toxity and low carbon printing production. These features enable unique applications and integrations, such as in wearable electronics, portable power and infrastructure integration. The ability to produce OPVs on flexible substrates supports cost-effective and scalable manufacturing, making them in unique form factor comparing to inorganic material based solar cells. Recent advances in non-fullerene acceptors [53,54], along with improved active layer designs, have pushed the single-junction device to achieve PCEs nearing 21% [55], and the module scale research is also advanced progressively.

In current stage, OPV still faces several key challenges. First, the V_{OC} remains a major efficiency-limiting factor. The best-performing devices show a V_{OC} of around 0.92 V, which is much lower than that of gallium arsenide and perovskite solar cells when bandgap is considered. Developing high-luminescence materials with minimal non-radiative energy loss is considered to be key to achieving further breakthroughs. Second, the understanding of the OPV operation mechanism needs to be elevated. Efforts need to be devoted to understand the physics and function of the blended semiconductor thin film, covering morphological aspects and electronic attributes. OPVs represent a highly complex semiconductor system, where the construction of fibrillar crystalline transport phases enables the *FF* up to 83%. In comparison, the perovskite solar cells have achieved an *FF* approaching 88% [56]. Achieving a similar level for OPVs requires the construction of a more favorable mixing phase to facility transport and reduce recombination. Third, the best balance between high efficiency and operational stability continues to be studied. Interfacial layers, as experience gained from organic light-emitting diodes, are key to ensure device stability and performances [57]. Fourth, scaling up from laboratory-scale devices to modules is one of the most important tasks at this stage. Finally, artificial intelligence aided OPVs research in material discovery and device optimization affords a faster track in enhancing efficiency and scalability [58].

In 2024, the Y-series material development and application are still the main effort [54]. These newly developed materials led to further improvement in the PCEs. Important progresses are delineated in Table 3, and pertinent methodologies will be commented. In March, a research team in Zhejiang University (ZJU) reported a self-assembled HTL 2PACz. This HTL, with a thickness of 2–6 nm, could form full coverage on the substrate via covalent and van der Waals bonding. Compared to the conventional PEDOT:PSS HTL, 2PACz demonstrated improvement in reducing parasitic absorption and enhancing light transmission, which substantially improved the J_{SC} of the OPV device. As a result, they achieved a PCE of 20.2% in laboratory conditions, which was certified to be 19.8% by the National PV Industry Measurement and Testing Center (NPVM) in Fujian, China. This HTL was proven to be suitable for semi-transparent OPVs and yielded a record-breaking light utilization efficiency of 5.34% [59]. In August, researchers at Wuhan University (WHU) developed a novel non-fullerene acceptor, L8-ThCl, and incorporated it as a guest component in layer-by-layer (LBL) device. The L8-ThCl exhibited dipole-dipole interactions with the host materials, enabling the

Table 3 Summary of the achievements of organic solar cells in 2024

Solar cell type	PCE/%	Area/cm^2	V_{OC}/V	J_{SC}/(mA·cm^{-2})	*FF*/%	Test center	Reportdate	Description
Organic	19.8	0.048	0.880	27.8	80.7	NPVM	Mar.	ZJU
Organic	20.0	0.041	0.907	27.4	80.4	NPQT	Aug.	WHU
Organic	20.1	0.034	0.924	27.5	79.0	SIMIT	Nov.	SJTU
All-polymer	19.1	0.032	0.951	25.7	78.1	NIM	Jul.	BHU
Organic (minimodule)	16.7	13.1	6.876	3.31	73.1	SIMIT	Jun.	SUDA
Organic (submodule)	14.5	204.1	31.60	0.615	74.6	FhG-ISE	Apr.	FAU

Notes: All measured under the global AM1.5 spectrum (1000 W/m^2) at 25 °C. NPVM: National PV Industry Measurement and Testing Center, China; NPQT: National Photovoltaic Product Quality Inspection and Testing Center, China; SIMIT: Shanghai Institute of Microsystem and Information Technology, China; NIM: National Institute of Metrology, China; FhG-ISE: Fraunhofer Institute for Solar Energy Systems, Germany. ZJU: Zhejiang University; WHU: Wuhan University; SJTU: Shanghai Jiao Tong University; BHU: Beihang University; SUDA: Soochow University; FAU: Friedrich-Alexander Universität Erlangen Nürnberg.

