INDIA'S PV MANUFACTURING AND ITS STRATEGIC INFLECTION POINTS

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The Energy and Resources Institute
Creating Innovative Solutions for a Sustainable Future

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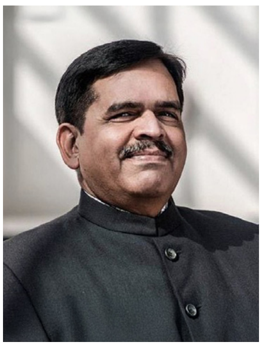
FOREWORD



India today stands at a pivotal juncture where economic aspirations, technological capability, and national self-reliance must converge to shape the future of the pathway of development. As a nation committed to broad-based growth rooted in resilience and equity, it is imperative that we build robust domestic capacities in sectors that will define the global economy of tomorrow. The photovoltaic (PV) industry is undoubtedly one such sector, one that sits at the heart of our ambition for clean energy leadership, strategic autonomy, and sustainable industrialization.

Over the past decade, the rapid expansion of India's solar deployment has demonstrated both our institutional will and the public's confidence in a renewable energy transition. Yet, as this report persuasively highlights, the true measure of long-term success lies not only in expanding installed capacity but in strengthening the upstream manufacturing ecosystem that underpins it. The ability to produce polysilicon, ingots, wafers, and high-efficiency cells at globally competitive cost and quality is no longer a peripheral aspiration; it is central to our economic sovereignty, energy security, and technological leadership.

As India accelerates towards a low-carbon, inclusive, and globally competitive economic model, the insights presented here reinforce a crucial point—domestic PV manufacturing is not simply an industrial strategy, but a developmental imperative. By nurturing indigenous capabilities, we not only shield our economy from external shocks but also create high-value employment, foster deep technological innovation, and enable a more secure and sustainable energy transition for households, enterprises, and communities across the country.

I am confident that the recommendations in this report will stimulate meaningful deliberation among policymakers, industry leaders, researchers, and civil society. More importantly, I hope they inspire unified action to convert these strategic opportunities into enduring strengths. A vibrant, self-reliant, and future-ready solar manufacturing ecosystem, aligned with the National Manufacturing Mission and anchored in the strategic importance of clean-tech manufacturing, will be instrumental in realizing India's vision of emerging as a global leader, not only in solar deployment, but in the science, innovation, and industrial enterprise that power it.

Dr Ashwani Mahajan
Member, Board of Governors, Council For International Economic Understanding (CIEU) & National Co-Convenor, Swadeshi Jagran Manch (SJM) , President, Bharat Climate Forum

FOREWORD

At TERI, our mission is to usher in transition to a cleaner and sustainable future through the conservation and efficient use of energy and other resources, and by developing innovative ways of minimizing and reusing waste. Driven by this mission, we carry out evidence-based research and build sustainable solutions. Needless to mention, the rapid evolution of India's photovoltaic sector is one of the most critical arenas where economic progress, energy access, and environmental stewardship intersect. In this regard, our collective resolve to embrace clean energy is worth highlighting, which is evident from the fact that India's solar capacity has grown more than tenfold over the past decade.

Yet, as this paper compellingly argues, the real strategic inflection lies upstream in the capacity to manufacture cells, ingots/wafers, and polysilicon at scale, with competitive cost and high quality. Strengthening domestic PV manufacturing is not merely an industrial objective but an imperative for economic growth; it is central to our energy security, our ability to meet climate commitments, and our ambition to drive a green industrial revolution.

This paper delineates the drivers of our current manufacturing gap, emerging opportunities, cutting-edge technologies, innovative policy instruments, and the promise of clustering and skill development initiatives in solar manufacturing hubs.

As we chart India's next phase of solar transition, it is essential that our strategies align with the twin goals of low-carbon growth and inclusive prosperity. Deepening our domestic PV manufacturing capacity will not only protect us against global supply-chain volatility but also create high-value jobs, strengthen technological innovation ecosystems, and accelerate the deployment of solar across urban and rural India.

I am confident that the insights and proposed recommendations in this paper will evoke robust dialogue and, more importantly, drive the concerted efforts needed to transform these strategic inflection points into sustained lines of growth. TERI stands ready to collaborate with all stakeholders in realizing this vision and co-create efficient alternatives where India emerges not only as a solar champion in capacity deployment but also as a leader in sustainable photovoltaic manufacturing innovation.

Dr Vibha Dhawan

Director General
The Energy and Resources Institute (TERI)

LIST OF ABBREVIATIONS

ADB	Asian Development Bank
AI	Artificial Intelligence
AIIB	Asian Infrastructure Investment Bank
ALD	Atomic Layer Deposition
ALMM	Approved List of Models and Manufacturers
BIS	Bureau of Indian Standards
BCD	Basic Customs Duty
BEL	Bharat Electronics Ltd
BHEL	Bharat Heavy Electricals Ltd
C&F (CIF)	Cost, Insurance, and Freight
CAPEX	Capital Expenditure
CBAM	Carbon Border Adjustment Mechanism
CBIC	Central Board of Indirect Taxes and Customs
CEA	Central Electricity Authority
CIGS	Copper Indium Gallium Selenide
CPCB	Central Pollution Control Board
CNY	Chinese Yuan (currency code)
DOE	Department of Energy (US)
DST	Department of Science & Technology
DPP	Digital Product Passports
DSS	Directional Solidification System (ingot- growth furnace)
EHS	Environment, Health & Safety
EPEAT	Electronic Product Environmental Assessment Tool
EPR	Extended Producer Responsibility
ERP	Enterprise Resource Planning
EVA	Ethylene Vinyl Acetate
EU	European Union
FIH	Freight, Insurance, and Handling
FOB	Free On Board
FY	Financial Year
GBI	Green Bonds Initiative
GCL	GCL Technology Holdings Ltd (equipment OEM)
GeM	Government e-Marketplace
GHG	Greenhouse Gas
GST	Goods and Services Tax
GW	Gigawatt
HF	Hydrofluoric acid
HJT	Heterojunction Technology

HHV	Hind High Vacuum (pilot-scale furnace OEM)
IBC	Interdigitated Back Contact
IFC	International Finance Corporation
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IIT	Indian Institute of Technology
INR	Indian Rupee
IRR	Internal Rate of Return
IRA	Inflation Reduction Act (USA)
ISMA	Indian Solar Manufacturers Association
ITRPV	International Technology Roadmap for Photovoltaic
kW	Kilowatt
$kgCO_2e/kWp$	Kilogram CO_2-equivalent per kilowatt-peak
LCOE	Levelized Cost of Electricity
LCD	Least-Cost Deployment
MeitY	Ministry of Electronics and Information Technology
MES	Manufacturing Execution Systems
MNRE	Ministry of New and Renewable Energy
MSIPS	Modified Special Incentive Package Scheme
NABL	National Accreditation Board for Testing and Calibration Laboratories
NISE	National Institute of Solar Energy
NREL	National Renewable Energy Laboratory
OEM	Original Equipment Manufacturer
ONDC	Open Network for Digital Commerce
OPEX	Operating Expenditure
PERC	Passivated Emitter and Rear Cell
PLI	Production-Linked Incentive
PPA	Power Purchase Agreement
PSU	Public Sector Undertaking
PV	Photovoltaic
PVPS	Photovoltaic Power Systems Programme
QA	Quality Assurance
QR code	Quick-Response code
R&D	Research and Development
RBI	Reserve Bank of India
SEIA	Solar Energy Industries Association
SEZ	Special Economic Zone
SME	Small and Medium-sized Enterprises
SSI	Solar Stewardship Initiative
TOPCon	Tunnel Oxide Passivated Contact

EXECUTIVE SUMMARY

EXECUTIVE SUMMARY

1. Strategic Context

This discussion paper, India's PV Manufacturing & Its Strategic Inflection Points, examines a pivotal moment in India's solar journey. By late 2025, global photovoltaic (PV) production capacity will hit 1.8 terawatts (TW), with over 80% concentrated in China. India has multiplied its solar installations tenfold in the past decade, yet its imports nearly all upstream essentials 98% of wafers and 100% of polysilicon. Rising demand, from 37 gigawatts (GWac) annually to 39 GWac by 2032, pairs with supportive policies like the Production-Linked Incentive (PLI) scheme and import duties, alongside advances in cell technologies such as TOPCon and heterojunction technology (HJT). These forces create a strategic inflection point—Can India build a robust, cost-effective, and sustainable manufacturing ecosystem to secure its energy future?

2. Core Questions the Paper Sets Out to Answer

1. Where does India stand across the PV value chain?
2. How large is the demand–supply deficit likely to be by 2030?
3. Which technology and equipment barriers hinder scaling?
4. What policies can bridge these divides effectively?
5. How can environmental, social, and governance (ESG) standards, circular practices, and traceability be woven in to sustain exports?
6. What strategies for workforce, funding, and clusters will fuel growth while promoting equity?

3. Key Highlights and Evidence

3.1 Capacity Realities: Strong Modules, Fragile Foundations

India has secured dominance in modules, with 144 GW annual capacity from over 130+ producers outpacing current demand of 54 GW_{dc}. However, cells lag at 35 GW/year shortfall (meeting ~81% of 2025 needs and facing a ~24 GW_{dc}/year shortfall), wafers and ingots stand at a mere 2 GW (with a looming 52 GW_{dc}), and polysilicon production is non-existent, requiring 54 GW_{dc} equivalents yearly by 2030. This upstream vulnerability risks derailing India's solar leadership, turning module wins into strategic losses.

3.2 Equipment Bottlenecks: The Hidden Constraint

Over 90% of vital upstream tools, like Siemens reactors, ingot furnaces, diamond-wire saws, and PECVD/ALD systems are imported, with Chinese firms controlling module assembly lines. Indian players, such as HHV and Cliantech on the other hand, offer only basic alternatives. This reliance amplifies foreign exchange risks, supply disruptions, and geopolitical tensions, especially in capital-heavy stages. Without targeted incentives and R&D, toolchains will remain the sector's silent saboteur.

3.3 Policy Momentum: Building Blocks in Place, Gaps Ahead

Central initiatives like PLI for efficient modules, basic customs duties, the approved list of models and manufacturers (ALMM), and state incentives are channelling investments. Yet, mismatched timelines and absent equipment-specific support threaten upstream progress, underscoring the need for aligned, forward-looking reforms.

3.4 ESG, Circularity, and Traceability: Essential for Global Access

Crystalline-silicon production yields tonnes of silicon kerf, chemical waste, and packaging scraps per module. Embracing circular recovery and blockchain-enabled tracking via QR-coded ALMM and digital passports is imperative amid US forced-labour audits and EU carbon border adjustments. These are not add-ons but enablers, transforming compliance into an export advantage for low-carbon, traceable Indian products.

3.5 Clusters and Talent: Engines of Distinction

Hubs in Gujarat, Tamil Nadu, Telangana, Karnataka, Maharashtra, and Rajasthan already have ports, talent, and incentives, but scaling to 280 GW modules and 171 GW cells will require a step-change in skilled manpower. Build Solar Semicon Technology Parks with open-access pilot lines (TOPCon, HJT, tandems), clean rooms, and reliability/testing labs, run by industry–research consortia, so qualification, training, and scale-up trials happen alongside factory build-out. Create a dedicated Skill Council that ties incentives to apprenticeships and delivers a 30% women workforce by 2030..

4. Recommendations Tailored for Decision-makers

4.1 Cohesive Policy Framework

- Extend ALMM upstream: Retain for modules, mandate cells by 2026, wafers/polysilicon by 2028–30 to signal market intent.
- To manage tariff impact, ring-fence the cell and upstream ALMM transition to government/PSU procurement or a capped annual tranche while allowing open-access and competitively tendered private projects to keep sourcing least-cost modules during the scale-up.
- Align tariffs to milestones: Hold 20% cell duties until supply matches demand, then phase down to curb cost spikes.
- Introduce PLI-Equipment: Incentives for local toolmakers, echoing module support.

4.2 Funding and Risk Mitigation

Blend sovereign green bonds, multilateral funds, and partial guarantees to drop upstream capital costs to 4–5%, paired with viability-gap aid for low-carbon polysilicon plants, making ambitious fabs financially viable against global rivals.

4.3 Talent and Equity Focus

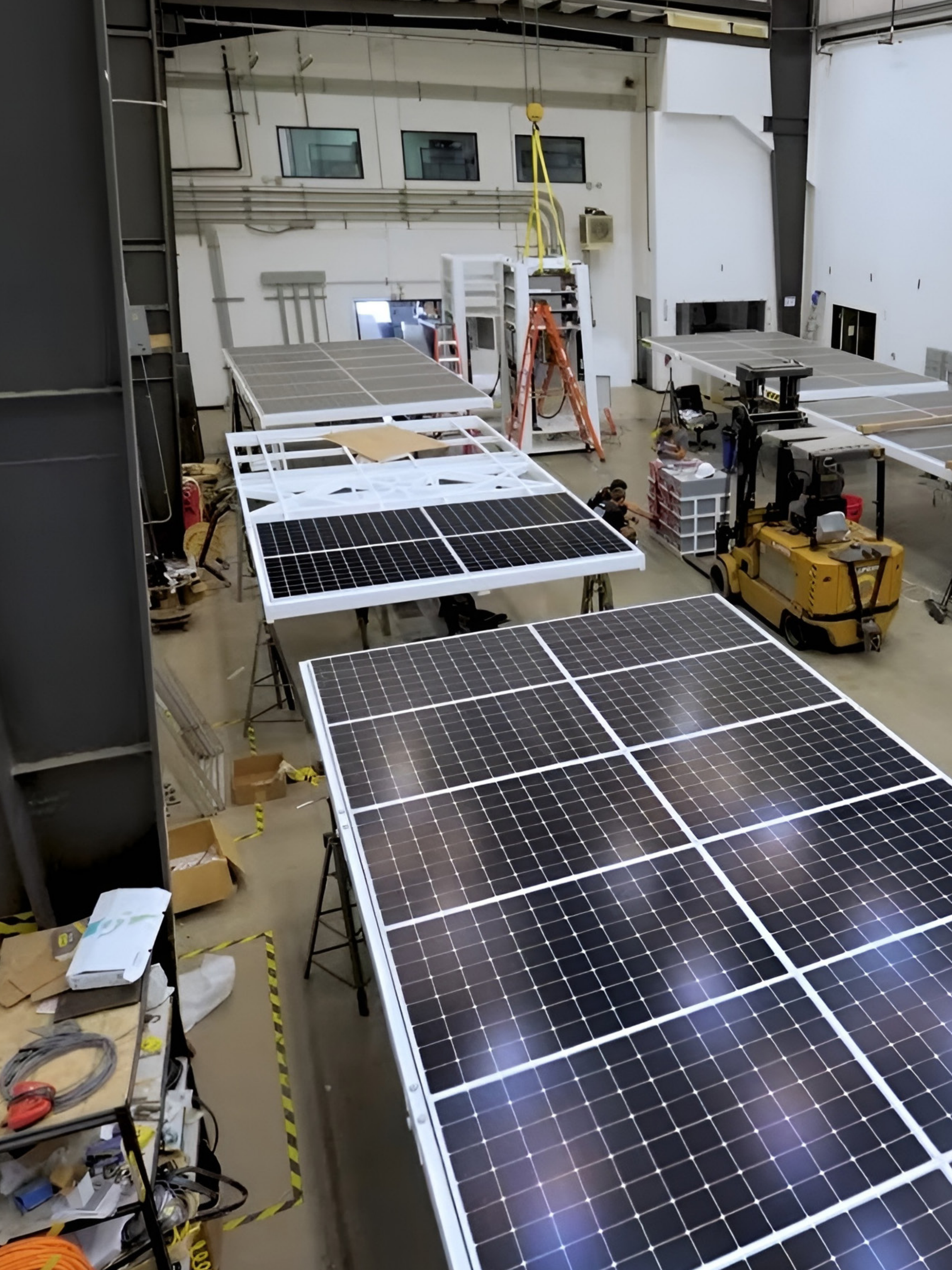
Form a PV-Semiconductor Skill Council with a decade-long training plan; tie PLI releases to apprenticeship and progressive targets for ≥30% women in roles by 2030.

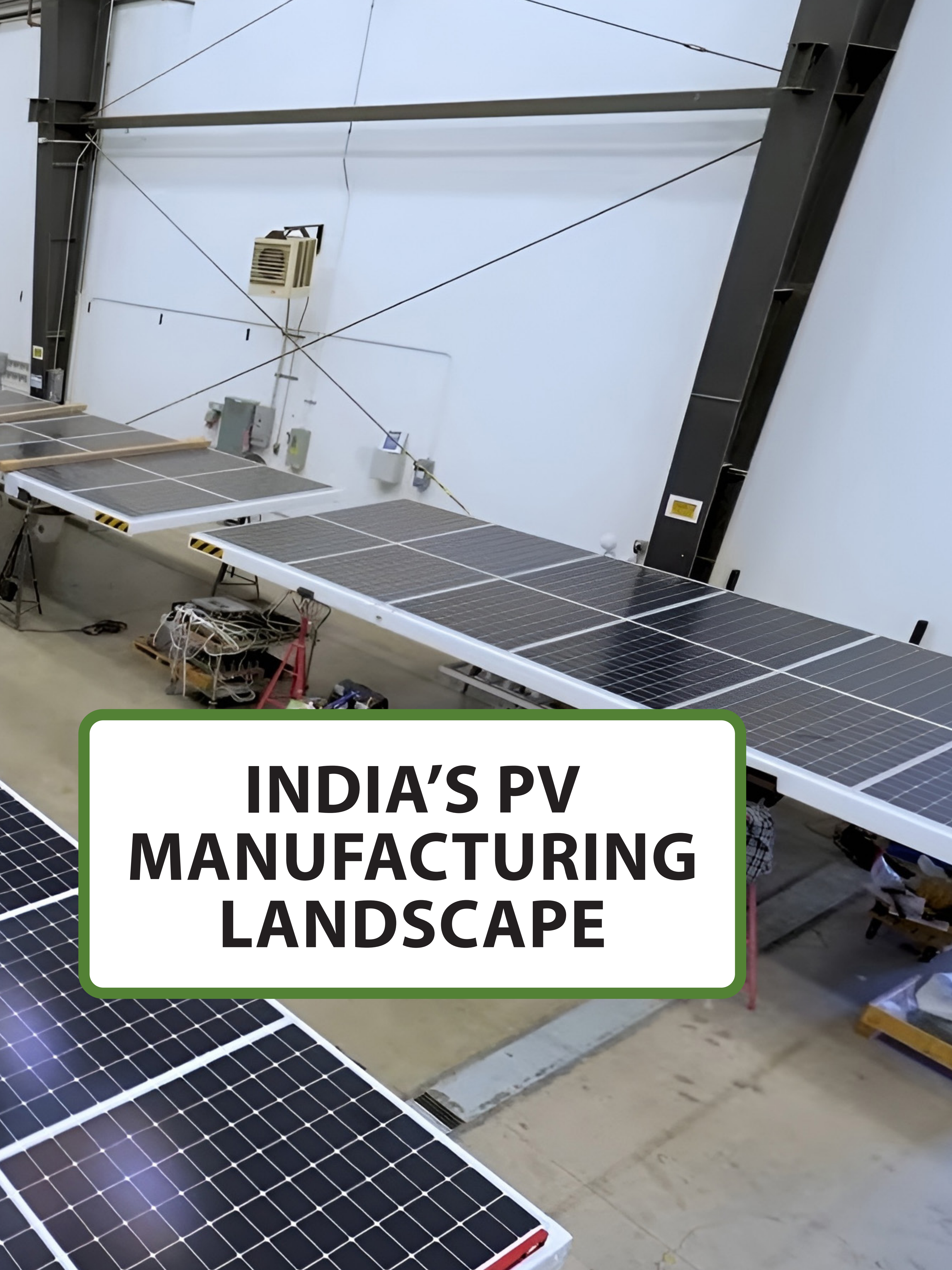
4.4 Oversight Mechanisms

Launch biennial reviews by the Ministry of New and Renewable Energy (MNRE), Ministry of Finance (MoF), and industry to adjust tariffs, PLI allocations, and ESG benchmarks based on actual capacity and market shifts.

