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## Perovskite Photovoltaics for Atmanirbhar Bharat: Roadmap to Sustainable Solar Independence by 2047

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Received: 20 March 2026 Accepted & Reviewed: 25 March 2026, Published: 31 March 2026

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### Abstract

India's ambition to achieve "Developed India @ 2047" is closely tied to ensuring the provision of dependable, affordable and clean energy. As the country aims for solar self-sufficiency, the new generation of metal-halide perovskite photovoltaics (PSCs) presents a revolutionary opportunity, offering high efficiency, cost-effective processing, and potential for swift deployment. This study provides a comprehensive roadmap for utilizing perovskite solar cells within the Indian framework, covering aspects from materials science and device engineering to manufacturing, policy, sustainability, and localization. We detail the current state and trends of perovskite technology, including lab-cell efficiencies exceeding 25%, and address the challenges related to stability, scalability, lead toxicity, and module deployment. The Indian strategy is then crafted to establish domestic value chains, promote R&D, facilitate large-scale perovskite module production, integrate perovskite-silicon tandem systems, and align with national solar and manufacturing initiatives, such as Make in India and Atmanirbhar Bharat. We suggest milestone targets for commercial module deployment by 2030, achieving grid-parity large-scale adoption by 2035, and attaining full localization and export capability by 2047. Finally, we explore techno-economic modeling, life cycle and circular economy considerations, and policy frameworks, including subsidies, duties, R&D grants, and standardized certification. Through this, we illustrate how perovskite photovoltaics can become a cornerstone of India's renewable energy future, facilitating sustainable solar independence in developed India.

**Keywords:** Perovskite solar cells, metal-halide perovskite, Atmanirbhar Bharat, solar independence, tandem photovoltaics, localization, India, manufacturing roadmap, stability, circular economy.

### Introduction

The vision for a "Developed India @ 2047" emphasizes the importance of energy accessibility, climate resilience, and local manufacturing. Solar energy is a key component of this vision because of India's plentiful sunlight, the falling costs of solar modules, and the global shift towards renewable energy. While traditional silicon photovoltaics (Si-PVs) have been at the forefront, new photovoltaic technologies are emerging with promising complementary benefits. Among these, metal-halide perovskite solar cells (PSCs) have garnered significant attention over the last decade for their swift efficiency improvements and potential for cost-effective, high-volume production[1]. This paper investigates how PSCs can be integrated into India's solar independence strategy by first summarizing the current state of science and technology, identifying opportunities and challenges for India, outlining a roadmap to 2047, and finally addressing policy, manufacturing, and sustainability issues pertinent to the Indian context. The remainder of this paper is organized as follows. Section 2 reviews basic perovskite photovoltaics, including materials, device structures, efficiency trends, and commercial potential. Section 3 discusses the key technical and manufacturing challenges, such as stability, scalability, lead toxicity, and module integration. Section 4 highlights the India-specific opportunities and strategic benefits. Section 5 presents a phased roadmap (2025-2035-2047) for the deployment and localization of perovskite PV in India. Section 6 discusses policy, manufacturing value chains,

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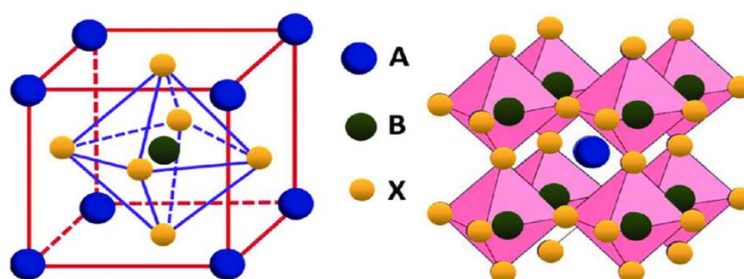
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circular economy, and sustainability concerns. Section 7 concludes the study with recommendations for stakeholders.