formation of fine and long dual nanofibril morphologies with enhanced structural order and a face-on orientation. Such a morphology is known to facilitate longer carrier diffusion and drift lengths [60]. Consequently, they achieved a PCE of 20.1% in laboratory tests, with a certified value of 20.0% provided by the National Photovoltaic Product Quality Inspection and Testing Center (NPQT) in Chengdu, China [61]. In November, a research team at SJTU reported an additive-assisted LBL device fabrication. Using the active layer formulation of D18-Cl/BTP-4F-P2EH, they systematically modulated the upper and lower layers with varying concentrations of additive 1-CN to achieve an interpenetrating fibril network active layer morphology. This effort resulted in a bulk p-i-n structure, where material interaction and crystallization were balanced to constrain the characteristic length scales to tens of nanometers and mixing region to a few nanometers. This morphology reduced recombination losses, thereby ensuring a high internal quantum efficiency and *FF*. Moreover, the use of high-boiling-point additives significantly reduced the solution viscosity and prolonged the solution state, generating an instability induced wrinkle surface morphology to enhance light absorption of the active layer. The SJTU team achieved a PCE of 20.8% in laboratory tests, with a certified efficiency of 20.1% by the Calibration Center of New Energy Device and Module at the Shanghai Institute of Microsystem and Information Technology (SIMIT) in Shanghai, China. Furthermore, leveraging the same formulation, they fabricated a mini-module with an area of 17.6 cm^2, and achieved a high PCE of 17.0% [55]. Additionally, all-polymer solar cells (APSCs) have achieved further advancements in 2024. In July, researchers from Beihang University (BHU) developed a novel polymeric acceptor, PY-DT-X, and constructed an all-polymer ternary system comprising PM6:PY-IT:PY-DT-X. They introduced a new solid additive, 2-alkoxynaphthalene (2-EN), to achieve stepwise regulation of the aggregation of donor and acceptor molecules during film casting and thermal annealing processes, resulting in the formation of a double fibril network morphology. Consequently, they attained an impressive PCE of 19.5% in laboratory tests, with a certified value of 19.1% by the National Institute of Metrology (NIM) in Beijing, China [62].

In the field of OPV modules, 2024 has marked significant advancements. In June, researchers at Soochow University (SUDA) conducted an in-depth investigation into the mechanisms of solid and liquid additives in blade coating. Their findings revealed that liquid additives could generate an outward Marangoni flow from the coating head toward the wet film's arc-shaped three-phase contact line (CTL). This phenomenon led to undesirable material aggregation and phase separation. Additionally, the high surface tension at CTL resulted in an uneven film. In contrast, solid additives acted as solutes and did not affect the fluid dynamics during the drying process, thereby facilitating superior film uniformity: An essential attribute for large-scale module fabrication. Utilizing the PM6:D18:BTP-eC9 active layer formulation with solid additive, the team achieved a high PCE of 16.7% for a 15.64 cm^2 mini-module, certified by SIMIT in Shanghai, China [63]. An additional groundbreaking development has emerged from Friedrich-Alexander Universität Erlangen Nürnberg (FAU), which was published in April. The active layer utilized the PM6:Y6-C12:PC$_{61}$BM formulation. Through the application of computational fluid dynamics and electrical finite element method simulations, the research team optimized the blade-coating fabrication process, achieving highly uniform coatings with thickness deviations of less than 5%. Additionally, they effectively minimized losses stemming from electrode resistances and inactive interconnect areas. As a result, there was virtually no performance loss observed when scaling up from small-area devices (4 mm^2) to large-area modules (204 cm^2). Notably, the module fabrication employed non-halogenated solvents, enabling safe and efficient production under ambient air conditions. The resulting sub-module achieved a certified efficiency of 14.5%, as verified by the Fraunhofer Institute for Solar Energy Systems (FhG-ISE) in Freiburg, Germany [64]. This accomplishment represents a new world record, as confirmed by the official "Champion Photovoltaic

Module Efficiency Chart” published by the National Renewable Energy Laboratory (NREL) [65].

In summary, the advancements in OPV laboratory-devices and modules highlight the rapid progress in bridging experimental research to large-scale fabrication. The year 2024 is remarkable for OPVs, with significant improvements in both efficiency and manufacturing. It is anticipated that OPV efficiency could reach 22%–25%, with module performance exceeding 20% within 3–5 years. Although balancing high efficiency and stability remains a challenge, the new material development could be a final solution.

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