5. Conclusion

India stands poised to evolve from gigawatt buyer to gigawatt maker throughout the value chain by 2030, if upstream integration, equipment self-reliance, ESG embedding, and skilled ecosystems take root. The proposed policies and financing tools would slash wafer and polysilicon imports, spawn jobs, and elevate Made-in-India modules as trusted players in US and EU-driven markets. For policymakers at home and abroad, the imperative is evident—this manufacturing resurgence is achievable, cost-effective, and strategically vital.




INDIA’S PV
MANUFACTURING
LANDSCAPE

Chapter 1

INDIA'S PV MANUFACTURING LANDSCAPE

1.1. Overview of India's PV Landscape

1.1.1. The Backdrop of Global Dynamics in the Solar Power Value Chain

The global photovoltaic (PV) industry has witnessed a remarkable evolution. The world's total cumulative PV installed capacity was at an impressive 2.2 terawatt (TW) at the end of 2024.[1] This growth is supported by the projected end-of-2025 figures, where the global PV module manufacturing capacity will reach 1.8 TW, with a staggering 80% of this capacity concentrated in China which includes the entire spectrum of the manufacturing process, polysilicon, ingots, wafers, cells, and modules as shown in Table 1.1.[2] China's supremacy is driven by vertically integrated supply chains, substantial economies of scale, and access to affordable renewable energy (RE), enabling cost efficiencies that remain unmatched by competing markets. In response to this monopoly, the US and the European Union have introduced policies to reduce reliance on Chinese imports. The US's Inflation Reduction Act (IRA) and the EU's Green Deal aim to bolster domestic production while incentivizing investment in innovative solar technologies. These initiatives highlight a growing global keenness to reshape the PV manufacturing landscape by fostering regional self-reliance and innovation. For countries such as India, this dynamic presents both a challenge and an opportunity. The confluence of China's dominance, coupled with intensifying competition and geopolitical risks, underscores the need for India to localize its solar manufacturing capabilities. By capitalizing on its growing manufacturing capabilities, abundant human resources and policy initiatives such as the Production-Linked Incentive (PLI) scheme, India has the potential to emerge as a cost-competitive and reliable alternative in the global market. However, realizing this potential would require addressing structural supply chain gaps, investing in advanced manufacturing technologies, and ensuring consistent policy and financial support to build a robust and self-sufficient solar ecosystem capable of meeting domestic and international needs.

TABLE 1.1 Market share of top PV manufacturing countries[3]

Top PV Manufacturing Countries Market Share (%)				
Country	**Module**	**Cells**	**Wafers**	**Polysilicon**
China	84.6	91.8	98	92
Vietnam	3.4	1.7	2	0
India	2.7	0.5	0	0
Thailand	2.3	0.6	0	0
USA	2.2	0.8	0	2
Malaysia	2.1	2.3	0	2
Germany	0	0	0	4
Rest of the world	2.6	2.0	0	0

1.1.2. India's Solar Manufacturing Value Chain

India is undergoing a solar manufacturing renaissance, rapidly transitioning from deep import dependence to building a more comprehensive domestic PV supply chain. As shown in Figure 1.1, India's FY 2025 manufacturing landscape is anchored by a strong downstream segment, module assembly capacity has reached nearly 120 GW/year, a substantial increase in recent years.[4] This expansion has been driven by supportive policies such as production-linked incentives (PLIs), high import tariffs on finished panels, and approved list of models and manufacturers (ALMM) creating a robust domestic demand for solar installations. Figure 1.2 captures the next phase of ambition where by 2030, India's module manufacturing capacity is projected to surpass 280 GW/year, with solar cell fabrication capacity rising from ~30 GW currently to about 171 GW/year.

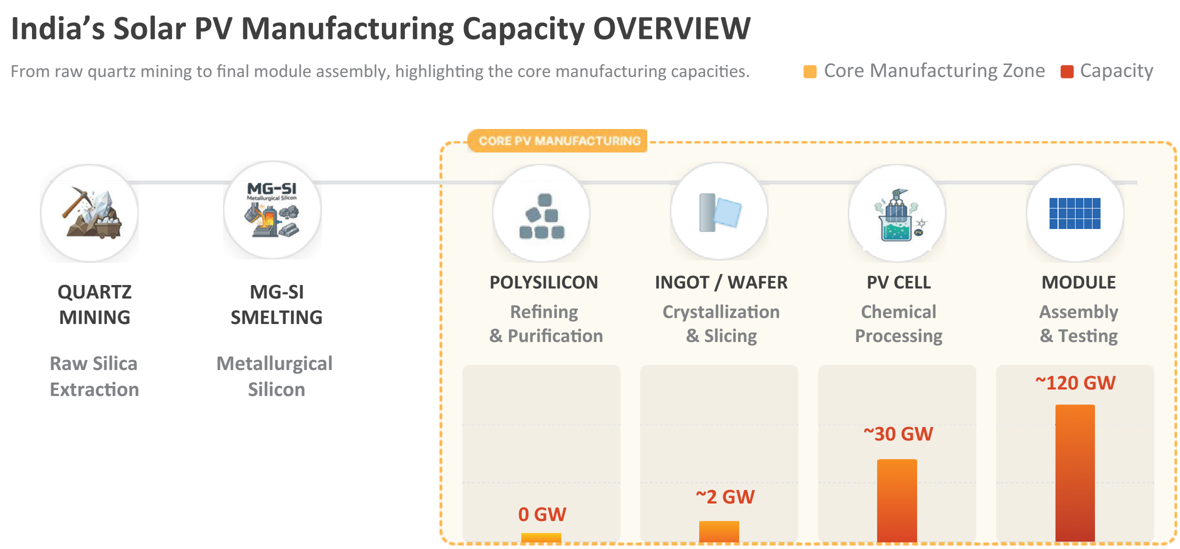


FIGURE 1.1 India's solar PV manufacturing (2025) capacity overview [6,7,8]

However, upstream segments remain nascent, wafer/ingot capacity is only about 2 GW today with no commercial-scale polysilicon production in India as of 2025, which explains why a material share of domestic modules remains dependent on imported cells and upstream materials. If India scales module manufacturing toward ~280 GW/year by 2030, utilisation will depend on predictable domestic installations rather than capacity announcements alone; sustained domestic absorption will boost manufacturer confidence to invest at scale.

The same constraint extends beyond silicon into balance-of-materials. The MNRE has flagged that domestic capacity is only approximately 15 GW/year for solar glass and around 17 GW/year for aluminium frames, levels that could become binding as module utilization rises, pushing manufacturers and developers back into import channels for critical inputs.[5] From a system-cost perspective, the quickest lever to reduce import exposure without raising tariffs remains the module and cell segment, because it represents the largest single equipment line-item in a utility-scale solar plant and therefore dominates near-term value-add, jobs, and bankability. At benchmark utility-scale capital costs typically cited in the ₹3.5–4.5 crore/MW range, policy calibration must balance manufacturing scale-up with delivered electricity affordability for industry and consumers.

The industry structure is bifurcating: the module assembly segment is highly fragmented with 129+ firms, while the cell manufacturing is more consolidated, as the top 10 manufacturers account for almost 100% of India's cell output. India's first meaningful move into upstream integration by Adani Solar commenced India's first large-scale ingot and wafer plant (2 GW capacity in Gujarat) in early 2024. This marks the first step towards an integrated supply chain. Polysilicon (solar-grade silicon)

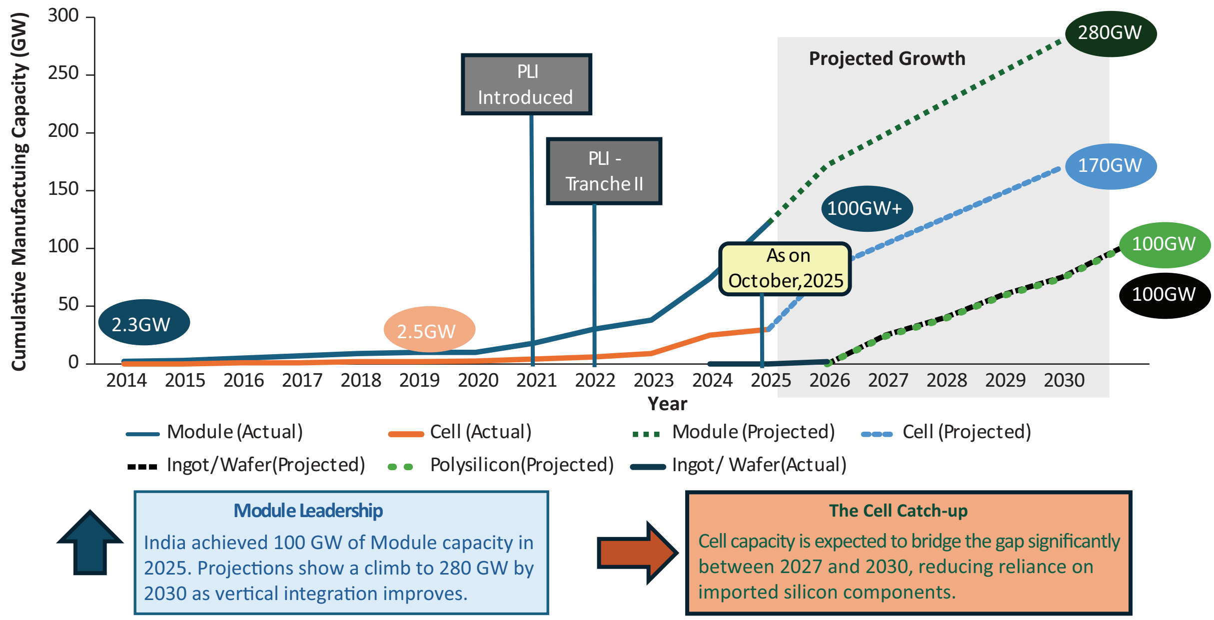


FIGURE 1.2. India's PV manufacturing projected growth

Source: Author's analysis and projections based on published manufacturing capacity data, policy announcements, and industry benchmarks. [10, 11, 12]

remains the critical missing link with several projects in the pipeline to close this gap (including new polysilicon plants by 2027–2028), with analysts projecting up to ~100 GW worth of polysilicon capacity (tens of thousands of tonnes annually) could be in place by 2030.[9] India now has the foundations of a large domestic module industry, but the competitiveness and resilience of this expansion will be determined by how quickly cells, upstream silicon, and the ancillary ecosystem scale in parallel. For manufacturers, this is where margin durability will be won; for lenders and policymakers, this is where the next tranche of risk and opportunity sits.

1.1.3. Geographical Clusters

India's emerging PV manufacturing is concentrated in a few key states. Gujarat has become a major hub; expanding solar manufacturing ecosystem located at Mundra and Jamnagar in Gujarat's coastal Special Economic Zone (SEZ), and the state is attracting other integrated facilities (including planned fabrication facility (fabs) at Dholera SEZ). In the south, Tamil Nadu hosts new module factories notably a 3.3 GW thin-film module plant and has a strong electronics manufacturing base supporting solar. Telangana and Karnataka have also developed clusters around Hyderabad and Bengaluru, respectively, these host cell/module plants are operated by firms like Premier Energies and Tata Power Solar. Maharashtra and Rajasthan have several module assembly units as well. Many of these facilities are in SEZs or industrial parks, benefitting from infrastructure and tax incentives for exporters. Figure 1.3 shows India's PV manufacturing footprint, a corridor of activity spanning Western India (Gujarat, Rajasthan, Uttar Pradesh), Southern India (Tamil Nadu, Karnataka, Telangana), and to a lesser extent northern states, aligning with states that offer investor-friendly policies and reliable power for energy-intensive manufacturing. This geographic clustering reflects the availability of ports (for importing raw materials and exporting modules), skilled workforce, and state-level incentives (discussed in Section 1.4) that these regions provide.

1.2. Demand-Supply Scenario

India's ambitious solar installation targets pose a demand–supply gap across the value chain. Annual solar PV demand is surging, India is on track to install solar generation capacity (new deployments) of the order of 35 GW in 2025, and the annual demand could increase to ~52 GW/year by 2032 to meet the nation's solar energy goals.[14,15] The National Electricity

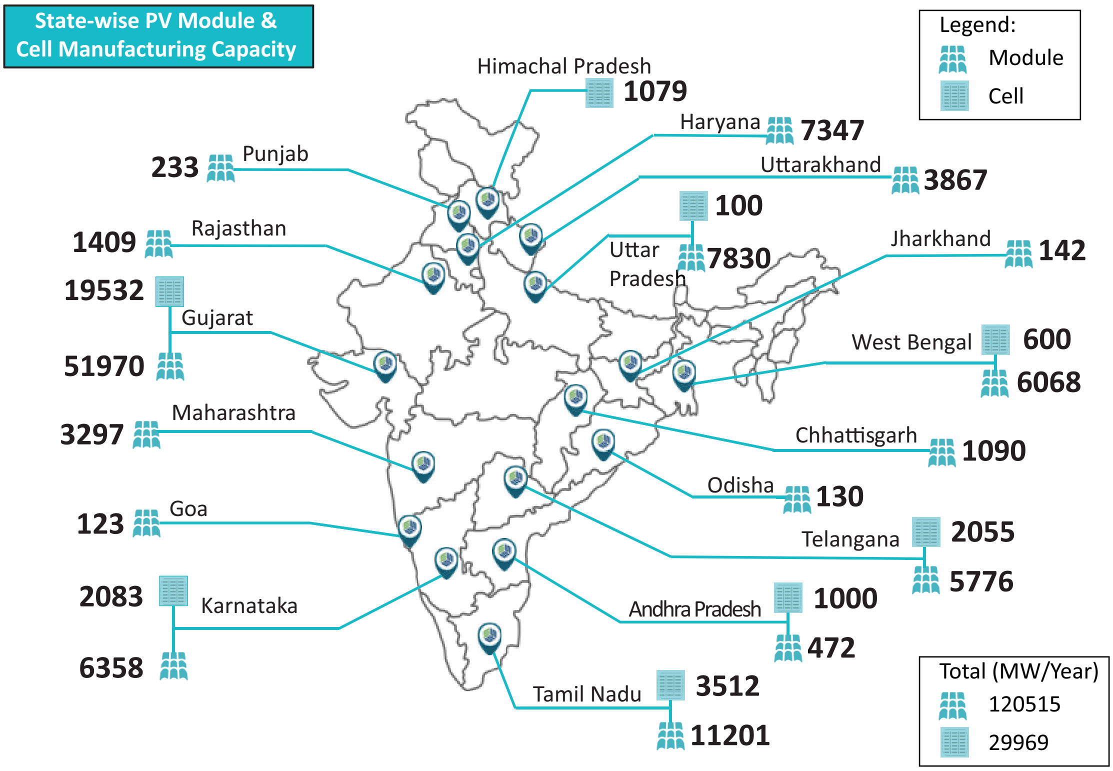


FIGURE 1.3 State-wise module and cell manufacturing capacity as of Oct 2025 (in MW) [4, 13]

Source: Author's analysis and compilation based on ALMM List I & II as of Oct 2025

Generation Plan (Volume 1) envisions total installed solar capacity of roughly ~280 GW by 2030 and ~365 GW by 2032, the current (November 2025) installed capacity is more than 132 GW implying an average addition of ~37 GW/year to meet 2030 target. Table 1.2 presents the domestic production capacity versus the solar installation 2030 demand for PV value chain, illustrating where India faces shortfalls.

As seen in Table 1.2, the module assembly capacity already exceeds current demand, India can theoretically produce far more modules than it installs domestically. In 2025, nameplate module capacity (120 GW) is already more than double the expected installations (~37 GW) by 2030, signalling that the overcapacity at the module stage in the next five years or so, can cater to export markets. India's cell production capacity (~30 GW) is just about enough to meet current module demand, but in practice many module lines still import cells due to technical or quality gaps. The shortfall is more acute for silicon wafers with only ~2 GW local wafer production capacity as against the requirement of ~37 GW; over 90% of wafers (and virtually 100% of polysilicon feedstock) must be imported. This reliance is primarily on China, which supplies ~95% of the world's wafers and polysilicon. Without rapid upstream investment, the supply–demand gap for these inputs will widen as installation volumes grow.

Closing this gap will require large capital expenditures for vertical integration. Manufacturing polysilicon and wafers is capital-intensive, with long lead times and high technological barriers. Industry estimates suggest setting up a modern integrated polysilicon–wafer–cell production facilities can cost approximately $150–$350 million per GW of annual capacity depending on the technology used.[16,17] Fully integrated polysilicon-to-module facilities may range from $200–$400 million per GW, reflecting additional module production costs and India-specific infrastructure challenges.[7,17] To achieve an additional 30–40 GW of upstream capacity (cells, wafers, polysilicon) by 2030, tens of billions of dollars will need to be

TABLE 1.2. Domestic supply vs demand for PV value chain

PV Value Chain	Current Manufacturing Capacity (GW/year)	Demand for 2030 (GW/year)	Surplus/ Deficit (-) (GW)/year	Supply–Demand Gap Analysis
Module	144	~54	90	Surplus, various export channel needs to be explored
Cell	30	~54	-24	With current planned capacities, the import reliance will be reduced
Ingots/Wafers	2	~54	-52	90 % of wafers still need to be imported; at least 30 GW of new slicing capacity is required before 2028.
Polysilicon	0	~54	-54	100 % reliance on foreign supply (chiefly China). Two announced mega-poly plants (Adani, Reliance) must be commissioned on time.

Source: Author's analysis and compilation based on current manufacturing capacity announcements, policy targets, and secondary literature on India's solar PV deployment outlook. Using the CEA NEP Assumption of 1.45 MWdc per 1 MWac

Note: Demand is approximated by annual solar installations (for modules) or the equivalent upstream material needed for those modules. For instance, ~1 GW of modules requires roughly 1 GW of cells, ~1 GW of wafers, and ~2,000–3,000 tonnes of polysilicon. All the values in Table 1.2 are in GWdc.

invested by the industry over the next few years. This not only includes the development of production facilities but also securing technology (See Appendix-A for detailed breakdown of Capex for 10 GW Plant).