## 2. Fundamentals of Perovskite Photovoltaics

### 2.1 Material structure and optoelectronic properties

Metal-halide perovskites exhibit the general structure  $ABX_3$ , where A represents a monovalent cation (such as methylammonium  $MA^+$ , formamidinium  $FA^+$ , or  $Cs^+$ ), B denotes a divalent metal cation (commonly  $Pb^{2+}$ ), and X signifies a halide anion ( $I^-$ ,  $Br^-$ ,  $Cl^-$ )[2]. This crystal structure is advantageous for photovoltaic applications because of its long carrier diffusion lengths, tunable bandgaps, and strong light absorption. For instance, perovskite absorbers can be engineered to achieve band gaps near the Shockley-Queisser optimum ( $\sim 1.3$ – $1.5$  eV) and can be processed at low temperatures using solution or vapor methods[3].



**Figure 1:** Perovskite structure. Reproduced from ref. [4] under Creative Commons Attribution License (<http://creativecommons.org/licenses/by/3.0>)

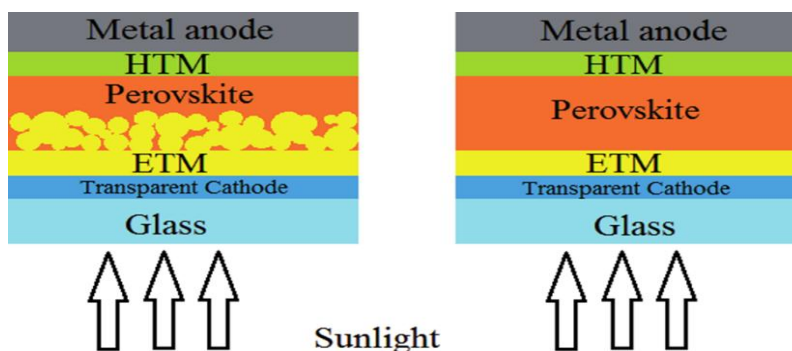
As one review summarizes:

“The perovskite materials show different merits like longer carrier diffusion lengths, wider-tunable bandgap in addition to higher potential of light absorption.” [3]

### 2.2 Device architectures and performance trends

Since the first demonstration of perovskite solar cells, efficiencies have climbed rapidly: laboratory cells now exceed 25 % power conversion efficiency (PCE) in single junction architectures.[5] Device architectures include mesoscopic scaffolds, planar heterojunctions, and inverted (p-i-n) stacks.[6] Moreover, tandem cells that combine perovskites with silicon or other perovskite layers can achieve even higher efficiencies and promise cost-competitive deployment. [7]

The schematic diagrams of typical perovskite architectures are illustrated below.



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**Figure 2:** Representative schemes of mesoporous (right) and planar PSC (left). Reproduced from ref. [4] under Creative Commons Attribution License (<http://creativecommons.org/licenses/by/3.0>)

### 2.3 Advantages for solar independence

The key advantages of PSCs relevant to India's solar independence include the following.

- **Low processing temperature & cost:** Many perovskite layers can be fabricated at low temperature and via solution processing, reducing capital and energy input[5].
- **High absorption and tunable band gap:** Enables thinner absorber layers, less material consumption, and compatibility with tandem architectures[8].
- **Rapid efficiency improvement:** The pace of improvement has been faster than most alternative PV technologies, indicating a strong innovation trajectory[9].
- **Light-weight and potentially flexible:** Perovskite films can be adapted to flexible substrates, building-integrated photovoltaics (BIPV), or non-traditional mounting, which expands the deployment options for India beyond large ground-mounted arrays.

These characteristics render perovskite solar cells (PSCs) a valuable addition to silicon photovoltaic (PV) systems in India's renewable energy portfolio. Having elaborated on the advantageous properties of PSCs, such as their high efficiency and cost-effective manufacturing, we have now addressed the substantial challenges that must be overcome. These challenges include stability, scalability, environmental impact, and the necessity for standardization, all of which are crucial for harnessing the full potential of PSCs in India's solar energy strategy.

### 3. Technical and Manufacturing Challenges

While the promise of PSCs is high, several critical challenges must be addressed, especially to support large-scale deployment in India by 2047.

#### 3.1 Stability and longevity

A persistent challenge is operational stability: perovskite absorbers are sensitive to moisture, oxygen, heat and ultraviolet radiation, and can degrade or phase-segregate over time[4]. The instability limits the commercial lifespan compared to well-established silicon modules. Addressing stability has become a major focus of recent research, including interface passivation strategies, improved encapsulation and compositional engineering (e.g., 2D/3D layered perovskites)[7].

