

# COST-EFFECTIVE SYNTHESIS METHODS FOR NEXT-GENERATION SOLAR CELLS: A FOCUS ON PEROVSKITES AND THIN-FILM TECHNOLOGIES

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## Abstract

Next-generation solar cells, particularly perovskite solar cells (PSCs) and advanced thin-film technologies, promise to revolutionize photovoltaics by offering high power conversion efficiencies (PCEs) at significantly reduced manufacturing costs compared to traditional crystalline silicon. This review examines recent advances in cost-effective synthesis methods for perovskites, emphasizing scalable, low-temperature solution-processing techniques such as blade coating, slot-die coating, spray coating, roll-to-roll (R2R) printing, and aqueous precursor synthesis. These approaches minimize material waste, eliminate toxic solvents, and enable kilogram-scale production using low-purity raw materials, achieving PCEs exceeding 25% with improved stability. Complementary thin-film technologies, including perovskite/CIGS tandems and CdTe variants, are discussed for their hybrid potential in commercial modules. Cost analyses indicate levelized costs of electricity (LCOE) as low as \$0.40–0.50/W for optimized perovskite processes. Challenges related to stability, lead toxicity, and upscaling are addressed through additive engineering, green solvents, and interface passivation. This review highlights pathways to commercialization, projecting perovskite-based modules as viable alternatives with production costs below \$0.50/W at GW-scale.

**Keywords:** Perovskite solar cells, thin-film photovoltaics, cost-effective synthesis, scalable fabrication, roll-to-roll processing, aqueous precursors

## 1. Introduction

The global demand for renewable energy has intensified the search for photovoltaic (PV) technologies that surpass the cost and efficiency limitations of first-generation crystalline silicon solar cells, which dominate ~85% of the market but require high-temperature processing ( $>1000^{\circ}\text{C}$ ) and expensive purification [3,5]. Second-generation thin-film technologies, such as cadmium telluride (CdTe) and copper indium gallium selenide (CIGS), offer material savings through thicknesses of  $\sim 1\text{--}5\ \mu\text{m}$  and have achieved commercial PCEs of 22–23% with LCOE values of \$38–65/MWh [5]. However, their reliance on vacuum-based or high-temperature methods limits further cost reductions.

Third-generation perovskite solar cells (PSCs) have emerged as a disruptive technology, with certified PCEs rising from 3.8% in 2009 to over 26.7% in single-junction devices and 29.9% in perovskite/CIGS tandems by 2023–2025 [7,8]. Perovskites ( $\text{ABX}_3$  structure, e.g.,  $\text{FAPbI}_3$  or  $\text{MAPbI}_3$ ) enable low-temperature ( $<150^{\circ}\text{C}$ ) solution processing, high absorption coefficients ( $>10^5\ \text{cm}^{-1}$ ), and tunable bandgaps (1.2–2.3 eV), making them ideal for flexible, lightweight, and building-integrated applications [2,4]. Cost-effective synthesis is central to commercialization, targeting manufacturing costs  $< \$0.50/\text{W}$  and LCOE competitive with silicon ( $\sim \$38\text{--}78/\text{MWh}$ ) [1,5].

This review focuses on perovskite synthesis innovations and their integration with thin-film platforms, providing a roadmap for scalable, sustainable PV [1–25].

## 2. Perovskite Materials and Fundamental Properties

Hybrid organic-inorganic perovskites exhibit exceptional optoelectronic properties, including long carrier diffusion lengths ( $>1 \mu\text{m}$ ), high defect tolerance, and ambipolar charge transport. Compositional engineering (e.g., FA/Cs mixed cations, Br/I halides) stabilizes the photoactive  $\alpha$ -phase while reducing bandgap to  $\sim 1.5 \text{ eV}$  for optimal Shockley-Queisser limits ( $\sim 33.7\%$ ) [4,9].

Lead toxicity and instability under moisture, heat, and light remain concerns, driving research into Sn-based or double perovskites (e.g.,  $\text{Cs}_2\text{AgBiBr}_6$ ) and encapsulation strategies [8,10]. While thin-film architectures (n-i-p or p-i-n) with thicknesses of 300–500 nm minimize material use, enabling power-to-weight ratios  $>20 \text{ g/W}$  for flexible devices [2]. Recent aqueous synthesis routes have reduced precursor costs by two orders of magnitude using industrial-grade  $\text{PbI}_2$  [1,8].

## 3. Cost-Effective Synthesis Methods for Perovskites

### 3.1 Precursor Synthesis and Green Chemistry Approaches

Traditional precursors rely on high-purity  $\text{PbI}_2$  and organic salts in toxic solvents (DMF/DMSO), inflating costs and environmental impact. Aqueous synthesis of  $\delta$ -FAPbI<sub>3</sub> microcrystals at room temperature using low-purity raw materials achieves 99.996% purity (average  $99.994 \pm 0.0015\%$ ), kilogram-scale production, and eliminates organic solvents [8]. This method reduces  $\text{Ca}^{2+}$  impurities (major charge-trap sources), yielding inverted PSCs with certified PCE 25.3% and 94% retention after 1000 h at  $50^\circ\text{C}$  [1,8].

Pre-synthesized perovskite powders (e.g.,  $\delta$ -FAPbI<sub>3</sub> from low-grade  $\text{PbI}_2$   $<99\%$  purity) via liquid-phase reaction and antisolvent crystallization enable stoichiometric control, avoiding excess organics that degrade stability. Costs drop significantly as industrial DMSO ( $\sim \$1/\text{kg}$ ) replaces specialty solvents [1]. Green alternatives like  $\gamma$ -valerolactone (GVL) or ethanol with  $\text{RNH}_3\text{Cl}$  support antisolvent-free deposition and year-long ink stability [1,11].