1.3. Emerging Global Demand and India's Export Opportunity

India's export opportunity in solar modules is shaped as much by relative cost competitiveness as by global demand growth. While India's solar PV manufacturing capacity is ramping up, Chinese firms still enjoy significant cost advantages from scale, supply chain integration, and cheaper capital. As of 2024, a Chinese module (mono PERC or TOPCon) could be produced at ~$0.20 per watt (W) or lower, whereas Indian modules are available at 20–30% higher costs (estimated in the ~$0.24–$0.26 per W range). This cost 'disability' for Indian modules stems from factors like higher raw material costs (since wafers/cells are imported), higher financing costs, and slightly lower operational efficiencies.[18] This combination of rapid demand growth and ultra-low pricing has fragmented the export landscape into two distinct market types. The first is price-led procurement, where the lowest delivered cost wins. The second is policy-shaped procurement, where trade remedies, local-content rules, and supply-chain compliance requirements constrain access for Chinese-origin components and create limited but attractive 'China-constrained' pockets. Italy's first auction restricted to non-Chinese equipment awarded over 1.1 GW, illustrating how such tenders can create pockets of bankable demand for alternative suppliers across Europe.[19]

This evolving structure has direct implications for India's export economics as Indian modules arrive in overseas markets at a higher landed cost considering freight and tariffs. The practical consequence is that India is unlikely to displace China in fully open, price-clearing markets on cost alone. Instead, India's competitive space is most credible where buyers value, or are required to diversify the supply chain, and where factors such as traceability, delivery assurance, and compliance reduce the weight of pure price competition. Table 1.3 captures this market-by-market reality by comparing prevailing import barriers and typical landed-cost of modules. Table 1.4 links these price realities to where demand growth is most likely to translate into bankable export volume for India. The key insight is that 'large demand' does not automatically equal 'high opportunity'. Recent trade outcomes reinforce this segmentation. India's PV module exports have been highly concentrated in the U.S.

market, with multiple analyses reporting that the U.S. absorbed roughly ~97% (or more) of India's module export value in FY2023–FY2025, leaving limited evidence of diversified pull in other price-clearing regions. At the same time, changes in U.S. tariff conditions have increased volatility and reduced the reliability of the U.S. as a volume sink, prompting some Indian manufacturers to publicly reassess export prioritisation. The strategic implication is that Africa, the Middle East and Latin America should be treated as selective destinations under commodity pricing. Such regions with fast growth but fully open access to ultra-low-priced Chinese supply will remain difficult for Indian modules unless India competes through a different lever, such as tied financing, differentiated quality and warranties, or structured partnerships to compete sustainably at today's global price floor.

TABLE 1.3 Module cost competitiveness and tariffs for export markets[20,21]

Market	Import Tariffs on Modules	Typical Landed Cost – Chinese vs Indian Module (2024)	Remarks
USA	Section 201 safeguard tariff of 14% (Feb 2025–Feb 2026) remains a baseline duty on modules, alongside a complex and tightening trade-remedy environment. In addition, the US imposed up to 50% tariffs on most exports from India, which took effect August 27, 2025, materially worsening India's price position in the US.	Chinese module: ~$0.26-0.28/W (with tariffs via Southeast Asia) Indian module: ~$0.30–0.35/W (with freight, any applicable duty)	The US remains the single largest premium destination, but it is now high-risk and margin-compressive for India because tariffs and scrutiny can change landed economics quickly. The strategic role of the US is shifting from 'growth engine' to 'selective outlet' for only the most compliant, fully traceable, contract-secured volumes.
Europe	0% standard import duty on modules; competitiveness is driven by price and bankability. However, policy-led non-Chinese tenders are emerging in pockets. This creates small but expanding 'policy premium' segments.	Chinese module: ~$0.084–0.088/W (delivered/CIF Europe) Indian module: ~$0.12–0.13/W (indicative) where India assembles using imported cells	Europe is an open, price-led market at today's benchmark levels. Opportunity for India is concentrated in policy-screened tenders and buyers with explicit diversification goals, rather than commodity spot procurement.
Africa	Varies by country (generally low import duties or none under the trade agreements), with many markets relying on concessional finance and donor-backed procurement; price sensitivity remains high.	Chinese module: ~$0.22–0.25/W (FOB Asia + transport) Indian module: ~$0.24–0.30/W (FOB India + transport)	African nations typically import most of the modules. China currently dominates African supply due to lower costs. Indian panels are geographically closer to East Africa, backed by India's export credit lines, but cost sensitivity is high in this market.

Market	Import Tariffs on Modules	Typical Landed Cost – Chinese vs Indian Module (2024)	Remarks
Middle East	Procurement is largely driven by utility-scale auctions where bankability and lowest costs prevail, keeping prices highly competitive. Gulf Cooperation Council (GCC) markets apply low or zero import duties, although some countries, such as Saudi Arabia, are beginning to introduce local-content requirements.	Chinese module: ~$0.085–0.090/W; Indian module: ~$0.11–0.13/W (indicative) using reported India cost for Indian-assembled modules (when cells are imported)	Middle-eastern utility auctions offer large scale but generally do not provide a price cushion, which means Indian exporters must compete through strategic EPC partnerships, bundled financing, or stronger compliance and delivery assurances rather than commodity pricing alone. The region continues to grow rapidly with mega-scale solar parks, and Gulf countries currently source heavily from China, supported by financing linked to the Belt and Road Initiative (BRI). While this creates strong price competition for Indian manufacturers, opportunities can still emerge where political relationships, reliability, and service quality influence procurement decisions.
Latin America	Tariff-light in several markets; procurement driven by auction pricing and access to low-cost financing; trade measures vary by country.	Chinese module: ~$0.08–0.09/W Indicative Indian module: ~$0.12–0.13/W	Strong growth potential, but the market clears on LCOE. India's realistic entry point is premium bankability, faster delivery for specific buyers, or tied financing (EXIM/LoC-style structures) rather than pure price competition.

Source: Author's analysis and compilation based on trade policy notifications, market price benchmarks, freight and tariff assumptions, and secondary literature on global solar PV trade.

Note: Typical landed cost is expressed in $/W for utility-scale, Tier-1 TOPCon/bifacial modules and represents indicative delivered pricing. Where published benchmarks are available, US values reflect delivered price references reported by OPIS/pv magazine and InfoLink. For Europe, Latin America and the Middle East, the China-linked values reflect prevailing regional spot price levels, while the India-linked ranges are indicative and derived using publicly reported India–China cost premiums for India-assembled modules (often using imported cells) relative to China-made equivalents, as reported by Reuters, applied to regional benchmarks. Actual landed prices can vary meaningfully with shipment size, technology and specification, warranty/bankability requirements, trade and compliance treatment (including rules-of-origin documentation), and contract structure. Freight, insurance and handling can shift delivered prices by several cents per watt. CIF (Cost, Insurance, and Freight), FOB (Free on Board).

TABLE 1.4 Emerging global solar PV demand (selected regions) and India's opportunity[22,23,24,25]

Region	Projected Solar Installations (GW)	Drivers of Demand	India's Export Opportunity
United States	739 GW total by 2035	Utility-scale buildout, corporate procurement, and system electrification, with rising emphasis on supply-chain security	High – Large market, but higher tariff and compliance uncertainty Opportunity is strongest in structured, compliance-clean supply contracts and in segments where buyers need diversification beyond SEA routing.
European Union	~750 GW total by 2030	Climate targets, electrification, and energy security, alongside subsidy reforms and tighter project economics in distributed solar	Moderate and policy-led – EU is open market but very price-sensitive. Indian firms need to offer low-cost, low-carbon products. Opportunities to partner under EU's solar initiatives or export to countries with lower tariffs.

Region	Projected Solar Installations (GW)	Drivers of Demand	India's Export Opportunity
Africa	~125 GW total by 2030	Electrification, falling PV costs, international funding for clean energy (e.g., World Bank, ISA initiatives)	Moderate – Indian government-backed projects can use Indian modules (Line of Credit programmes). Private market being cost-driven, Indian manufacturers' competition with Chinese firms will be on pricing. Proximity to African markets (especially, East Africa) is an advantage.
Middle East	~100 GW total by 2030 (Gulf and Middle East)	Economic diversification (solar for oil exporters), very high solar potential and ambitious giga-projects (Saudi Arabia, UAE, etc.)	Selective/Niche – Scale procurement is unforgiving on price. Opportunities improve through partnerships, local presence, and turnkey reliability guarantees. Indian modules proven in hot climates can be a selling point.
Latin America	Annual PV demand projected to rise to ~46.7–54.8 GW by 2030	Competitive auctions, merchant renewables for C&I, and strong resource quality in major markets	Moderate – Growth is real, but the clearing price is highly competitive. India's best route is tied financing, bankability-led buyers, and delivery reliability rather than spot price competition.

Source: *Author's analysis and compilation based on regional solar deployment projections, policy targets, and secondary literature on global renewable energy markets.*
Note: US outlook is from SEIA's Solar Market Insight Executive Summary (2025). Europe's 2030 capacity requirement is cited in Reuters reporting based on Solar Power Europe analysis (2025). Latin America demand forecast is from InfoLink (2025). MENA outlook is from IEA's regional analysis (2024). Sub-Saharan Africa outlook is from IEA Renewables 2025.

1.4. Policy Framework Driving the Transition

1.4.1. Production-Linked Incentive (PLI) Scheme

The PLI Scheme is the centrepiece of India's efforts to establish a globally competitive solar manufacturing ecosystem. This programme extends over five years following commissioning and providing financial incentives linked to the scale and efficiency of production, encouraging the adoption of efficient technologies such as TOPCon and HJT modules. Under Tranche I (2021), ₹4,500 crore (~$0.54 billion) were allocated to support 8.7 GW of module manufacturing capacity (refer Figure 1.4). This was followed by Tranche II (2022), which introduced ₹19,500 crore (~$2.5 billion) to target 39 GW of additional capacity and anticipated to generate 9,75,000 direct and indirect jobs across the PV manufacturing value chain.[26] Under the two tranches of this scheme, India anticipated adding ~48 GW of module, including 23 GW of integrated polysilicon-to-module capacity by 2027. By 2023, PLI had boosted India's module manufacturing capacity to 38 GW from 15 GW in 2020, with projections to reach 172 GW by 2026.[7,10] The PLI scheme provides producers with direct financial incentives tied to their output and efficiency: higher efficiency and more integrated manufacturing lines get larger subsidies per watt. As of 2025, these schemes have spurred construction of multiple gigafactories. Phase-I winners have started commissioning plants, and Phase-II projects are in various stages of execution (targeting completion by 2026–27). The government has also begun disbursing initial payouts to firms that met milestone targets (e.g., First Solar's plant in Tamil Nadu, which began operations in 2023, is eligible for PLI disbursement after meeting sales and efficiency criteria). In essence, PLI is bridging the viability gap by helping Indian factories compete with established global players until they achieve scale.

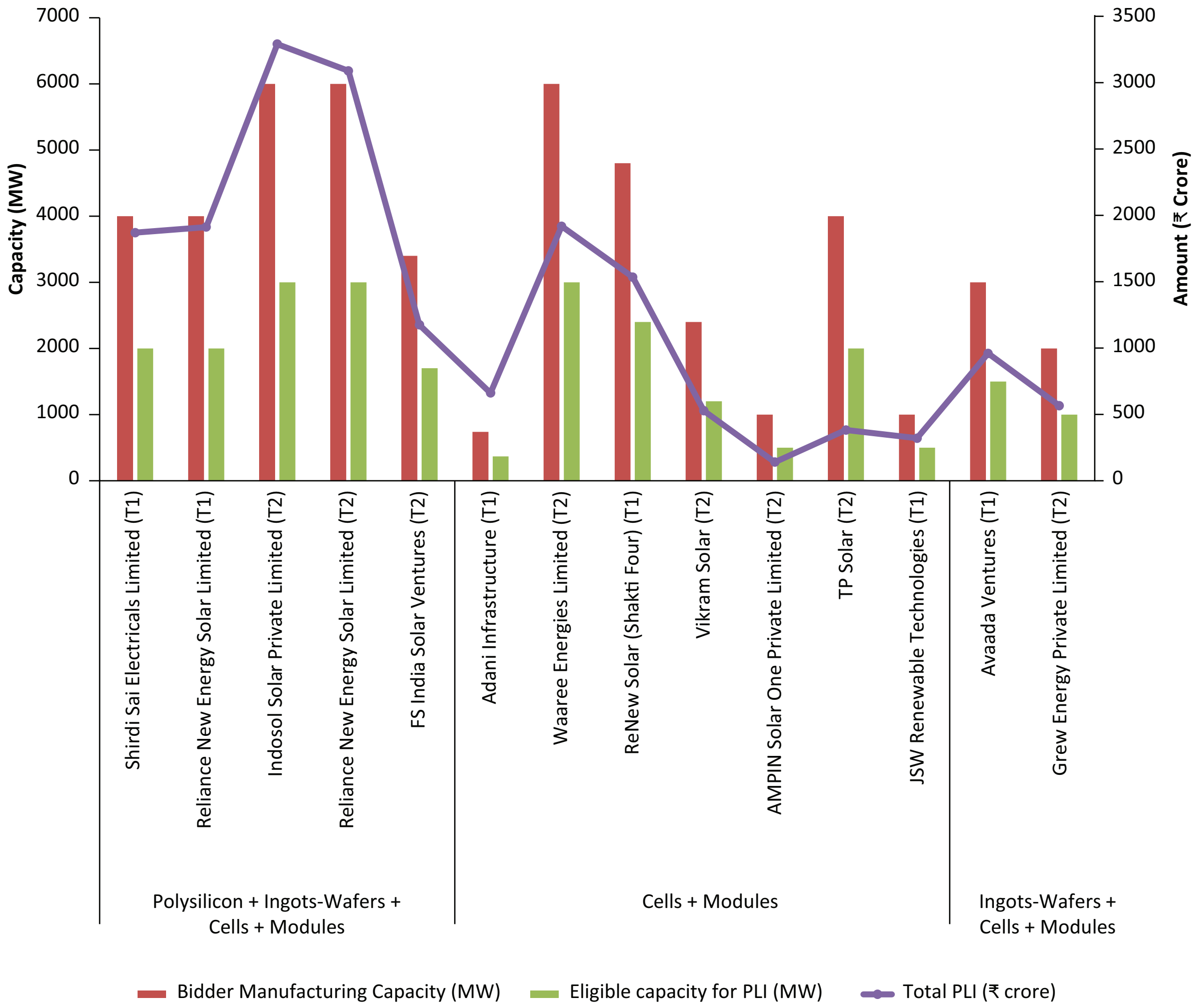


FIGURE 1.4 PLI scheme bidders manufacturing capacity[27]

Source: Author's analysis based on data compiled from Ministry of New and Renewable Energy (MNRE) PLI Scheme Guidelines (Tranche-I and Tranche-II) and Press Information Bureau (PIB) releases on approved bidders and capacities.

1.4.2. Import Tariffs (BCD) and Domestic Procurement Rules (ALMM)

To protect nascent domestic industry from low-cost imports, India introduced a Basic Customs Duty (BCD) on solar products. Since April 2022, a BCD of 40% on modules and 25% on solar cells has been in effect. This is a steep tariff deliberately aimed at tilting the economics in favour of buying Indian-made panels (which face zero duty) over Chinese imports. The BCD has indeed reduced imports Chinese module shipments to India dropped in 2022–2023 as developers turned to local suppliers, despite initially higher prices.

Complementing this, the ALMM mandates that solar projects in India (especially those tied to government schemes or utilities) use only PV modules from approved domestic manufacturers. The ALMM list, maintained by MNRE, currently features Indian companies and their models that meet specified quality standards. By design, this excluded foreign module brands, creating a de-facto domestic content requirement. The updated list from October, 2025 includes 132+ manufacturers with a cumulative enlisted capacity at 122 GW/year, indicating a large base of approved domestic supply. However, the implementation of ALMM has seen some flexibility: recognizing short-term module shortages and project delays, the government temporarily suspended the ALMM requirement in 2023, allowing developers to source abroad, if needed. This pause (valid through March 2024) was to ensure that installation targets could be met in the interim while

TABLE 1.5 India's solar PV trade and localization policies

Instrument	FY-23 Setting (Apr 2022)	FY-26 Setting (Apr 2025 Budget)	Rationale	Evident Market Effect
BCD on c-Si modules	40%	20%	Price umbrella while module capacity crosses 80 GW/year; gradual rollback to reduce LCOE	Module import value fell 66% YoY in FY-23, rebounded in FY-24 as projects front-loaded ahead of ALMM reinstatement
BCD on c-Si cells	25%	20%	Preserve differential but narrow gap ahead of ALMM-II on cells	Imports surged into double-digit GW levels during the gap between module build-out and cell availability, highlighting continuing reliance on overseas cell supply even as module assembly expanded.
ALMM List-I (modules)	Mandatory April 2022; paused March 2023–March 2024; reinstated April 2024	Mandatory	Guarantees that government-linked demand is met by vetted Indian producers	130+ manufacturers, 120 GW enlisted (MNRE list Oct, 2025)
ALMM List-II (cells)	—	Mandatory from June 1, 2026*	Extends localization to 70–80% of module value	Developers obliged to verify cell traceability

Source: Author's analysis and compilation based on Union Budget documents, MNRE notifications, customs tariff schedules, and secondary literature on India's solar PV policy framework.

* If the last date of bid submission is on or before 31 August 2025, the project is exempt from using ALMM List-II cells and must comply only with ALMM List-I modules (where ALMM applies). If the last date of bid submission is after 31 August 2025, the tender must require both ALMM List-I modules and ALMM List-II cells.

Note: While BCD applies to cells and modules (not wafers), the domestic price wedge persists because the largest value and cost exposure sits in cell processing and the full module BOM and financing stack; wafers being duty-free does not make the delivered module price converge to China spot levels.

domestic capacity ramps up. Going forward, ALMM List-II for cells is expected to be enforced by June 2026, thereby, guaranteeing a captive market for Indian cell manufacturers. Together, the BCD and ALMM create a protective umbrella under which domestic industry can grow, BCD guards against price undercutting by imports, and ALMM steers demand to local producers. These measures, however, must be calibrated with timelines; the intent is not permanent protection but to kick-start improving self-reliance and competitiveness. The industry is cognizant that in the long run, Indian modules must become cost-competitive without high tariffs, especially if India aspires to be a global exporter (excessive tariffs cannot be sustained indefinitely without raising domestic solar power costs). Still, in the short-to-medium term, these policies are a powerful driver of the manufacturing shift.

1.4.3. State-level Incentives and Support

In addition to central government schemes, various states in India offer their own incentives to attract solar manufacturing investments. Tamil Nadu, for instance, has provided a package of incentives (including subsidized land in Chennai's industrial corridor and electricity tax exemptions) to investors in the renewable manufacturing space. Gujarat, which leads in overall solar capacity, launched a special Semiconductor Policy 2022–27 that, while aimed at chip fabrication facilities (fabs), also extends benefits to any polysilicon or solar wafer plants (e.g., capital subsidy upto 50% on land cost in designated manufacturing clusters, and competitive electricity tariffs for high-load industries). Telangana and Andhra Pradesh have been proactive as well, they offer GST reimbursements, stamp duty waivers, and tailor-made support for companies setting up cell and module factories in their industrial parks (Hyderabad's E-City and Andhra's Kadapa Solar Park are examples). Some states, like Odisha and Chhattisgarh, are focusing on upstream facilities as they are rich in minerals and power along with signalling interest in hosting polysilicon or metallurgical-grade silicon plants by offering cheap land and power (since polysilicon refining is energy-intensive, constant affordable power supply is a key incentive). The competition among states has generally been positive, leading to emerging clusters as noted in Section 1.1.3. Infrastructure is another area of support: states are setting up plug-and-play manufacturing zones with common facilities, and fast-tracking permits for mega projects. These sub-national incentives complement central schemes, effectively reducing the investment cost and operating cost for manufacturers who choose those locations. As a result, we see different parts of the value chain gravitating to different regions, e.g., cell and module assembly in states with established electronics sectors, and raw material processing in states with resource and power advantages.