#### 3.2 Scale-up and manufacturability

Transitioning from lab-scale small cells ( $< 1 \text{ cm}^2$ ) to modules of tens to hundreds of square metres introduces challenges: uniform film formation, defect control, large-area coating, yield, and integration with module electronics[10]. Achieving module PCEs, ensuring reliability and yield, and building manufacturing lines require substantial investment and process development.

#### 3.3 Lead toxicity and environmental concerns

Most high-performance PSCs still use lead ( $\text{Pb}^{2+}$ ) as the B-site cation, which raises concerns regarding toxicity and end-of-life recycling. Researchers are pursuing lead-free perovskites (e.g., tin (Sn)-based) but these lag

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behind in performance and stability[11]. For India, with strict environmental rules and large-scale deployment in habitats, recyclability containment and safety manufacturing are crucial.

### 3.4 Module certification and reliability standards

To integrate perovskite modules into utility-scale solar plants or grid-tie systems, they must satisfy rigorous reliability and certification standards (IEC and IS standards). Given the newer technology, the establishment of long-term field data, degradation models, and standard testing protocols is still ongoing.

### 3.5 Cost dynamics and supply chain

While perovskites promise lower processing costs, the total system cost includes the balance-of-system (BOS), module integration, installation, and operations. A supply chain for perovskite precursor chemicals, scalable deposition equipment, encapsulation, and module assembly must be developed, especially if India is to localize manufacturing under the Atmanirbhar Bharat scheme.

## 4. Opportunities for India - Strategic Fit

India enjoys several favourable conditions that position the country to seize the perovskite PV opportunity:

### 4.1 Solar resource and deployment scale

Click or tap here to enter the text. Moreover, recent national goals (e.g., 500 GW by 2030) signal a strong demand and governmental commitment to solar power[12]. This demand has created a runway for the development of innovative PV technologies.

### 4.2 Make in India & Atmanirbhar Bharat impetus

The Government of India's "Make in India" and "Atmanirbhar Bharat" initiatives prioritise domestic manufacturing, technology localisation and export-oriented growth[13]. A home-grown perovskite solar-manufacturing ecosystem is perfectly aligned with these processes.

### 4.3 Potential for Technological Advancement

India possesses a distinctive opportunity to bypass the limitations of traditional silicon manufacturing by embracing perovskite photovoltaic (PV) technologies, which are currently in the developmental phase. This approach allows the adoption of innovative, flexible manufacturing platforms that are optimized for cost-effectiveness and high production efficiency.

### 4.4 Integration with hybrid and tandem systems

India's future solar infrastructure will likely include hybrid systems (solar and storage) and tandem modules (silicon and perovskite). Indian labs and startups could focus on tandem perovskite-silicon modules, leveraging existing silicon PV bases, and gradually migrating to full perovskite systems.

### 4.5 Export potential and regional leadership

Upon reaching full development, India has the potential to not only satisfy its domestic demand but also export perovskite modules to other developing nations with comparable irradiation profiles. This would enhance the economic value and bolster India's leadership in global climate initiatives.

## 5. Roadmap to 2047: Phased Milestones

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Below we propose a phased roadmap for India's deployment of perovskite photovoltaics, aligned to the "Developed India @ 2047" vision.

### Phase I: 2025–2030 – Establish R&D, pilot manufacturing & demonstration

- Strengthen national R&D: Establish a dedicated "Perovskite Solar Programme" under the Ministry of New & Renewable Energy (MNRE) / Department of Science & Technology (DST), with funding for materials, process engineering, stability testing, tandem architectures and Indianized precursor chemistry.
- Build pilot manufacturing lines (10–50 MW scale) in collaboration with industry, demonstrating module fabrication, encapsulation, reliability testing, and yield optimization.
- Demonstration projects: Perovskite modules are implemented in selected utility-scale parks, such as a 100 MW demonstration, as well as in Building-Integrated Photovoltaics (BIPV) applications, to collect field data and enhance confidence among utility providers.
- Create standards and certification laboratories: Indian standards bodies (BIS) to adopt or develop test protocols for perovskite modules (temperature cycling, humidity freezing, and UV stress).
- Localization: Map the supply chain of raw materials (precursors, substrates, inks), deposition equipment, encapsulation materials, and module assembly for perovskite cells.