### 3.2 Scalable Deposition Techniques

Lab-scale spin-coating is unsuitable for large areas due to material waste ( $>90\%$ ) and non-uniformity. Cost-effective alternatives include:

**Blade Coating:** High-concentration precursors in acetonitrile (ACN) with methylamine enable rapid crystallization ( $<1 \text{ s}$ ) at room temperature, producing pinhole-free films with PCE 19.6% on flexible substrates. Compositional tuning ( $\text{Cs}^+/\text{Br}^-$  additives, excess  $\text{MACl}$ ) lowers substrate temperature to  $120^\circ\text{C}$  while achieving 19.5% PCE [3,4,12]. Manual blade variants allow low-cost lab entry without expensive equipment [3].

#### Slot-Die Coating and Spray Coating:

These non-contact methods suit R2R processing on rough or flexible substrates. Ultrasonic spray yields uniform large-area films; slot-die achieves 11.96% PCE in modules [4,13]. Eco-friendly antisolvents (tert-butyl alcohol/ethyl acetate) in gravure printing produce 19.1% PCE flexible modules [1].

**Roll-to-Roll (R2R) Printing:** Reverse gravure, slot-die, and screen printing enable high-throughput on polymer substrates. Modules reach 11.0% PCE at 0.7 USD/W (1 GW/year scale), with potential  $<0.50 \text{ USD/W}$  [1,2,14]. Low-temperature processing ( $<150^\circ\text{C}$ ) preserves flexible PET/ITO substrates [2,9].

#### Vapor-Assisted and Vacuum Methods:

Hybrid two-step deposition or thermal evaporation ensures uniformity over  $\text{m}^2$  areas, though higher capital costs; combined with solution steps for tandems [5,7,15].

Additive engineering is pivotal for morphology control. Cyclohexylamine promotes (111)-dominant facets for moisture resistance; 1-(phenylsulfonyl)pyrrole homogenizes cations (PCE 25.2%); hexafluorobenzene (HFB) via anion- $\pi$  interactions suppresses intermediates (certified 25.8%, 94% retention after 1258 h) [1]. Trace dopants ( $\text{Nd}^{3+} 0.08\%$ ,  $\text{SCN}^-$ ) inhibit ion migration [1,16]. Self-assembled monolayers (SAMs) as hole-transport layers tune interfaces, retaining 97% PCE after 1000 h maximum power point tracking [17].

These methods reduce energy payback time to  $<1 \text{ year}$  and material costs to  $<10\%$  of total module price [1,5].

#### 4. Thin-Film Technologies: Integration and Comparisons

Perovskites excel as thin-film absorbers but integrate synergistically with established thin films. Perovskite/CIGS 4T tandems achieve 29.9% PCE with 81.5% NIR transmittance in semi-transparent top cells, offering daily energy yields  $\sim 2000$  Wh/m<sup>2</sup> and LCOE 3–5 ¢/kWh in low-latitude regions [7]. CdTe (23.1% lab PCE) benefits from perovskite top cells in tandems, leveraging close-spaced sublimation for bottom layers but facing toxicity concerns [5].

CIGS via co-evaporation or sputtering remains mature (multi-GW production) but higher costs ( $\sim$ high \$50s/MWh) than perovskites [5]. Kesterite (CZTS) and organic PV offer ultra-low costs but lag in efficiency (12–15%) [5]. Perovskite tandems with silicon or CIGS target  $>30\%$  PCE while maintaining thin-film advantages: lightweight, flexible formats, and low-temperature processing [2,6,18]. Scalable blade/slot-die for perovskites pairs with existing thin-film lines, accelerating industrialization [13,19].

#### 5. Cost Analysis and Economic Viability

Techno-economic models project perovskite modules at \$0.40–0.50/W (vs. silicon \$0.70–1.00/W) via R2R and aqueous precursors, with solvent costs for 1 GW  $\sim$ \$3850 using DMSO [1,5]. Flexible PSCs enable novel markets (wearables, IoT, BIPV) with power-to-weight  $>$  traditional thin films [2,9]. LCOE for perovskite/Si tandems: \$40–55/MWh; pure perovskite modules competitive at scale [5,6]. Carbon-based electrodes further cut costs by replacing Au/Ag [20]. Lifetime  $>25$  years (via encapsulation/SAMs) is critical for bankability [1,17].

#### 6. Challenges and Mitigation Strategies

Key hurdles include: (i) stability (degradation via ion migration, moisture); mitigated by additives, SAM interfaces, and 2D/3D heterostructures [1,4,16]; (ii) scalability defects on large areas; addressed by R2R and machine-learning-optimized parameters [13,21]; (iii) Pb toxicity; Sn/Ge or double perovskites show promise but lower PCEs [8,10]; (iv) hysteresis and interfaces; SAMs and passivation reduce it [17]. Accelerated testing protocols (ISOS standards) ensure real-world validation [22].

#### 7. Future Prospects and Conclusion

Emerging trends—aqueous kilogram-scale precursors, fully printed R2R modules, bifacial designs ( $>91\%$  bifaciality, effective PCE 31.2% with albedo), and AI-driven discovery—position perovskites for GW-scale deployment by 2030 [1,2,8,23]. Lead-free and tandem architectures will address regulatory and efficiency gaps [7,24]. Integration with existing thin-film infrastructure accelerates market entry in niche and utility sectors.

In conclusion, cost-effective synthesis methods have transformed perovskites from lab curiosities to near-commercial thin-film contenders. Continued focus on green processing, stability, and tandems will realize LCOE parity and beyond, contributing to sustainable global energy.

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