PV MANUFACTURING EQUIPMENT ECOSYSTEM IN INDIA

Chapter 2

PV MANUFACTURING EQUIPMENT ECOSYSTEM IN INDIA

2.1. Mapping Domestic Equipment Base

India's domestic solar PV equipment industry is nascent, with most high-tech production machinery still imported. A majority of new cell/module factories rely on foreign tool vendors, often Chinese, due to cost and availability. India currently imports 70–100% of production equipment for wafers and cells, and module assembly, underscoring limited local options. For instance, Jinchen Machinery (China) alone has installed ~44 GW of module production lines in India by 2024, supplying nearly all major module makers.[28,29] This heavy import reliance highlights the gap in India's domestic equipment manufacturing capabilities.

That said, a few of Indian firms have begun producing selected solar manufacturing tools, primarily for module assembly. Table 2.1 provides a snapshot of key equipment types, and known Indian manufacturers, along with their throughput/yield versus global peers' benchmarks.

TABLE 2.1 Key solar PV manufacturing equipment: India's domestic players vs global suppliers

Equipment/Tool/Process	Indian Manufacturer(s)	Global Benchmark (Leading Supplier)	Throughput/Yield (India vs Global)
Polysilicon Reactors & Purification	None; Proposed ventures in planning	GCL Technology Holdings Ltd(China)[30], OCI Company Ltd (S. Korea)[31]	100% import currently (India); ~60–80k tonnes/year per plant (China)
Ingot Growth Furnace (DSS)	HHV (Hind High Vacuum) – Pilot scale directional solidification (DSS) furnace built[32]	Jinggong (China)[33], GT Advanced (Now, Onsemi) (US)[34]	~100 kg ingot per run (HHV) vs 800 kg+ (state-of-art)
Wafer Slicing (Wire Saw)	None; under development with NexWafe's planned kerfless tech[35]	Meyer Burger (Germany)[36], Applied Materials (US)[37]	No Indian tool yet vs 3,000 wafers/hour wire saw; Meyer Burger focuses on diamond wire cutting
Cell Diffusion Furnace	None (Imported from Europe/China)	Centrotherm (Germany)[38], Tempress (Netherlands)[39]	Indian fabs rely on imports (~5,000 wafers/hour)
PECVD/ALD (Cell Passivation)	None (Imported – e.g., from Singulus (Germany)[40], Maxwell (China, etc.)[41]	Leadmicro (China), Applied Materials	India imports PECVD/ALD tools from Leadmicro (China) and Applied Materials, with foreign systems achieving >5,000 wafers/hour; high uptime and maintenance-free designs

Equipment/Tool/ Process	Indian Manufacturer(s)	Global Benchmark (Leading Supplier)	Throughput/Yield (India vs Global)
Laser Process (Cutting, Grooving)	Limited; R&D focused (Suresh Indu Lasers)[42]	3D-Micromac Germany)[43], Coherent(US)[44]	Lab-scale in India vs high-volume industrial lasers globally
Screen Printer (Metallization)	None	ASYS Group (Germany)[45], Baccini (Italy, now acquired by applied materials)[46]	~1,500 wafers/hour × 24/7 operation ≈ 25–30 MW/year per production line; precision gap in fine-line printing
Module Tabber-Stringer	Cliantech Solutions – up to ~1,500 cells/hour (estimated)[47]	Ooitech (China)[48], TeamTechnik (Germany)[49]	1,200–1,500 cells per hour (cph) (Cliantech) vs 5,000+ cph (Ooitech) – Indian models Indian models operate at ~25–30% of global throughput, with higher breakage rates (≤2‰ vs <0.3‰) and slower cycle times (2.0s vs 1.7s)
Laminator	Few small suppliers (Akshar Enterprise; mostly for <100 MW lines)[50]	Jinchen (China)[51], Mondragon (Spain)[52]	~3 min cycle, single-tray (India) vs multi-tray 1.5 min cycle (global); throughput gap ~2×
Sun Simulator & EL Tester	Few local integrators (assembling kits), e.g., Cliantech Solutions (with HSPV/Asic)[53]	MBJ Solutions (Germany)[54]	Cliantech Solutions (India) assembles Class A solar simulators using imported kits, while global leaders like Berger (Germany) supply Class A+ systems with 120–2000 tests/hour and sub-0.5% accuracy. India lacks domestic high-resolution EL testers, relying on basic cameras (5–12MP) vs global 40MP systems (MBJ Solutions)
Factory Automation & Manufacturing Execution System (MES)	Local industrial automation firms (e.g., Precitec, ATS India) – custom solution[55,56]	In-House by OEMs, Bosch Rexroth (Germany)[57]	Indian integrators handle material handling and SCADA; advanced AI/ vision QA mostly via foreign tech

Source: Author's analysis and compilation based on industry disclosures, equipment supplier specifications, tender documents, and secondary literature on solar PV manufacturing technologies.

Domestic capabilities exist in niches, e.g., Hind High Vacuum's (HHV) indigenous furnace for casting multi-crystalline ingots, or Cliantech's turnkey module lines (integrating stringers, bussing, laminators with foreign subcomponents).[32] However, these Indian tools often have lower throughput and shorter track records compared to global peers. For example, Cliantech's automated stringer operates at roughly one-third the speed of the latest multi-busbar stringers from Europe or China. Yield and uptime also trail slightly: HHV's furnace can produce quality polycrystalline ingots but at smaller scale, while Indian module assembly lines typically run at higher loss rates initially (until optimized). On the positive side, Indian suppliers have begun case deployments; Cliantech has successfully delivered multi-gigawatt module lines (e.g., 2.2 GW for Credence/ Alpex combined) and automated 5 GW factory expansions for players like Rayzon and Sahaj.[58] The current equipment base is limited, particularly for high-tech cell processes (diffusion, deposition, plating) there are no homegrown OEMs of scale. Bridging this gap is crucial for India to avoid bottlenecks as manufacturing capacity soars.

2.1.1. Import Dependence Scorecard

India remains heavily reliant on imported equipment at each step of the PV value chain. This import dependence poses risks in terms of supply security, forex outflows, and potential delays, as seen during Covid-19 when Chinese engineers/ equipment deliveries were delayed.

TABLE 2.2. Import reliance scorecard for PV manufacturing equipment

Equipment Category	Percentage of Tool Imported	Technical Lock-In (Proprietary Technology)	Supply Chain Risk (Concentration)
Polysilicon Production	~100% (no domestic kits)	High – Complex Siemens process, few global suppliers	High – China ~95% capacity (material & reactors)
Wafering (Ingot & Saw)	~100% (except pilot furnace)	High – Precision wire saw & crystal tech patented	High – Few makers (Europe/ China); shipping constraints for large furnaces
Cell Fab Equipment	>90% (all major tools)	Medium – Several foreign OEM options (EU, China, US)	Medium – Concentrated in China/EU, but multiple vendors per tool type
Module Assembly Line	~70–80% (some local integration)	Low–Medium – Stringer/ laminator tech more standardized	Low – Many global suppliers
Testing & QA Systems	~80% (high-end testers)	Medium – Niche high-precision instruments (imported)	Medium – Few Tier-1 metrology OEMs (mostly US/EU), but not supply-constrained

Source: Author's analysis and compilation based on industry data, equipment vendor information, and secondary literature on supply-chain concentration in solar PV manufacturing.

Polysilicon/wafer equipment has the highest import lock-in-virtually no Indian supply, with technology and capacity dominated by China (95%+ share). This is a critical vulnerability, if geopolitical or trade disruptions occur, Indian integrated projects could face delays. Cell equipment also relies on imports (over 90% of cell line capex is foreign). However, the risk is moderated by diverse sources, India can procure diffusion furnaces, PECVD tools, etc., from multiple countries namely, Germany, Switzerland, China, the USA. Still, leading-edge cell tools (for n-type, heterojunction) often have proprietary designs (e.g., Meyer Burger's heterojunction line or Applied Materials' deposition tools), implying a technical lock-in until domestic alternatives emerge. Module line equipment has relatively lower risk: it's technologically less complex and a number of suppliers (especially from China) exist, which Indian firms, like Cliantech, leverage. Indeed, Chinese OEMs have been eager to supply to India, e.g., Jinchen has a local office in Gujarat and has extended vendor financing/leases to Indian clients (making imports easier). The table highlights that upstream equipment (polysilicon, wafer, cell) is the weakest link, high spend and high dependency, whereas downstream assembly tools are somewhat more indigenized in the near term. Reducing these import dependencies will require a mix of local capability building and strategic international tie-ups.

2.2. Technology Gaps and Innovation Needs

To become globally competitive, India must address key technology gaps in solar PV manufacturing equipment. These gaps can be grouped into (a) Incremental improvements for current tech generations, (b) Disruptive innovations that leapfrog conventional processes, and (c) Digital advancements for smarter manufacturing. Table 2.3 summarizes these categories, including technology readiness, payback horizon, and IP ownership.

TABLE 2.3. Technology gap categories in PV equipment – Status and outlook

Category & Examples	TRL (Technology Readiness Level) in India	Payback Period (if adopted)	Key IP Ownership/Recent Moves
(a) Incremental: Next-gen cell production (PERC → TOPCon, HJT), e.g., tunnel oxide PECVD tools, metallization lines for heterojunction, etc.	TRL 8 (Proven tech globally)	~3–5 years (higher efficiency yields lower $/W)	Largely foreign IP (Europe/China). Jinchen–Singulus JV formed to offer HJT/TOPCon turnkey solutions in India. Reliance acquired 4.8 GW of HJT equipment from China's Maxwell.[59] Indian firms now integrating these tools, but limited domestic designs are available.
(b) Disruptive: Kerfless wafering (e.g., epitaxial wafers) and Tandem solar cells (silicon-perovskite hybrids). These can revolutionize upstream steps by bypassing sawing or boosting cell efficiency >30%.	TRL 5–6 (Lab to pilot stage)	5–10 years (longer-term, high risk/high reward)	IP held by startups/foreign labs. Reliance–NexWafe: Reliance invested $29 M to access NexWafe's kerfless wafer IP and plans giga-scale wafer fab in India.[60] Tandem cell research ongoing at IITs & startups; notable global IP by Oxford PV, HZB, etc. No Indian commercial tool yet; requires consortia for scale-up.
(c) Digital & AI: Automation, AI-driven quality control, Manufacturing Execution Systems (MES), digital twins for process optimization. These enhance throughput and yield across all stages.	TRL 7–8 (Adopted in parts of industry 4.0)	~2–3 years (quick RoI via waste reduction & uptime)	Software/IP is more accessible. Many tools use imported machine vision systems today. Indian IT strengths mean local startups (e.g., employing AI for cell defect detection) are emerging. Some module OEMs already use AI for EL image analysis. Scope for public-private R&D in sensor fusion, predictive maintenance algorithms tailored to PV lines.

Source: Strategic technology assessment by the author based on industry announcements, technology readiness literature, and recent investment and IP developments in solar PV manufacturing.

For incremental upgrades, the challenge is less about invention and more about technology access and adaptation. TOPCon (n-type) and HJT cell architectures are becoming mainstream globally, the 16th ITRPV report forecasts n-type wafer technologies have 70% of the market share, overtaking the p-type PERC in early 2024. Indian manufacturers cannot afford to lag; hence, they are importing the needed tools. The opportunity here is to localize components (for example, domestic suppliers for plating equipment or Atomic Layer Deposition (ALD) tools under license) and to train Indian engineers on these advanced lines, so that operation and maintenance expertise becomes indigenous. The PLI scheme has provisions favouring high-efficiency tech, which nudges manufacturers to adopt TOPCon/HJT, but domestic equipment makers still lack reference installations for these tools.

For disruptive innovations and genuine technology leapfrogging, India must root each new push in a clear understanding of what its laboratories have already achieved and where the gaps remain. A consolidated review of completed and ongoing solar-PV R&D projects at premium institutes/research centres should be the first step. This exercise will help identify proven prototypes, stalled ideas and knowledge gaps, allowing realistic milestones and fresh collaborative targets to be set. Against this evidence, two disruptive avenues stand out: Kerfless wafering, e.g., NexWafe's direct gas-phase growth could eliminate the silicon lost as kerf in conventional sawing and cut both capex and energy use, an attractive option precisely because India has no legacy wafer slicing industry to cannibalize. Perovskite-silicon tandem cells promise > 30% module efficiencies; although market penetration is unlikely before ~2035, early patenting and pilot lines will position domestic firms ahead of the curve.[61] Establishing a 'National Solar Innovation Consortium' that links premier institutes with equipment makers and cell/module manufacturers, while tracking lessons from past projects can concentrate resources on kerfless growth, tandem integration and other high-impact themes, ensuring that, as these technologies mature, Indian entities hold a meaningful share of the intellectual property and manufacturing know-how.

Finally, digital enhancements are low-hanging fruits that can significantly improve competitiveness. Automation levels in Indian PV factories are improving but still trail global best practices. Many new fabs still rely on manual intervention for material movement or inspection. Incorporating advanced robotics (for wafer handling, cell string layup, etc.) and AI-based inspection can boost yields. For instance, AI vision systems can detect micro-cracks or soldering defects in real-time, reducing downstream scrap. These technologies are largely software-driven, an area where India has abundant talent. By integrating IT with manufacturing (the essence of Industry 4.0), Indian OEMs can differentiate their equipment offerings (e.g., a domestic tabber-stringer equipped with smarter vision/feedback control could match foreign machine performance). Some leading module manufacturers already use such systems with the goal of domestic equipment vendors providing integrated automation solutions. Summarily, closing the tech gaps will require parallel efforts, acquiring and indigenizing current-gen tech while investing in R&D for next-gen and leveraging India's software prowess to enrich hardware with intelligence.

2.3. Cost and Competitiveness Benchmarking

Indian-made solar equipment and locally built factories currently face a disadvantage as compared to China, but this gap is narrowing with scale and policy support. Table 2.4 benchmarks key cost factors from capital expenditure (CAPEX) and operating costs to yields and financing to assess India's position versus global peers (China, EU, US).

TABLE 2.4 Cost structure comparison – Solar manufacturing (India vs China, EU, US)

Cost Component	India (2025)	China (2025)	EU/US (2025)
CAPEX (Equipment)	Higher: Equipment investment costs ~20–30% higher than China. Domestic cell fabs have capex ~$0.8/W vs ~$0.6/W in China (due to smaller scale, higher import costs). PLI subsidy bridges ~80% of this gap.	Lowest: World's lowest capex. Large scale orders, local OEM base, and cheaper engineering – module line <$0.5/W. Turnkey Chinese 1 GW module line ~$15 M vs India ~$20 M (estimated).	Highest: ~40–50% above China. EU/US capex inflated by high equipment & construction costs.
OPEX (Labour, Power)	Mixed: Labour is low-cost (skilled engineers at fraction of Western wages), giving an edge. Power costs higher than China's subsidized rates but lower than European Union's. Overall OPEX per watt slightly above China but far below EU.	Lowest: Huge scale yields bargaining on materials; electricity often subsidized. Labour productivity very high, offsetting wage differences.	High: Labour expensive (especially EU). Energy costs in EU are >3× India/China (gas price impact). US power cheaper than EU but labour and overhead high.[62]

Cost Component	India (2025)	China (2025)	EU/US (2025)
Yield & Scrap Losses	Improving: Initially slightly higher scrap rates in new Indian fabs (cells/modules), ~2–3% yield loss, narrowing as experience grows. Absolute efficiency of Indian cells ~0.5% lower than cutting-edge China for now.	High Yield: Industry-leading process control yields >98% utilization. Cell efficiencies at cutting-edge (24%+ PERC, 26% TOPCon). Low defect rates due to matured automation.	Varied: Established EU firms (Meyer Burger) have high quality, but newer US lines may have learning curve. Generally good yields, but not significantly above China.
Depreciation & Finance	Varied: Established EU firms (Meyer Burger) have high quality, but newer US lines may have learning curve. Generally good yields, but not significantly above China.	Advantage: Chinese firms access low-cost capital (state banks ~3–5% loans). Longer depreciation (10+ years) given support to industry, easing annual cost. Vendors often offer lease/credit to overseas buyers.	Mixed: US IRA provides tax credits (reducing effective capex by 30%+). EU considering similar absent subsidies, western capital costs are moderate (4–6%), but still higher cost base needs longer depreciation to be viable.
Duties & Logistics	Protected market: 20% BCD on cells, 20% on modules encourages local production. However, equipment imports largely duty-free or low duty (to not penalize capacity building). Logistics: importing heavy equipment adds lead time and cost. Domestic production would save this.	Export-driven: Minimal duties internally; Chinese suppliers benefit from scale logistics (in-country deliveries). Exports face shipping costs but often mitigated by vendor presence in target market (local warehouses).	Tariffs & shipping: US imposed tariffs on Chinese modules (Section 201, etc.), raising import cost—this indirectly helps domestic module makers but also raises equipment import costs.

Source: Author's analysis and compilation based on industry cost benchmarks, published manufacturing studies, policy documents, and secondary literature on global solar PV manufacturing economics.

Note: Tender and spot module prices are not a proxy for wafer costs; they embed short-term market pressure, contract terms, product class (power bin, warranty), and supplier strategy under oversupply. For example, recent Chinese centralized procurement and spot benchmarks for n-type TOPCon modules have printed in the RMB ~0.62–0.75/W range in multiple datasets, which is a useful reference for competitiveness, but should not be interpreted as a simple cost-plus reflection of wafer value.

The latest data indicates that TOPCon module production costs in vertically integrated Indian factories average ₹16.2–17.4/Wp ($0.195–0.209/W), compared to global spot prices of $0.097–0.11/W (₹8.1–9.1/Wp) for TOPCon and back-contact (BC) modules in China, as seen in recent tenders reaching CNY 0.70/W (₹8/Wp).[18,63,64] However, India's domestic market prices remain higher at ₹18–22/Wp ($0.22–0.26/W) due to protective tariffs on imported cells and reliance on foreign wafers, which inflate input costs, this cost base reflects a combination of imported upstream inputs (especially wafers and equipment-linked consumables), lower utilisation during ramp-up, higher cost of capital, and additional compliance and traceability overheads. India's PLI scheme aims to narrow the cell-cost gap with China by 2026–27, while labour and logistics advantages partially offset the module-assembly cost disparity, the cost convergence remains constrained by smaller factory scales and lower automation rates. To align prices more closely with actual costs and support wider adoption, measures such as greater cost-and-margin transparency for subsidized manufacturers, a polysilicon-linked reference price for government tenders, and incentives targeted towards project developers rather than upstream margins could help improve market efficiency without compromising the objective of a self-reliant solar industry.

On operating costs, India's strength is its workforce, highly-skilled engineers at a fraction of western labour costs, and this partially compensates for any efficiency shortfall in equipment. Power is a moderate cost factor; some states are offering renewable energy at competitive rates to new fabs to further cut OPEX. Economies of scale are also kicking in: whereas older

Indian facilities were 100–500 MW (hence high overhead per unit), the new wave of factories are multi-gigawatt. As a result, overheads (management, cleanroom costs, etc.) per MW are dropping sharply.