### Phase II: 2030–2035 – Commercial module deployment & scaling

- The target cost for commercial modules, adjusted to the Indian context, is set at or below US\$0.20 per watt, inclusive of the balance of system (BOS).
- Begin large-scale deployment of perovskite modules (both ground-mounted and rooftop) to supply 20–30 GW capacity by 2035.
- Indian manufacturing capacity: Achieve ~5 GW/year of domestic perovskite module manufacturing, creating supply chain jobs and export potential.
- Tandem transition: Deploy perovskite-silicon tandem modules with >30 % PCE to replace first-generation silicon panels.
- Circular economy and recycling: Launch module take-back and recycling infrastructure for end-of-life perovskite modules, establishing industry norms for safe disposal and reuse.

### Phase III: 2035–2047 – Full localisation, export leadership & solar independence

- By 2040, perovskite modules are projected to achieve cost parity or even surpass mature silicon photovoltaic (PV) technologies, thereby becoming the predominant choice for new installations.
- By 2047, coinciding with the centenary of India's independence, it is projected that over 70% of the newly installed photovoltaic (PV) capacity will comprise perovskite or tandem perovskite technologies. This development positioned India as a leading global exporter of perovskite modules and associated technologies.
- India has developed a comprehensive domestic value chain encompassing precursor synthesis, module assembly, recycling, and export logistics, thereby achieving self-sufficiency and enhancing global competitiveness.

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- India achieves "solar independence" by reducing its reliance on imported photovoltaic (PV) modules and raw materials and integrating its grid with renewable energy sources, storage solutions, and smart management systems. This advancement significantly contributes to global climate change mitigation efforts.

The table below summarizes these milestones:

Phase	Years	Key Deliverables
I	2025-2030	R&D programmes; pilot modules; standards; supply-chain kick-off
II	2030-2035	Commercial deployment (20–30 GW); manufacturing scale (~5 GW/yr); tandem modules; recycling systems
III	2035-2047	Dominant perovskite deployment; export leadership; full localisation; solar independence realised

## 6. Policy, Manufacturing & Sustainability Considerations

### 6.1 Policy Levers and Incentives

To effectively implement this roadmap, it is imperative that policy mechanisms are harmonized. The recommended instruments include the following.

- Research and development grants as well as mission funding are allocated for the advancement of perovskite photovoltaic technology, tandem devices, and research focused on stability, encapsulation, and lead-free alternatives.
- Capital subsidies or viability gap funding for pilot production lines, manufacturing facilities, and module assembly units under the Atmanirbhar Bharat initiative.
- During the initial phases, from 2030 to 2035, the implementation of preferential tariffs or feed-in tariffs for utility and rooftop projects utilizing perovskite modules will significantly enhance their adoption.
- Regulatory mandates or content requirements, such as local value-added thresholds, are designed to promote domestic manufacturing.
- The standardization and labelling framework for perovskite modules encompassing efficiency ratings, durability classifications, and recycling tags was implemented through the Bureau of Indian Standards (BIS) and the Ministry of New and Renewable Energy (MNRE).
- Export promotion schemes, duty incentives, and the facilitation of technology transfer empower Indian companies to compete on a global scale.

### 6.2 Manufacturing value chain and localisation

The Indian manufacturing ecosystem for perovskite photovoltaic (PV) technology encompasses several key components, including the synthesis of precursor chemicals (such as halides and organic cations), production of substrates and foils (comprising glass and flexible polymers), and development of coating and deposition equipment (including blade coating, slot-die, and vapor deposition techniques). Additionally, it involves the provision of encapsulation materials (such as barrier foils and adhesives), the establishment of module assembly lines, the operation of testing and certification laboratories, and recycling and end-of-life

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management processes. Each of these elements presents significant opportunities for domestic industry, ranging from the production of specialty chemicals to the manufacture of machine tools. Collaboration between academic institutions, startups, and large conglomerates is essential for advancing this sector.

### 6.3 Circular economy, environment & sustainability

In light of the concerns associated with the lead and end-of-life phases of modules, the application of circular economic principles is imperative.