In summary, while today an Indian integrated plant might have a slightly higher ₹/W cost than a Chinese plant, the gap is closing fast. With full PLI disbursement, improved yields, and supply chain localization of inputs, analysts expect Indian-made modules could reach cost parity with imports by ~2026. Competitiveness drivers to watch include the rupee exchange rate (affecting import costs of equipment/materials), global commodity prices (silicon, silver), and how quickly Indian firms climb the learning curve for new technologies. The next section discusses policy tools to accelerate this convergence.

2.4. Make in India Policy Toolbox

To catalyse domestic PV equipment manufacturing and reduce import dependence, a suite of 'Make in India' policy measures is either in place or under consideration. These tools target various needs from upfront capital support to R&D facilitation and involve multiple agencies (MNRE, MeitY, state governments, etc.). Table 2.5 outlines the key elements of the policy toolbox, with their status and timeline.

TABLE 2.5. Policy tools to boost domestic PV equipment industry in India

Policy Measures / Incentives	Description & Benefits	Timeline & Status	Lead Agency/ Stakeholders
Production-Linked Incentive (PLI) – Solar (High-Efficiency PV Modules) – Proposed Sub-Scheme for Equipment	A precision equipment PLI could similarly reward domestic tool makers for supplying Indian fabrication facilities (fabs) (e.g., per MW of equipments sold). This would offset cost disadvantages and encourage global OEMs to localize manufacturing in India.	Equipment-PLI requires a new budget allocation over a long-term period.	MNRE (solar PLI nodal), NITI Aayog, Ministry of Heavy Industries (for capital goods) – coordination needed for equipment scheme. Industry: PV OEMs, Indian Solar Manufacturers Association (ISMA) supporting extension to manufacturing equipment.
Modified Special Incentive Package (MSIPS 2.0)	Revival of MSIPS(which expired 2018) to support electronics manufacturing – extending it to solar equipment.[65] Would grant 20–25% capital subsidy on plant and machinery investment for eligible PV equipment factories (like for semiconductor fabs).[66] Particularly useful for high-value equipment (furnaces, PECVD) requiring upfront capex.	MSIPS was in place during 2012–2018; version 2.0 for renewables can be recommended	MeitY (Electronics Ministry) with MNRE; States may add their own capex subsidy on top once central scheme in place

Policy Measures / Incentives	Description & Benefits	Timeline & Status	Lead Agency/ Stakeholders
Customs Duty & Tax Reforms (Custom Duty Rebates, GST)	Adjusting import duties to favour local value addition. For instance, zero-duty import of raw materials/ parts for making PV equipment, while maintaining tariffs on finished solar modules (to protect end-product market). Additionally, GST rebates or interest-free import duty deferment for equipment manufacturers could improve cash flow.	Equipment parts duty exemptions could be notified via customs tariff schedule updates.	Ministry of Finance (CBIC) for customs/GST. Can be auctioned via annual budget and notifications.
Testing & Certification Infrastructure	A transparent nationwide performance audit, benchmarked against Tier-1 International Electrotechnical Commission (IEC) standards, should first map gaps in India's PV test centres (e.g., long-term TOPCon/HJT degradation rigs, ±1 % metrology). New public funds should flow, via competitive calls, only to facilities with demonstrable technical strength, independent governance and a time-bound National Accreditation Board for Testing and Calibration Laboratories (NABL)/IEC-accreditation plan, assuring credible third-party validation that de-risks emerging technologies for early adopters.	Could be set up by 2030 if funded in next 1–2 years. Some existing infrastructure at research institutes can be repurposed for a demo 100 MW cell line lab.	MNRE (NISE), Ministry of Science & Technology International collaboration possible (e.g., tie-ups with Fraunhofer ISE or NREL for validation procedures). Once established, domestic OEMs and startups could utilize facilities for testing and certification of Indian manufacturing equipment.
Collaborative R&D Consortia (Public-Private Partnerships)	Formation of consortia that bring together equipment makers, PV manufacturers, and research institutions to jointly develop critical technologies. Modelled on successful semiconductor consortia globally, this could focus on, say, indigenizing HJT equipment or developing a homegrown laser tool for cell cutting. Government can fund part of the R&D and facilitate licensing of foreign IP. These efforts ensure that Indian companies build proprietary know-how rather than purely assembling foreign kits.	Several ongoing small-scale collaborations	DST (Department of Science & Technology), MNRE, Industry partners (equipment firms, cell/ module makers). Needs multi-agency funding. Likely to start with a few pilot projects (e.g., Indian plating tool for TOPCon) and scale based on results.

Source: Author's analysis and compilation based on existing industrial policy instruments, government scheme documents, and stakeholder discussions on solar PV manufacturing and capital goods development.

In addition to the above, state governments are offering incentives for manufacturing units such as stamp duty waivers, land at concessional rates in industrial parks, electricity tariff rebates, etc. These incentives indirectly benefit equipment suppliers too, as they reduce overall project costs for new factories. Some states like Gujarat and Tamil Nadu, keen on attracting the solar supply chain, may consider introducing special packages for equipment makers (similar to what was done for electronics and EV components).

Another important policy instrument is the ALMM. Initially applicable only to modules, ALMM was expanded to cover solar cells as well. From 2026, only ALMM-listed cells and modules can be used in projects, essentially mandating local or approved products. While ALMM does not directly list equipment's, its intent to ensure traceable domestic supply chains pressuring module producers to source more locally and invest in backward integration. For example, ALMM List-II (cells) requires cells made with domestically processed wafers, which in turn creates a market for any domestic wafer or ingot equipment that might emerge. In essence, ALMM + local content rules pull demand through the chain, and the above toolbox (PLI, subsidies, etc.) pushes supply-side readiness.

2.4.1. Action Roadmap & KPI Dashboard

To translate the above strategies into outcomes, an action roadmap with specific milestones, along with Key Performance Indicators (KPIs) to track progress is outlined (Figure 2.1). Responsibilities may vest with the relevant stakeholders like central government, state authorities, public sector undertaking (PSUs), and private industry:

The Government of India (especially MNRE, Ministry of Heavy Industries, MeitY, and NITI Aayog) play a pivotal coordinating role formulating schemes like PLI/MSIPS and ensuring inter-ministerial alignment. State governments are crucial for providing infrastructure and local incentives their industry departments may create single-window clearances for equipment manufacturing plants and possibly set aside land in upcoming solar manufacturing parks specifically for equipment suppliers. Public sector undertakings (PSUs) can lead by example. For example, Bharat Heavy Electricals Ltd (BHEL) or Bharat Electronics (BEL) could partner in developing certain machinery (they have manufacturing know-how and can absorb initial risks), similar to the manner in which BEL developed cell-lines decades ago. Private OEMs (both existing Indian equipment manufacturers and new startups) are on the frontlines they must execute on manufacturing, innovation, and after-sales support for any tools deployed. Industry associations like ISMA and Indian Electrical and Electronics Manufacturers Association (IEEMA) can assist by aggregating demand, identifying what tools industry needs most urgently, channel this information through existing platforms like Government e-Marketplace (GeM) and the Open Network for Digital Commerce (ONDC), to enable efficient buyer-seller matchmaking or set up new platforms for buyer-seller interactions.

To ensure accountability, a dashboard of KPIs may be reviewed every 6 months by a joint task force with representatives from MNRE, MeitY, industry, and academia. Metrics could include percentage of domestic content in new projects, number of domestic equipment orders booked, volume of imports of PV machinery (targeting a year-on-year reduction), and technology metrics like best efficiency achieved with Indian-made tools, etc. By tracking these, policymakers can course-correct for instance, if local content isn't rising, additional support or import disincentives might be applied and if targets are missed, the review can trigger graduated penalties proportional to the shortfall.

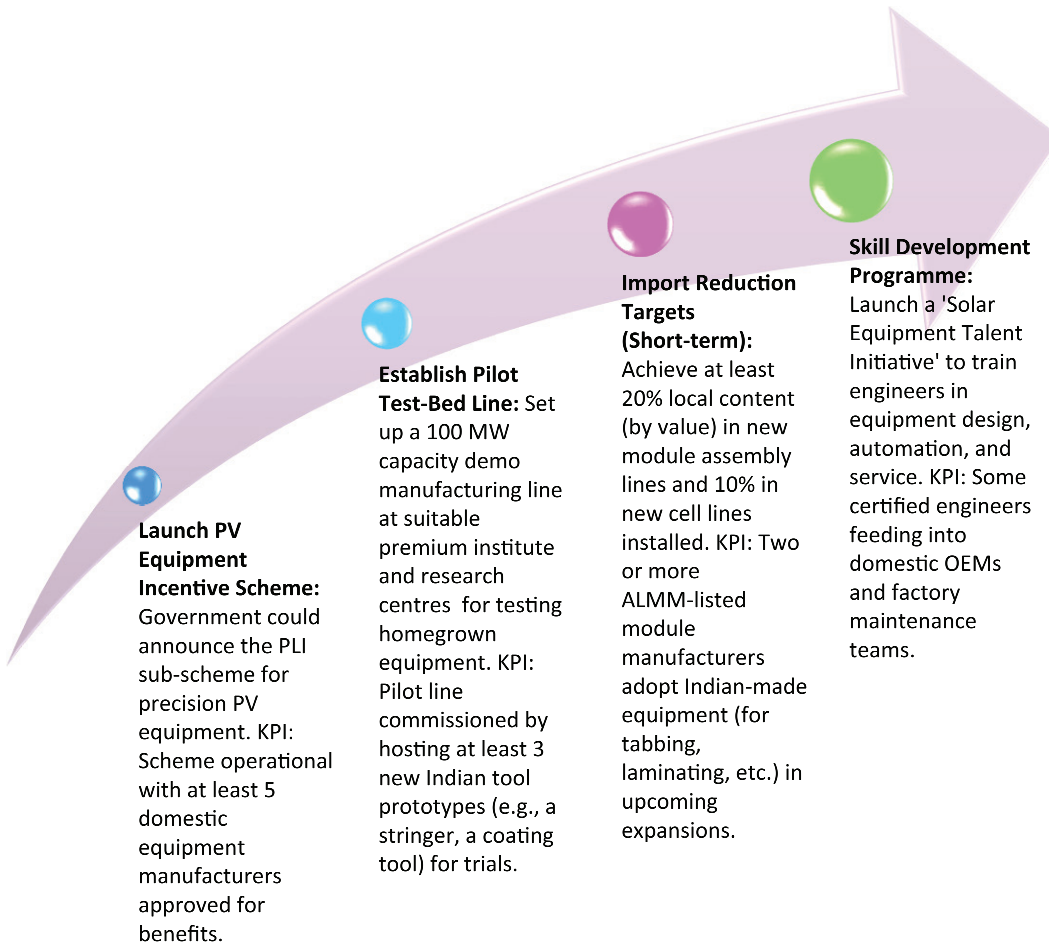


FIGURE 2.1 Short-term action plan

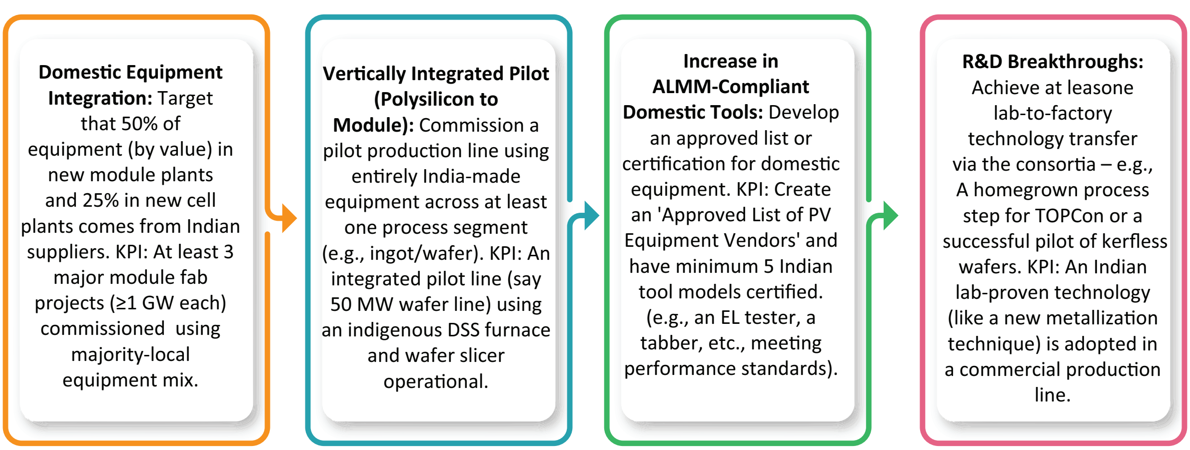
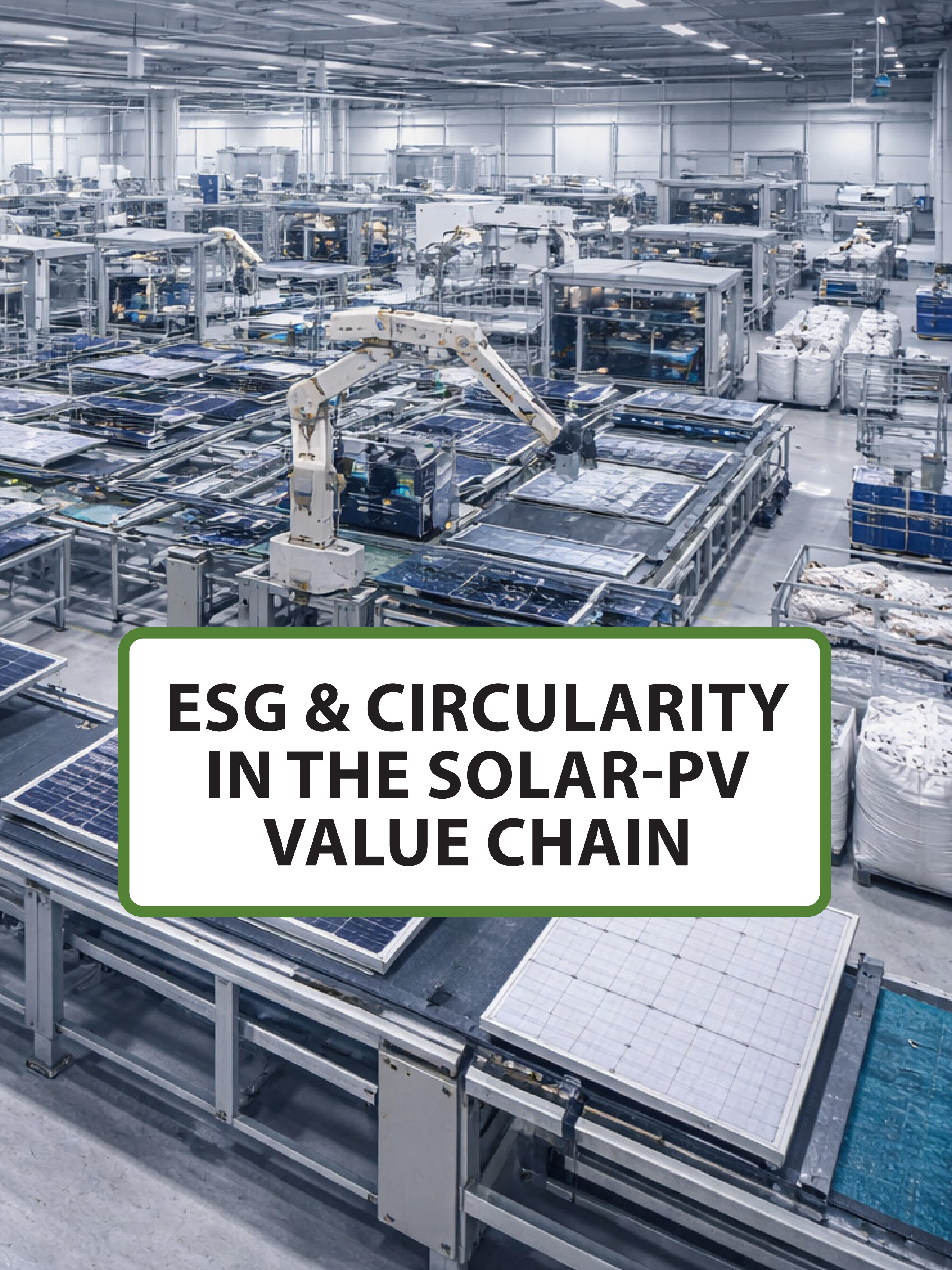


FIGURE 2.2 Long-term action plan



ESG & CIRCULARITY IN THE SOLAR-PV VALUE CHAIN

Chapter 3

ESG & CIRCULARITY IN THE SOLAR-PV VALUE CHAIN

3.1. ESG Drivers and Investor Expectations

Indian PV manufacturers face increasing expectations to demonstrate strong environmental, social, and governance (ESG) performance as they integrate into global supply chains. A key driver is the emergence of solar-specific ESG standards like the Solar Stewardship Initiative (SSI), launched by SolarPower Europe and partners as a one-stop framework to validate sustainability at PV manufacturing sites. The SSI's ESG standard draws on international norms and covers governance ethics, GHG emissions, water and waste management, and labour and human rights, providing independent certification that a production facility meets rigorous ESG criteria.[67] Such industry-led standards signal to overseas buyers that Indian-made modules uphold responsible sourcing and ethical production. This addresses concerns (e.g., forced labour or high carbon footprints) that have bothered the global solar supply chains in the past.

Global financial institutions and investors are likewise raising the bar. Multilateral development banks (MDBs) and export credit agencies now routinely require ESG due diligence for solar manufacturing projects and procurement. The International Finance Corporation's (IFC) Performance Standards, for instance, have become a de-facto benchmark over $4.5 trillion in emerging-market investments have adhered to IFC's environmental and social risk management standards or their equivalents in the past decade.[68] This means any Indian module factory seeking funds from institutions like IFC, World Bank, or Asian Development Bank (ADB) must comply with strict safeguards on issues ranging from labour conditions and community impact to pollution control. In practice, manufacturers need to implement grievance mechanisms, worker health and safety programmes, and resource-efficiency measures to meet these standards. Many private investors and solar developers echo these requirements; ESG compliance is seen as a proxy for long-term resilience and market access. Large asset managers increasingly screen module suppliers for red flags such as unsafe work practices or opaque supply chains. For example, US and European solar project developers now often require documentation that modules are free of any materials linked to forced labour, in line with import laws and the EU's Corporate Sustainability Due Diligence Directive (CSDDD).[69] This push for transparency and ethics is not just altruistic, investors fear reputational damage and legal risks if they support suppliers who violate ESG norms.

Multilateral climate finance is also shaping expectations. Institutions like the World Bank, Asian Infrastructure Investment Bank (AIIB), and green funds link financing rates to ESG outcomes, rewarding low-carbon manufacturing and robust social practices. For Indian exporters targeting Organization for Economic Co-operation and Development (OECD) markets, compliance with schemes like the EU's upcoming Digital Product Passport (part of the Eco-design regulation) will be crucial; this electronic product passport will store sustainability and traceability data for each product, enabling European regulators to enforce environmental standards across the supply chain. In short, ESG has shifted from a 'nice-to-have' to a market entry requirement. Indian PV firms that align with global ESG norms stand to gain easier access to capital, premium markets, and partnerships, whereas those that fall short may face non-tariff barriers (e.g., held-up shipments or rejection over compliance issues). Private equity and institutional investors are increasingly vocal that robust ESG performance, such as using renewable energy in production, ensuring fair labour, and transparent governance; influences their valuation of manufacturing companies. This convergence of investor expectations and formal standards is thus a strategic driver for India's PV industry to internalize ESG best practices as it scales up. Indian policymakers and industry leaders recognize that meeting these expectations is not only about risk management but also about differentiating 'Made in India' solar products as sustainable and future-proof, which can strengthen India's export brand in a decarbonizing global economy.

Low-carbon manufacturing is another investor expectation. Investors with climate mandates now favour 'ultra-low carbon' solar supply chains. In 2023, First Solar's panels became the world's first to receive the EPEAT Climate+ designation for having <400 kg CO_2e/kWp footprint.[70] Europe is moving to incentivize low-carbon PV too, the EU is discussing a carbon border adjustment that could, in the future, penalize carbon-intensive PV imports. As a pre-emptive step, some manufacturers like China's GCL are introducing module-level carbon tracing each panel carries a blockchain-protected QR code disclosing its precise carbon emissions across production steps.[71] Such transparency is geared towards upcoming EU rules and it also gives climate-conscious investor confidence that a module is net-zero compatible.

Finally, governance and community factors are gaining attention as well. ESG-minded investors expect solar firms to uphold strong anti-corruption practices, community engagement, and safety records. Any lapse, be it a pollution incident or local conflict, can lead to investor divestment or project delays. In India, this has highlighted a gap ESG disclosure is still voluntary for most PV manufacturers, although large public companies now file business responsibility and sustainability reports. Closing this disclosure gap will impose audit, reporting and process-upgrade costs that could widen the price gap with Chinese suppliers. A data-driven impact study, quantifying the rupees-per-watt cost of full compliance against the financing advantage and export premium it unlocks; should therefore precede any mandate. During this transition, a government-backed facility, e.g., rebates on third-party audit fees or concessional green-credit lines linked to verified ESG milestones can underwrite those initial expenses, allowing domestic firms to meet higher standards without sacrificing price competitiveness.

As global investors increasingly allocate capital in line with ESG mandates, India's solar sector must elevate its ESG performance to attract these funds. The upside is significant with over a quarter of global assets in ESG funds are projected to reach over $40 trillion by 2030, demonstrating exemplary ESG compliance can lower financing costs and open doors to green bonds and climate finance.[72] In summary, robust ESG practices are becoming a competitive advantage: they de-risk projects, meet rising investor expectations, and position India's PV industry to compete not just on cost and efficiency, but on sustainability leadership.

3.2. Circular-Economy Pathways

A transition from today's linear 'take-make-dispose' model to a circular economy is imperative as the first generations of solar panels approach end-of-life. There are two broad waste streams to manage manufacturing-stage waste (silicon kerf, rejected cells, packaging, etc.) and end-of-life (EoL) waste (retired modules glass, metals and polymers). EoL waste comes from PV modules that have completed their service life (typically ~25–30 years) or failed early, while manufacturing waste is generated during production (from silicon purification to module assembly). Tackling both requires new processes, infrastructure, and policies. Circular-economy pathways address both by maximizing material recovery and reuse, thereby mitigating environmental impacts.

3.2.1. End-of-Life PV Waste – A Looming Threat?

As India's solar deployment surges, the industry faces an imminent challenge managing end-of-life (EoL) PV waste in a sustainable, circular manner. PV modules have an expected lifespan of over 25 years, but early failures and routine replacements are already generating significant waste. India's cumulative PV waste, which was only ~1,00,000 tonnes in

2023, is projected to increase dramatically to around 6,00,000 tonnes by 2030 and could reach 1,90,00,000 tonnes by 2050 under high solar-growth scenarios.[73] In order to give a practical sense of 6,00,000 tonnes of PV waste, it is mentioned that it is equivalent to filling 720 Olympic-size swimming pools with discarded panels.[74] This upcoming wave of solar e-waste poses both a resource opportunity and an environmental risk. On one hand, retired PV panels contain valuable raw materials that can be recovered to reduce reliance on virgin mining. On the other, without proper handling, toxic elements (like lead or cadmium in some panels) could leach into ecosystems, and large volumes of glass and polymers could end up in landfills.

Composition of EoL PV Modules—Understanding module composition is key to recycling. Crystalline-silicon (c-Si) PV modules (which dominate the market) consist mostly of common materials. By weight, a typical silicon PV panel is about 75% glass, 10% polymer (encapsulant and backsheet), 8% aluminium (frame), 5% silicon and 1% copper, with only <0.1% comprising critical or hazardous metals like silver, tin and lead.[75,76] Thin-film PV technologies, in contrast, use different semiconductor materials but still have a high glass content. For example, modern CIGS (Copper Indium Gallium Selenide) modules are ~89% glass and ~7% aluminium (frame), with ~4% polymers.[77] CdTe (Cadmium Telluride) thin-film modules often have glass-glass structure with ~96–97% glass by mass and only 0.3–0.5% semiconductor/metals (Cd, Te and minor elements).[78] These are usually frameless or have minimal aluminium. Emerging perovskite PV technologies use glass or flexible substrates coated with just a few microns of a lead-based perovskite semiconductor, resulting in only a few grams of lead halide per module less than the amount of lead used in the solder of conventional silicon PV panels.

TABLE 3.1 Typical composition of a crystalline-Si PV module and recyclability[75,76,77,79]

Component	Approximate Mass Percent	Recovery Rate (in optimized recycling)	Recovered Products
Glass (tempered)	~75% (15 kg)	~95% recovered as glass cullet	Glass cullet (for new glass or insulation)
Aluminium (frame)	~8% (1.6 kg)	~100% recovered	Re-melted aluminium ingots
Silicon (cells)	~5% (0.7–1 kg)	~85–90% recovered	Silicon feedstock (for metallurgical or solar reuse)
Polymers (EVA, backsheet)	~10% (2 kg)	0% material Often incinerated, emerging pilot recycling recovers EVA/fluoropolymers; scale-up and economics remain uncertain.	(Incineration energy or residue)
Copper (wires, ribbons)	~1% (0.2 kg)	~85–90% recovered	Recycled copper metal
Silver (cell contacts)	~0.05% (~10 g)	~90–95% recovered	Reclaimed silver (bullion or industrial)
Lead (solder)	~0.1% (10–15 g)	~95% recovered	Refined lead (for reuse or safe disposal)
Tin (solder)	~0.1% (~20 g)	~30% recovered	(Portion reclaimed; remainder in residue)

Source: Author's analysis and compilation based on published PV recycling studies and industry benchmarks.

Environmental and Health Risks of Improper Disposal—While intact PV modules are environmentally benign, broken or landfilled panels can leach toxic substances over time. In silicon modules, the main concern is lead from solder (and to a lesser extent tin); if panels are crushed in landfills and rainwater percolates, lead could seep into soil or groundwater. Thin-film panels contain cadmium, which is classified as a hazardous heavy metal, however, in CdTe modules the cadmium is in stable chemical form and sandwiched between glass, greatly limiting leachate under normal conditions. Nonetheless, in a landfill fire or under severe breakage/acid conditions, cadmium or selenium from shattered thin-film panels could be released. Studies by the IEA PVPS Task 12 have assessed scenarios like module breakage and fires they found that properly encapsulated modules have minimal emissions in leaching tests, often passing regulatory leachate thresholds.[80] For example, used silicon panels that pass TCLP (Toxicity Characteristic Leaching Procedure) can be classified as non-hazardous waste in the US However, if large volumes of PV modules are simply dumped without oversight, there is a risk of localized pollution, especially from older modules that used lead-based solder or from certain thin-film panels. Another environmental issue is the sheer volume of glass and plastic occupying landfill space and wasting resources, if not recovered. Overall, the consensus is that PV panels are safe in use and even in disposal if handled properly, but a lack of EoL management could pose avoidable hazards. This underlines the importance of proactive waste pathways: recycling greatly diminishes any risk by safely extracting and managing hazardous materials (like lead or cadmium) and by diverting bulk materials into productive reuse rather than into the ground.

Recycling Costs vs Rewards—Today, recycling PV modules is possible but not yet widely economical. Indicative estimates for India suggest recycling costs of roughly ₹4.11–5.02/W, equivalent to ₹41–50 lakh per MW of modules processed (before any EPR-linked revenue support), with module procurement/buy-back a major share of recurring costs. The challenge is that current resale prices for recovered glass and silicon barely offset the costs of collection, transportation, and processing making landfill the cheaper option in many regions. However, the situation is starting to change rising commodity prices and looming material bottlenecks (for example, limited supplies of high-purity polysilicon, silver, etc.) are driving up the potential value of recycled content. Analysis by Rystad Energy shows recyclable materials from retired PV panels will be worth over $2.7 billion by 2030 and a whopping $80 billion by 2050.[81] By 2040, recovered materials could account for 6% of solar PV investments (vs practically nil today) as manufacturers increasingly reuse glass, aluminium frames, and semiconductor materials from old panels. This financial upside, coupled with stricter regulations, may soon tip the balance in favour of recycling.[81] Already, solar recycling startups are emerging in the US, EU, and Asia, with large waste management firms eyeing PV as the next big growth area in e-waste.

A typical 1 MW of c-Si PV contains roughly 7–13 kg of silver depending on module type and about 40–50 tonnes of glass and metal that can be reused.[76,79,82] By 2050, the cumulative recovered materials from PV waste (if fully recycled) could exceed $15 billion globally, effectively creating a 'solar materials mine.[76] However, today the economics of PV recycling are challenging. The low value of some recovered materials (glass cullet, plastic) and the costs of collection and processing mean that without policy support, pure market forces might not drive high recycling rates. A recycler in India notes, "once dismantled, there is hardly any money from each individual part, the solar glass has no value".[83] Currently, the value drivers in recycling a silicon panel are the aluminium frame and copper and silver content these help offset the recycling cost. But trends such as thinner frames and reduced silver per cell (due to metallization innovations) are incrementally reducing the recoverable value per panel. This makes efficient logistics and perhaps subsidies or take-back mandates important to ensure recycling is economically viable. On the flip side, recycling prevents future costs of environmental remediation and can reduce reliance on virgin mining of materials (like aluminium, silica, silver) which has economic and strategic benefits (for example, silver and tellurium are on critical minerals lists). Some PV manufacturers also see recycling as an extension of their value chain; for instance, First Solar recovers cadmium and tellurium to feed back into new module production, thus securing a supply of costly tellurium.[84] Summarily, while current recycling revenue from materials is modest, the broader economic rationale including environmental externality savings and resource security, makes a strong case for institutional support of PV recycling programmes.

Regulations and EPR (Extended Producer Responsibility) — Around the world, policymakers are beginning to address PV module EoL through regulation. The EU has been a leader by including PV panels in the EU Waste Electrical and Electronic Equipment (WEEE) Directive since 2012. This established an EPR framework wherein PV manufacturers/importers in the EU must finance the take-back and recycling of solar panels at end-of-life. Thanks to this move, a dedicated industry infrastructure has developed in Europe. The EU sets targets (currently ~85% recovery by weight for PV modules) that recyclers must meet.[80] Compliance is high, and the cost is internalized by the PV industry, typically a small fee added to module cost to cover future recycling.

In India, recognizing the coming surge in solar waste, the government included PV modules under the e-waste management regime. In 2022, solar panels were officially added to India's E-Waste (Management) Rules, making producers responsible for handling and recycling PV waste. Manufacturers, asset owners, and importers are now required to register for EPR and ensure collection of EoL panels. The rules set an eventual goal of 80% recycling for electronics including PV modules by 2028–29.[85] However, these targets do not yet fully apply to PV waste.[86] India's Central Pollution Control Board (CPCB) has an online EPR portal tracking e-waste, and solar producers have begun obtaining EPR certificates.[87] In practice though, India's PV recycling infrastructure is nascent. There are only a few authorized e-waste recyclers handling solar equipment, and most end-of-life panels are either stockpiled, sold cheaply to scrap traders, or in some cases, dumped improperly. Logistics pose a challenge large solar farms in remote areas must transport bulky retired panels to recycling facilities, which can be costly for low-value output. As a result, informal sector involvement is a concern anecdotal evidence suggests some contractors simply remove panels to central yards and then don't know what downstream traders do with them. This could lead to unsafe dismantling (e.g., burning off backsheet to retrieve copper). The coming years are likely to see more explicit PV waste rules or guidelines to operationalize the EPR mandate.

TABLE 3.2. The comparative indicators illustrate circular-economy aspects of different PV technologies[75,88]

PV Technology	Hazardous Content (Yes/No)	Notable Hazardous Material	Critical Material Dependence	Estimated Recyclability (Recoverable % by Weight)
c-Si (PERC/ TOPCon)	Yes – low (lead solder)	Pb ~0.1%	Moderate – Ag (silver) use	~95%
c-Si (HJT/IBC)	Yes – low (lead, indium)	Pb (solder), Indium (ITO in HJT)	Moderate – Ag, In (for HJT)	~95% (similar to other c-Si)
Thin-film CdTe	Yes – moderate (cadmium)	Cd ~0.06% (in CdTe)	High – Tellurium (rare metal)	~90%
Thin-film CIGS	Yes – low (Cd in buffer)	Cd (in CdS layer), Se (selenium)	High – Indium, Gallium (scarce)	~90% (in theory)
Perovskite	Yes – moderate (lead)	Pb ~0.02% (in absorber)	Low – no precious metals (uses common Pb, Iodine)	~90% (anticipated, if designed for recycling)

Source: Author's analysis and compilation based on peer-reviewed literature and international assessments on photovoltaic material composition, hazardous substances, and recycling potential.
Note: Please find the detailed comparative breakdown of different PV technologies in Appendix-B (Table B.1)

3.2.2 Manufacturing Stage Waste in the PV Value Chain

While end-of-life waste is a delayed challenge, manufacturing-stage waste is an immediate reality for solar manufacturers. Ensuring circularity in the solar industry, therefore, requires attention to the entire production chain from silicon refining to cell/module fabrication not just end-of-life. Manufacturing-stage waste arises as scrap material, effluents, and emissions at various steps. Reducing and recycling this waste can improve resource efficiency, lower production costs, and reduce environmental footprints of PV manufacturing. Here we map the key process stages and their waste streams, along with typical quantities and management practices.

Key Process Steps and Waste Generation—The crystalline silicon PV value-chain has four main production steps—polysilicon production, wafer slicing, cell fabrication, and module assembly. Each step has characteristic waste outputs.

- *Polysilicon Production*: High-purity polysilicon is produced from quartz via chemical processes (e.g., Siemens process) that involve hazardous chemicals (silane, hydrogen, HCl). The waste from this stage (for integrated manufacturers) can include silicon tetrachloride (a toxic liquid by-product) and other chlorosilanes. However, modern polysilicon plants recycle most of these chemicals in closed loops unreacted silicon tetrachloride is typically converted back to feedstock, achieving >98% reuse. Thus, when well-managed, polysilicon manufacture's waste is minimal per unit of output, though it is energy intensive.
- *Ingot/Crystal Growth*: Polysilicon is melted and solidified into ingots (for mono-Si) or cast blocks (for multi-Si). Waste at this step might include crucible debris (quartz crucibles that sometimes break or wear out) and off-cuts from trimming the ingot ends. Spent crucibles (silica) can sometimes be recycled as raw material for ceramics or new crucibles. Overall, waste at this stage is relatively small (a few percent of the silicon). Some broken crystal material can be re-melted.
- *Wafer Slicing*: This is a major waste-generating step. Hard silicon ingots are sliced into thin wafers (~150–180 microns thick) using wire saws. The cutting process produces kerf loss essentially silicon sawdust. About 30–40% of the silicon is lost as fine powder in this step.[89] For example, to yield 1 kg of finished wafers, one must slice through ~1.4–1.7 kg of silicon, producing roughly 0.4–0.7 kg of kerf dust.[90] This kerf is mixed with the coolant (historically an oil-based slurry with abrasive SiC particles, now often a water-based lubricant with diamond wire). The resulting waste is a silicon sludge. It is estimated that around ~2,600–4,000 kg of silicon kerf waste is generated per MW of silicon solar panels produced (depending on wafer thickness and saw technology).[90,91] Managing this waste is challenging, it is high-purity silicon but in powdered form with contaminants. Past practice often involved disposing this sludge in landfills or attempting to recover the coolant. Today, there is intensive R&D on kerf recycling.[92] Some approaches include purifying and melting the silicon powder into ingots (difficult due to surface oxidation and impurities) or using the silicon waste in other products. One innovative reuse is in the cement industry, silicon kerf (after removing oil) can be used as a supplementary cementitious material, adding strength to concrete while sequestering the waste.[93] Companies are also investigating converting silicon kerf into silicon carbide or battery anode materials. While not yet widely implemented, kerf recycling represents a significant circular economy opportunity, as it could reduce the effective silicon consumption per watt. The silicon usage has already improved from ~16 g/W a decade ago to ~3–4 g/W today through thinner wafers and kerf reduction recycling kerf could lower it further.[94]
- *Cell Fabrication*: In this stage, the silicon wafers are turned into functioning solar cells through a sequence of chemical and high-temperature processes. This is another stage that generates substantial waste, especially in terms of chemical effluents and hazardous materials. Key waste streams in cell manufacturing include (detailed in Figure 3.1).
  a. Chemical Etching and Texturing Waste
  b. Doping and Diffusion Waste
  c. Metallization and Printing Waste
  d. Yield losses – Broken Wafers/Cells
- *Module Assembly:* In this final production step, cells are encapsulated in polymers, laminated between glass (and possibly a backsheet), and framed. Waste generated here is mostly non-hazardous solid waste for example, trimmings

A

Chemical Etching and Texturing Waste: Wafers are etched with acids/alkalis (like hydrofluoric acid, nitric acid, or sodium hydroxide) to clean and texture the surface. The spent acids and rinsing water form an effluent that is neutralized with lime, producing an acidic sludge (fluoride-rich). For example, neutralizing HF and other acids creates calcium fluoride sludge, a hazardous waste requiring disposal. A manufacturer reported that it generated 2.35 tonnes of HF-containing sludge per MW of cells, though it cut this to 0.91 tonnes/MW by process optimizations (REC Group, 2022).88 This highlights both the magnitude (hundreds of kg per MW) and the improvement potential (through better chemical management). Efforts are ongoing to recover and reuse acids, e.g., systems to reclaim HF from waste solution and re-introduce it in etching, which could dramatically reduce sludge.

B

Doping and Diffusion Waste: Cell production involves diffusing dopants (phosphorus or boron) into the silicon. Traditional processes use $POCl_3$ (phosphorus oxychloride) which can produce phosphoric acid waste and acidic off-gases (HCl). These are captured by scrubbers and result in a neutralized sludge similar to above.

C

Metallization and Printing Waste: : Silicon cells are metallized by screen-printing silver and aluminum pastes to form electrodes. Excess paste from screen cleaning, and rinse water containing solvent and metal particles, constitute another waste. Some silver/metal can be filtered out and recycled, but a portion becomes chemical waste. Newer cell technologies that use plating (e.g., plating Ni/Cu instead of some silver) generate plating baths and sludge. For instance, nickel plating can produce nickel hydroxide sludge (hazardous) when the bath is treated for disposal. Similarly, copper plating leads to copper-bearing waste. These sludges must be handled as hazardous waste due to heavy metal content.