- Design modules for disassembly and recycling; recover lead, halides, and other materials.
- Assessing the lifecycle environmental impact (LCA) of perovskite modules compared to silicon is expected to be favourable given a thinner absorber and lower energy input, but must be a factor in stability/lifespan.
- Encourage development of non-lead (e.g., tin, germanium) perovskites to future-proof the technology[14].
- Implementation of safe manufacturing practices, worker protection, and module disposal protocols to mitigate environmental risks.

### 6.4 Integration with the broader solar ecosystem

Perovskite photovoltaics (PV) must be integrated into India's broader renewable energy framework, encompassing grid integration, energy storage, smart grid technology, rooftop adoption, building-integrated photovoltaics (BIPV), and rural electrification. The flexibility of perovskite PV, characterized by their thin film and lightweight properties, facilitates deployment in areas where traditional silicon modules are less suitable, such as remote or off-grid microgrids and built structures. Consequently, India's objective of achieving "24×7 Power by 2030" can be bolstered through the deployment of perovskite PV in conjunction with energy storage solutions and smart management systems.

## 7. Challenges and Risk Mitigation

Despite this strong opportunity, India must proactively mitigate risks.

- **Stability shortfall:** Until module lifetimes equivalent to those of silicon (20-25 years) are demonstrated, the associated risks persist. To mitigate this risk, it is recommended to establish reliability test centres in India, implement field monitoring, and adopt early warranty and guarantee mechanisms.
- **Manufacturing bottlenecks:** Challenges include underdeveloped deposition tools, yield inefficiencies, and supply chain disruptions. The proposed mitigation strategies involve fostering public-private partnerships, enhancing technical collaborations, and providing subsidies for equipment.
- **Tech obsolescence:** Perovskite PV is a dynamic field, and alternative technologies may leapfrog. Mitigation: Maintain agility in R&D and open innovation collaborations.
- **Lead regulatory/compliance risk:** Large-scale lead-based module deployment in India may trigger environmental liabilities. Mitigation: Early investment in lead-free perovskites, robust recycling frameworks, and regulatory clarity.
- **Market competition from silicon PV:** Given silicon cost reductions, perovskite must offer clear advantages (cost, manufacturing ease, and deployment flexibility). Mitigation: Focus on tandem modules, BIPV, flexible form factors, and integrated Indian manufacturing advantages.

## 8. Conclusion & Recommendations

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To realize the vision of a "Developed India @ 2047," it is imperative to adopt an ambitious and progressive solar strategy. Perovskite photovoltaics represents a highly promising technological catalyst for this objective, offering a combination of high potential efficiency, cost-effective manufacturing, deployment versatility, and opportunities for domestic industrial expansion. The following key recommendations have been proposed for India to effectively leverage these advantages.

1. **Launch a national perovskite solar mission** by 2025, integrating academic, government, and industrial stakeholders, and aligning with Atmanirbhar Bharat manufacturing goals.
2. **Invest domestic manufacturing infrastructure** for perovskite PV—not just modules, but precursor chemistry, deposition equipment, and module assembly- to create indigenous supply chains.
3. **We set clear milestones and targets** (as per the roadmap above) to scale from pilot to commercial and export readiness by 2047.
4. **Develop standards, certification, and reliability protocols** specifically for perovskite modules, and encourage on-ground demonstration projects to build trust among utilities and investors.
5. **Prioritize sustainability and circular economy** in the design and deployment phases. It is crucial to prioritize the use of lead-free materials, implement recycling strategies, ensure the recovery of modules at the end of their life cycle, and conduct comprehensive life cycle assessments.
6. **Integrate perovskite PV into India's broader solar and energy storage ecosystem**, utilizing it in rooftop installations, remote or off-grid settings, Building-Integrated Photovoltaics (BIPV), and tandem applications to optimize the impact.
7. **Export orientation:** India is not merely a domestic consumer of perovskite photovoltaic technology but a global manufacturing and export hub targeting sunshine-abundant developing nations.

In conclusion, perovskite photovoltaics do not merely represent incremental advancements over silicon-based technologies; rather, they signify a paradigm shift. If India acts decisively and strategically within the next decade, it can achieve solar independence, foster low-carbon economic growth, and establish a robust new manufacturing sector. Consequently, the vision of a developed clean-energy-powered India by 2047 becomes significantly more attainable.

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