D

Yield losses Broken Wafers/Cells: During cell processing, some wafers break or cells are discarded for defects. Broken silicon pieces with metal coatings or dopants can't simply be re-melted in the normal flow; they are often collected as waste. Some companies send this broken cell scrap to specialty recyclers who recover silver and copper, and sometimes reclaim silicon in lower-grade form. This scrap is relatively small (a few percent of input wafers). For example, if cell yield loss is 2%, that's ~20 kg of broken cells per MW (assuming ~1000 kg of wafers per MW). In summary, cell fabs primarily deal with hazardous chemical wastes (sludges, spent solutions) and minor solid wastes (scrap pieces). According to REC, the total hazardous waste from its integrated cell+module plant was about 1.06 tonnes per MW in 2021 (down from 2.57 t/MW in 2020), with the majority coming from chemical treatment sludge. The composition of REC's hazardous waste was 86% HF/acid sludge, ~10% sealing and potting compounds, ~4% broken wafers, and ~1% solvents (REC Group, 2022).88 This breakdown is likely similar in other cell fabs, fluoride or etch sludge dominates by mass.

FIGURE 3.1 Key waste in cell manufacturing

Source: Author's analysis

of EVA film and backsheet, edge strips of glass from cutting, discarded defective modules, and general packaging materials. There is also some use of sealants and potting compounds (for junction boxes) excess or expired material can become waste (some categorized as hazardous if they contain certain chemicals). A certain fraction of modules may fail quality control and be scrapped; these scrap modules are an internal waste stream that some manufacturers actually recycle in-house (REC reports it has a module recycling programme for its production scrap, achieving 100% recycle of those modules' materials. The non-hazardous waste per MW from module assembly and associated operations can be on the order of a few tonnes. REC's data showed 3.72 tonnes of non-hazardous waste per MW in 202.[95] This includes packaging (cardboard, wooden pallets which alone were ~37% of their non-hazardous waste), excess glass, plastic, etc. Much of this is recycled REC achieved a 58% recycling rate of its non-hazardous waste in Singapore by segregating metals, glass, paper, etc. Common practices include sending glass cullet to glass recyclers, recycling metal strapping or wires, and reusing or recycling wood pallets. Backsheet and EVA scrap, however, often end up in landfills because they are mixed plastic waste an area for improvement. Overall, module assembly waste is less problematic environmentally (being mostly inert), but reducing it improves resource efficiency and cost. Some manufacturers optimize sheet cutting to minimize off-cuts and return unused EVA/backsheet pieces to suppliers for re-melting when possible.

Waste Management and Circularity in Manufacturing: Manufacturers are increasingly adopting circular practices to handle these production wastes. Many larger PV manufacturers have environmental management systems (ISO: 14001) and track metrics like waste generated per MW and waste recycling rates. As seen with REC, concerted efforts can cut waste per MW significantly, they cut hazardous waste by >50% in one year through recycling and process tweaks. Some best practices include:

- *Chemical Recovery*: Installing systems to recover acids, bases, and solvents for reuse. This not only reduces waste but also lowers chemical purchase costs. For instance, recovering hydrofluoric acid (HF) from waste etch stream, or regenerating plating baths rather than disposing them after a few operating cycles.
- *Waste Valorization*: Finding external industries or partners that can use the manufacturing waste. An example of this is selling neutralized sludge (calcium fluoride) to companies that extract fluoride or use it in cement. REC's Norwegian operation sells over 90% of its process residues as products (e.g., a liming agent branded 'Solarite' from its silicon refining waste).[95] This effectively turns waste into a resource. Similarly, broken wafer/cell glass can be supplied to glass recyclers or fibreglass manufacturers.
- *Internal Recycling Loops*: Reintroducing scrap into the process. Ingot manufacturers can crush and remelt edge off-cuts. Cell fabs can sometimes recycle fractured wafers by melting them into feedstock for poly or ingots (if sufficiently pure). Module assembly scrap (like aluminium frame cuttings) can go right back to aluminium recyclers and then come back as new frames. Several companies also collect scrapped new modules (production fallout) and send them to the same recyclers handling end-of-life panels, this closes the loop and avoids those modules being wasted.
- *Design for Less Waste*: Improving process yield so that fewer items are rejected. For example, better handling equipment reduces wafer breakage rates; optimized printing reduces silver paste wastage; and precise laser cutting of backsheet can reduce trim scrap. The ongoing technology improvements, like larger wafers and thinner kerf diamond wire slicing, inherently yield less waste per unit output, e.g., moving from 180 μm to 150 μm wafers saves material, and diamond wire saws waste less silicon than older slurry saws.
- *Regulatory Compliance*: Manufacturing wastes, especially hazardous ones, are subject to industrial waste regulations. In India, for instance, the hazardous waste management rules apply meaning cell/module plants must get authorization to dispose of hazardous sludge and must hand it over to licensed treatment/storage/disposal facilities if not recycling it. Similar rules globally ensure acid sludges, heavy metal wastes, etc., are not dumped illegally. Compliance adds costs but also drives companies to find creative recycling solutions to avoid hefty disposal fees.

From Table 3.3, it is clear that for every MW of panels produced, several tonnes of assorted waste are generated. The largest contributor for silicon is kerf (which is non-hazardous but material-intensive), followed by chemical sludge (hazardous). The good news is that much of this waste is being tackled for instance, companies report recycling well over half of their non-hazardous waste and continuously reducing hazardous waste generation. Some, like REC, have even branded circular

TABLE 3.3. Major manufacturing waste streams in PV production (c-Si example) and management

Process Stage	Key Waste Stream	Approximate Quantity (per MW)	Management Practice
Wafer Slicing	Silicon kerf (sawdust sludge)	~2,600–4,000 kg/MW (30–40% of Si input)[96]	Filtered from coolant; exploring recycling (e.g., re-melt or use in concrete)
Cell Texturing/ Etch	Acid/alkali waste (HF, HNO_3, etc.)	~900 kg/MW (as neutralized CaF_2 sludge)[97]	Neutralize and landfill as hazardous waste; pilot systems to recover acids
Cell Diffusion	Spent dopant gases/ chemicals (e.g., $POCl_3$)	Few ~1-3kg/MW (as P-containing sludge)[98]	Scrubbed and neutralized; resultant sludge (phosphates) landfilled or treated
Screen Printing	Excess paste & cleaning solvents (Ag/ Al pastes)	~5–10 kg/MW (wet waste with metals)[99]	Distilled solvents for reuse; send metal-rich residue to smelters for metal recovery
Plating (if used)	Metal plating bath sludge (Ni, Cu)	~1–5 kg/MW (dry solids)100	Treat in-house or via hazardous waste contractor; recover metals where economical
QA/QC Fail cells	Broken/rejected cells & wafers	~20–50 kg/MW (2–5% yield loss)[98]	Collect and send to specialized recycler (to recover Ag, Cu, Si) or re-melt if feasible
Module Lamination	EVA/backsheet edge trim	~10–30 kg/MW[101]	Currently landfilled or incinerated (no easy recycling of mixed laminate)
Framing	Aluminium scrap (cuttings)	~5 kg/MW[102]	Recycled (re-melted)
General	Packaging materials (cardboard, pallets, plastic)	~300–500 kg/MW[103]	Reused when possible, otherwise recycled (paper, metal) or disposed (soiled plastics)

Source: Author's analysis and compilation based on representative industry data and secondary literature.

products from their waste (turning silane residue into a marketable soil treatment product). If kerf recycling methods become commercially viable, the silicon PV manufacturing process could approach a closed loop in terms of silicon usage significantly reducing the need for raw polysilicon for the same output.

Towards Circular Manufacturing—As India expands its PV manufacturing value chain, integrating circular economy principles from the outset will be beneficial. This includes investing in proper waste treatment facilities co-located with factories (for example, effluent treatment plants that can handle fluoride and heavy metals), training staff in waste segregation to maximize recyclables, and collaborating with recycling industries. Policymakers can encourage this by setting industry standards for waste recycling rates, rewarding facilities that exceed them with incentives and imposing proportionate penalties on those that fall short. Globally, organizations like the International Technology Roadmap for PV (ITRPV) now include resource efficiency metrics such as silicon utilization efficiency, lead-free solder, which push manufacturers towards waste reduction goals. There is also an opportunity in India to develop local recycling markets for manufacturing scrap e.g., a domestic smelter could specialize in extracting silver and copper from PV scrap (both manufacturing and EoL), ensuring valuable metals are not lost and creating jobs in recycling. The circular economy pathways in solar PV must encompass both the factory and the field turning today's waste into tomorrow's resource and ensuring solar remains a truly clean technology throughout its life cycle.

3.3. Traceability and Transparency Tools

In tandem with ESG and circularity efforts, the PV industry is rapidly adopting traceability and transparency tools to ensure that every step of the solar value chain can be verified and trusted. Indian module-assembly lines have begun integrating traceability measures mostly barcode or QR-code labelling linked to Enterprise Resource Planning (ERP) databases mandated under the ALMM; yet coverage is still partial, and data often stop at the cell or bill-of-materials level. To accelerate full end-to-end transparency, the PV sector can draw on proven models from regulated industries like pharmaceutical. Traceability has become especially pertinent after reports in recent years highlighted opaque supply chains for instance, concerns that polysilicon sourced from certain regions was linked to forced labour prompted major regulatory responses. Both the US and EU now mandate proof that imported solar products are free of conflict labour and meet ethical sourcing standards.[104] To meet these demands, manufacturers are leveraging cutting-edge tools, from blockchain to digital passports, alongside rigorous supply chain audits.

Blockchain Tracking—One emerging solution is using blockchain technology to create an immutable ledger of material provenance. In practice, this means each batch of raw material (polysilicon, silver, glass, etc.) and each PV module can be assigned a unique digital token that records its origin and custody through the supply chain. Several pilot projects in the solar industry have explored blockchain for tracing panels from factory to field. For example, a blockchain-based platform can log the source of polysilicon (by mine and smelter), the factory where wafers and cells were made, and the conditions under which a module was assembled. Once recorded, these entries cannot be tampered with, and authorized stakeholders (regulators, buyers, financiers) can instantly verify the data. Hence, the benefit is enhanced trust and auditability if an end-buyer or customs authority wants to check that an Indian module uses, say, only polysilicon from countries with no forced-labour allegations, the blockchain record provides a verifiable certificate. Blockchain can also streamline compliance by replacing paper trails (which can be forged or lost) with a secure digital trail. While challenges remain such as getting all suppliers to participate and ensuring data authenticity at the entry point this technology shows promise for complex global supply chains. Indian manufacturers could join consortiums working on blockchain traceability to stay ahead of import requirements.

Digital Product Passports (DPP)—The EU is in the process of implementing digital product passports for many goods, potentially including PV modules, as part of its sustainability legislation.[105] A DPP is essentially a digital profile for each product that contains standardized information such as composition, origin of components, carbon footprint, reparability, and end-of-life handling instructions.[106] For solar modules, a DPP might include data like the factory and country of manufacture, a materials list (including critical minerals content), the module's carbon emissions per watt during production, and whether the producer has an EPR scheme for take-back. The aim is to empower regulators and consumers with transparency for instance, European importers could scan a module's passport to check compliance with EU regulations (like restriction of hazardous substances or recycling rates). The DPP would also facilitate recycling later recyclers could quickly see what materials and in what quantities are in a module from its passport data. For Indian exporters, the implication is clear products will need rich data disclosure. Aligning with DPP requirements could become a prerequisite for market entry in Europe and other advanced markets. Indian firms and policy bodies should therefore watch the EU's developing specifications closely (the Eco-design & Energy Labelling Working Plan) and begin compiling the necessary data for their products. Establishing a national database or registry for Indian-made modules, where manufacturers upload key product information, could be a step towards a domestic digital passport system that can interface with global ones.

Supply Chain Risk Mapping—Beyond high-tech solutions, companies are returning to fundamentals by thoroughly mapping their supply chains and identifying ESG risk hotspots. This involves creating a supply chain map from raw materials to final product, listing all tier-1, tier-2, etc., suppliers and the countries of origin. Alongside this map, firms conduct risk assessments for example, flagging that polysilicon from a certain region may carry risk of forced labour, or that a particular supplier of silver paste does not have ISO 14001 environmental certification. Specialized analytics firms and industry initiatives now assist solar companies in this process, often using big data. By mapping out the chain, manufacturers can prioritize which links need closer monitoring or an alternative source. For instance, if 60% of a module's carbon footprint comes from aluminium framing sourced from coal-based smelters, the company knows to seek greener aluminium suppliers or offset that impact. Supply chain mapping also feeds into product carbon footprint labelling and lifecycle assessments, which are increasingly demanded by project developers. Notably, under the EU's Carbon Border Adjustment Mechanism (CBAM) and other emerging climate policies, the embedded carbon in industrial products could be taxed a scenario where Indian modules made with coal-heavy grids would become pricier in export markets. Traceability tools can document renewable energy use in manufacturing (e.g., if a module was produced in a factory powered 50% by solar or wind, the data can be traced and verified, potentially qualifying it for a lower carbon tariff or preference).

To support these efforts, several global standards and protocols have been introduced.

- The Solar Energy Industries Association (SEIA) Supply Chain Traceability Protocol (developed in partnership with Clean Energy Associates) is a practical guideline for documenting the source of components in solar modules.[104] It was created in response to the US Customs' Withhold Release Orders (WRO) on solar imports suspected of using forced labour. Indian manufacturers shipping to the US have begun adopting this protocol, which involves providing documentation packages tracing the origin of polysilicon in their modules (e.g., affidavits from suppliers, batch tracking numbers, transportation documents). The protocol effectively standardizes what evidence is needed to prove a clean supply chain. Compliance teams in India are now expected to maintain meticulous records at the batch level; a single missing link could result in a shipment being detained by US customs. Thus, adhering to such protocols is becoming a competitive necessity.
- The Solar Stewardship Initiative (SSI), mentioned earlier for ESG, is also developing a chain-of-custody traceability standard published in December 2024.[107] This complements the SSI ESG certification by enabling end-to-end verification of where each of the PV product's components come from. SSI traceability certification might allow Indian module makers to prove that, for example, every silicon wafer in their module was sourced from an audited conflict-free supplier. If formally recognized by the EU (as SolarPower Europe advocates), such certifications could streamline compliance with European due diligence laws. Indian exporters should consider piloting the SSI traceability system, as it may become a marketing advantage (SSI-certified clean supply chain) when selling in Europe, the UK, and other regions that value ethically sourced solar.
- Broader frameworks like the UN Guiding Principles on Business and Human Rights and the Organization for Economic Co-operation and Development (OECD)'s due diligence guidance for minerals also inform what transparency is expected. Under the new Corporate Sustainability Due Diligence Directive (CSDDD), even indirect suppliers to European companies must identify and mitigate human rights and environmental risks.[108] This essentially pushes due diligence obligations upstream to manufacturers. In practical terms, an Indian PV manufacturer might soon be contractually required by an EU customer to conduct annual third-party audits of its silicon or copper suppliers, publish sustainability reports, or implement grievance mechanisms for workers, all as a part of traceability and accountability.

India's Readiness and Gaps—Currently, the Indian PV manufacturing ecosystem has limited traceability practices in place, especially beyond tier-1 suppliers. Most module makers source their cells or wafers from a mix of domestic and international suppliers but may not have visibility further upstream (e.g., where the supplier's supplier got their polysilicon from). A gap analysis reveals several areas for improvement— (1) Data infrastructure – Firms need IT systems to track and store supply chain data (potentially integrated with blockchain or ERP software) instead of ad-hoc paperwork. (2) Supplier engagement – Indian companies will have to demand more information and compliance from their suppliers; this might be challenging for smaller firms buying from commodity markets or traders.

TABLE 3.4. Solar-PV supply chain — traceability and verification checkpoints

S. No.	Stage	Traceability Data Elements	Traceability Tool	Why Does This Matter?
1	Mining — quartz, silver, copper ores leave the mine	Mine-site ID, labour & ESG risk rating	Blockchain batch ID + "risk flag"	Locks origin before materials can move
2	Transport to refinery	Container route, seal status	GPS smart seal	Stops diversion or switching of cargo
3	Polysilicon refining	Energy source, carbon footprint, audit sign-off	Energy-meter feed → Digital Product Passport	Confirms low-carbon, lawful production
4	Ingot & wafer slicing	Lot number, wafer thickness, yield	Factory MES → Product Passport	Links each wafer to its material history
5	Cell fabrication	Cell efficiency, chemicals used	Inline test data → Product Passport	Verifies performance and chemical safety
6	Module assembly	Bill of materials, panel serial-number	QR/NFC tag linked to passport	Prevents counterfeits, quick customs scan
7	Global shipping	Country of origin, CO_2 for border levy	E-bill of lading on blockchain	Blocks trans-shipment fraud, automates CBAM
8	Installation on site	GPS location, installer ID, date	Installer app writes to passport	Starts warranty, ties panel to location
9	Operation & recycling	Lifetime performance, recycling proof	SCADA/drone data + recycling token	Supports insurance claims & closed-loop recovery

Source: Author's analysis and conceptual compilation drawing on policy literature on Digital Product Passports, blockchain-based supply-chain traceability, ESG due-diligence requirements, and PV lifecycle management practices.

(3) Standards adoption – As of 2025, few Indian module manufacturers have obtained international certifications like ISO 20400 (sustainable procurement) or undergone third-party social audits for their supply chain. There is a knowledge gap that industry associations and the government can help fill by providing training on compliance and creating templates for traceability documentation.

On a positive side, India's drive for Atmanirbhar Bharat (self-reliance) in solar manufacturing could indirectly aid traceability. As more upstream materials (cells, wafers, polysilicon) are made in India under the PLI scheme, the supply chain shortens and becomes more transparent domestically. A polysilicon plant in India, for instance, would be subject to Indian labour laws and environmental oversight, which are easier for Indian module companies to monitor than a distant foreign operation. This localization combined with digital tools can enhance overall traceability. Moreover, Indian startups in the blockchain and IoT space are well-positioned to offer homegrown traceability solutions, for example, using IoT sensors and QR codes on pallet shipments of solar glass or cells, feeding into a blockchain ledger accessible to all stakeholders.

Government policy can support these tools by incentivizing their adoption. A possible measure could be to integrate traceability requirements into the ALMM criteria or future quality standards for instance, mandating that to be ALMM-listed (hence eligible for domestic projects), a manufacturer must provide a supply chain disclosure and commitment to ethical sourcing. This would push even those focused on the domestic market to upgrade their transparency practices, preparing them for export as well. Additionally, trade promotion agencies could market Indian solar products as responsibly made, if the industry widely implements traceability, turning compliance into a competitive edge.

The traceability and transparency are posed to be the new normal far from being a bureaucratic burden, they are strategic instruments to ensure supply chain resilience and market acceptability of Indian solar products in an ESG-conscious era.

3.4. Policy and Incentive Alignment

Achieving the ESG and circular economy goals outlined above will require smart alignment of policies and industry incentives. India already has several supportive policies in place the task now is to tweak and expand these instruments to explicitly promote sustainability in the solar manufacturing ecosystem.

Existing fiscal benefits—Solar panels enjoy a relatively concessional Goods and Services Tax (GST) rate of 12% (as opposed to standard 18%), which was set to encourage renewable energy deployment.[109] While this primarily spurs demand, a similar approach could incentivize sustainable manufacturing, e.g., a further GST reduction or rebate for modules that use recycled content or have an eco-label could be considered. Additionally, India is developing a domestic carbon credit trading market under updated energy conservation laws. Solar manufacturers who invest in carbon-cutting measures (like using solar power for their factories or improving energy efficiency of ingot furnaces) may be able to monetize the carbon reductions. For example, if a PV company powers 50% of its production with onsite renewables, it could earn tradable carbon credits under the forthcoming framework, creating a revenue stream that offsets the cost of green electricity. On the international front, companies that document low product carbon footprints can potentially earn a premium or avoid future carbon border taxes. Aligning fiscal tools with these advantages, such as offering accelerated depreciation or tax write-offs for capital spent on pollution control, waste recycling equipment, or ESG certifications would nudge firms to invest in sustainability.

Production-Linked Incentive (PLI) scheme adjustments—The flagship PLI scheme for high-efficiency solar PV modules has catalysed large investments in integrated manufacturing. PLI offers manufacturers with cash incentives per watt of output based on efficiency and domestic value addition. This can be evolved into a vehicle for ESG promotion by adding ESG-linked bonus incentives. Concretely, the government could introduce a 'green bonus' (say 1–2% extra incentive) for manufacturers who meet specific sustainability milestones. These milestones might include achieving a certain recycled content in their modules, for example, using renewable energy such that the module carbon footprint is ≤1.5 kg CO_2/W, or designing modules for ≥90% recyclability. This idea echoes global trends; the US, under the Inflation Reduction Act, provides production tax credits for clean energy manufacturing and is exploring higher credits for lower-carbon products.[110] While India's PLI is a domestic scheme, tweaking it to reward sustainability would encourage new factories to invest in things like wastewater recycling, renewable power usage, and eco-design, giving India a head-start on emerging trade norms. A policy tweak could also incentivize R&D in green manufacturing under PLI, a portion of the outlay could be earmarked as grants for researching lead-free solder, non-toxic encapsulants, or high value recycling processes, aligning manufacturing growth with sustainability innovation.

Approved List of Models and Manufacturers (ALMM) as an ESG Gatekeeper—The ALMM policy, which mandates the use of domestically approved models for projects in India, can be a powerful lever to enforce ESG compliance. Currently, ALMM criteria revolves around product quality (IEC standards, BIS certification) and manufacturing in India. Going forward, ESG criteria can be layered onto ALMM. For example, the ALMM application could require manufacturers to submit an ESG compliance plan including proof of an EHS (Environment, Health & Safety) management system (such as ISO 14001 and ISO 45001 certifications for environment and occupational safety), a commitment to EPR (module take-back agreements or tie-ups with recyclers), and perhaps a basic supply chain due diligence report. The government could stipulate that by a certain date, only companies that have a verified EPR system (per the e-waste rules) will remain or be added on the ALMM. The ALMM could thereby act as a filter ensuring any panel sold in India is backed by responsible manufacturing and end-of-life stewardship.

Additionally, differentiation within ALMM could be introduced. A tiered system say ALMMG+ might highlight manufacturers with superior ESG performance (akin to a green channel). Government tenders could then give preference or weightage to ALMMG+ manufacturers. For instance, public-sector solar plants might score bids higher if panels come from an ALMMG+ (ESG-rated) source. This creates market rewards for ESG leaders. It also aligns with international expectations, because if Indian developers are using ESG-compliant modules at home, those modules will more easily meet export market norms too.

Extended Producer Responsibility (EPR) Enforcement and Incentives—Under the 2022 rules, every PV manufacturer/importer has quantifiable responsibilities to collect and recycle a portion of sold modules.[86] The policy challenge is to ensure that this is taken seriously and not treated as a paperwork exercise. One step is to develop a robust monitoring mechanism like requiring annual public disclosure of how many tonnes of solar waste each company collected and recycled, versus its obligation.[111] Making this data transparent (for example, publishing an EPR compliance leaderboard) would use reputational pressure to drive compliance. Non-compliant firms should face penalties or loss of licenses enforcement provisions that need to be detailed in the upcoming EPR guidelines. On the incentive side, the government could integrate EPR with fiscal benefits. For example, companies that exceed their EPR targets (collecting more waste than required or achieving higher recycling rates) might earn additional import duty exemptions on raw materials or equipment. Conversely, repeated failure in EPR could result in suspension from schemes like PLI and ALMM or penalties, creating a direct business case for compliance. Another idea is a deposit-refund scheme**,** at the time of module sale, a small environmental deposit (perhaps ₹1 per module or per kg) could be charged—this pooled fund would refund or reward manufacturers for proper end-of-life recycling of those modules in the future. Such a scheme shares the burden between producer and end-user and ensures funds are available when recycling is due.

TABLE 3.5. Comparative status – ESG & circularity frameworks in PV (India vs Global)

Aspect	India (2025)	European Union	United States	China
ESG Compliance Enforcement	**Moderate:** Mandatory ESG reporting for top corporations, supply chain due diligence is largely voluntary. Investors increasingly demand IFC/Equator compliance for large projects.	**High:** Comprehensive regulations—e.g., Corporate Sustainability Reporting Directive (CSRD) and upcoming due diligence laws compel companies to assess ESG risks. Strict import bans on forced-labour products and taxonomy rules promote clean supply chains.	**Medium:** No broad ESG disclosure mandate yet, but strong import enforcement (UFLPA) on labour standards. Many utilities and developers follow ESG criteria for procurement. Federal renewable projects often require domestic content and labour standards (via IRA).	**Moderate:** Government issues guidelines for green supply chains, and top firms publish ESG reports, but less transparency overall. Forced labour or pollution standards exist on paper, but enforcement is inconsistent. Focus is more on localization and cost than on independent audits.

Aspect	India (2025)	European Union	United States	China
EPR & PV Waste Policy	**Emerging:** Solar panels added to e-waste rules in 2022, requiring producers to register for EPR. No specific collection targets for PV yet, recycling industry at pilot stage. (MoUs like NISE-Attero for R&D).[112]	**Mature:** WEEE directive covers PV modules since 2012, making producers finance end-of-life recycling. Well-established take-back networks. Upcoming Digital Product Passports to further ease recycling by providing material data.	**Limited:** No federal EPR for PV. Only a few states (e.g., Washington) have solar panel stewardship programmes requiring manufacturers to plan for end-of-life. Recycling mostly market-driven, with a few startups (e.g., SolarCycle) scaling up.	**Developing:** No nationwide PV EPR law. Government encourages comprehensive utilization of solar waste; a few recycling facilities exist (often run by big manufacturers for internal needs). Focus on reusing silicon and glass in new panels. Large volumes of waste expected post-2035, so policies likely to evolve.
Circularity infrastructure	**Nascent:** A handful of labs and startups working on PV recycling. Informal sector currently handles most scrap (inefficiently). No dedicated recycling plants at scale yet.	**Advanced:** Several commercial PV recycling plants operational (in France, Germany, Belgium). Established logistics for collection (via installers or municipal waste). Glass, aluminium from old panels are routinely recovered and fed into industry. R&D ongoing to improve recovery of silicon and silver.	**Emerging:** Growing interest due to large utility solar fleet. A few pilot recycling facilities. New investments spurred by the sheer volume of retiring panels by 2030. However, without mandates, landfill is still common.	**Moderate:** Top manufacturers (e.g., Trina, Jinko) have internal recycling for factory scrap and are researching EoL recycling. Government set targets for overall recycling rate in renewables. Some provinces may pilot circular programmes. Still, most used panels are stockpiled, large-scale recycling will be needed as domestic installations age.

Source: Author's analysis and compilation based on policy documents, regulatory frameworks, and secondary literature on ESG compliance and PV waste management.

Roadmap for Sustainable Solar PV Manufacturing (India) – Short, Medium & Long-Term Actions

1. Short-Term (1–2 years) – *Establish the Foundation*

   a. *Finalize EPR Guidelines for Solar PV Manufacturing*– Notify detailed rules on collection and safe disposal of PV waste. For instance, define responsibilities for setting up collection points, starting with states having large deployment of solar PV and begin reporting collection volumes. Provide initial incentives to kickstart at least 2–3 specialized PV recycling plants as required.

   b. *Supply Chain Transparency Mandate*– Require solar manufacturers (especially PLI beneficiaries) to disclose key supply chain information. Create a national registry where manufacturers report the origin of critical materials (silicon, cells) and certify compliance with labour and environmental standards. This could tie into ALMM listing e.g., only list companies that share traceability data. Leverage tools like SSI's traceability standard once available.

2. Medium-Term (3–5 years) – *Scale and Integrate Circular Practices*

   a. *Incentivize Green Design & Manufacturing*— Introduce a Green PV Mark or rating. Modules that are made with ≥50% renewable energy or contain ≥20% recycled content or are fully restricted of hazardous substances (RoHS) compliant (no toxic lead) could get a certification and a fiscal incentive (lower GST or preference in tenders). This would push the manufacturers to invest in low-carbon processes and design for recyclability (e.g., detachable frames, recyclable backsheets).

   b. *Invest in Recycling & Recovery Infrastructure*— Set up regional solar waste processing hubs (North, West, South India where most solar capacity lies). Use public-private partnerships to build facilities that can collectively handle at least 50,000 tonnes of PV waste per year. Simultaneously, develop a skilled workforce for dismantling and recycling. The government can facilitate tie-ups between module manufacturers and recyclers (like the NISE-Attero collaboration and ensure recyclers have access to steady waste supply (possibly by retiring old government-owned panels early for recycling trials).[104]

3. Long-Term (5–10 years) – *Transform and Lead*

   a. *Closed-Loop Manufacturing Ecosystem*— Aim to use a significant portion of recovered materials in new Indian-made panels. For example, target that 30% of new solar panels made in 2030–32 use some recycled glass/aluminium from old panels. Encourage contracts between recyclers and manufacturers for material offtake. This will reduce import dependence on raw materials and create a truly circular value chain. Government can support R&D for refining recycled silicon for new wafers—a game-changer for closed-loop production.

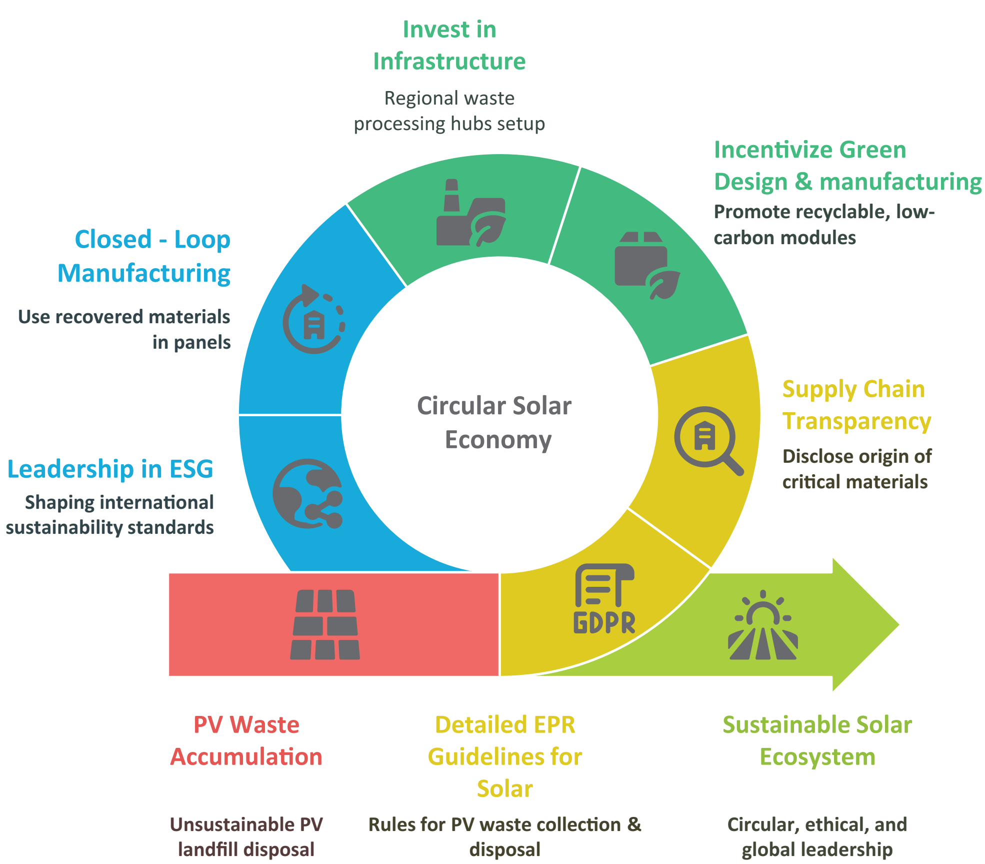


FIGURE 3.2 Achieving sustainable solar in India

b. *Leadership in ESG Standards*— India should position itself as a global leader in sustainable solar by shaping and adopting international standards. Indian firms should not just comply with EU or US norms but also help define them. This could involve Indian representation in bodies like IEC (for new standards on PV Lifecycle), co-developing the digital product passport framework, and exporting not only panels but sustainable practices. In the longer run, being a leader means Indian solar products are globally recognized for quality, sustainability, and ethics, giving them an edge in markets worldwide.

Roles & Responsibilities

- *Government of India*— Set clear regulatory standards (EPR targets, labour and environmental norms) and provide enabling policies (PLI tweaks, tax incentives for recycling). Ensure inter-ministerial coordination so that industrial policy (Make in India) and environmental policy (Circular Economy initiatives) reinforce each other. Lead by example by requiring ESG criteria in all government solar procurement.
- *State Governments*— Facilitate the setup of recycling facilities and sustainable manufacturing plants by allocating land, swift approvals, and even state-level green industrial policies. They can also enforce compliance at ground level—e.g., ensuring that end-of-life solar panels (especially from state-run solar parks) are properly handed over to authorized recyclers, not scrap dealers. States like Gujarat, Rajasthan, Tamil Nadu (with high solar deployment) should pilot take-back programmes in collaboration with manufacturers.
- *Solar PV Manufacturers (OEMs)* — Integrate ESG in corporate strategy—assign teams for compliance and sustainability, obtain relevant certifications, and publicly report ESG performance. Proactively set up end-of-life management programmes (for instance, offer to take back panels sold 10–15 years ago). Collaborate to form an industry PV Recycling Association to collectively fund recycling R&D and infrastructure. Also, engage in supplier development by helping upstream suppliers (silicon, glass, etc.) to improve their ESG standards through audits and capacity-building.
- *EPCs & Solar Farm Developers*— Design projects with circularity in mind (use durable, easy-to-disassemble mounting structures, maintain documentation of component serial numbers for future tracking). Work with module suppliers that provide sustainability documentation. As project owners, plan for decommissioning even at the commissioning stage set aside decommissioning bonds or reserves that will fund future recycling. Developers can also aggregate and provide volumes of end-of-life panels to make recycling economically viable (acting as the link between many distributed small generators and the recycling industry).
- *MSMEs & Startups*— Innovate in niches like low-cost recycling tech, blockchain traceability solutions, AI for supply chain monitoring, or services for refurbishing/reusing panels. Smaller enterprises can seize new business opportunities in solar asset management by offering module cleaning/maintenance that extends life, or secondary market platforms for used panels (delaying waste). Government incubators and green funds should support these cleantech startups, as they add agility and creativity to the sector's sustainability efforts.
- *Investors & Financial Institutions*— Incorporate rigorous ESG due diligence in lending and investment decisions for solar manufacturing and projects. This means requiring borrowers to have waste management plans, supply chain maps, and necessary certifications. Provide preferential financing rates or improved terms for projects/components that meet high ESG benchmarks (for example, a green loan that has a lower interest rate if the borrower achieves certain ESG KPIs).

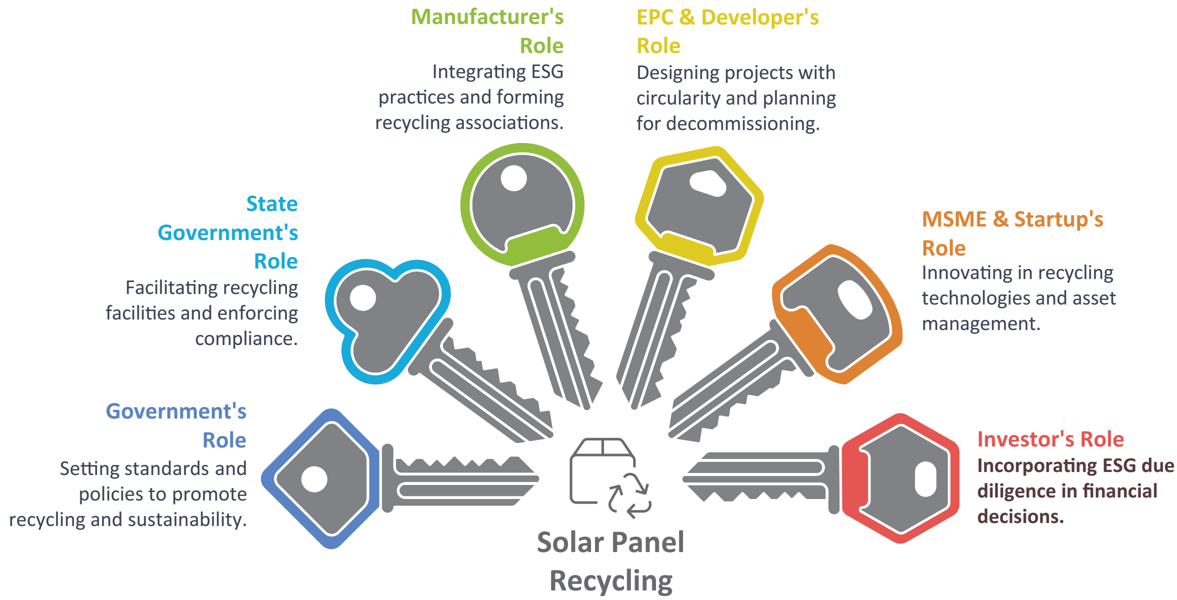


FIGURE 3.3. Stakeholder roles in solar sustainability

By following this multi-pronged roadmap and clearly assigning responsibilities, India can ensure that its solar power revolution is not only gigawatt-rich but also sustainably grounded. In doing so, India's solar industry can mature into a model that harmonizes with environmental goals and meets global investor expectations, securing its place at the forefront of the clean energy economy for decades to come.

WAY FORWARD AND RECOMMENDATIONS

Chapter 4

WAY FORWARD AND RECOMMENDATIONS

4.1. Integrated Policy Roadmap

A coordinated policy roadmap is crucial to capitalize on these opportunities and systematically close gaps. India's policy toolkit for solar manufacturing including domestic content mandates, import tariffs and production incentives must evolve in an integrated, forward-looking manner. Key recommendations are:

- *Phased Extension of Domestic Content Requirements (ALMM) Upstream*— India should extend ALMM, which currently certifies module makers to the entire value chain. MNRE has already announced ALMM for cells from June 2026, now it is time to extend it to wafers and polysilicon starting a year or two thereafter. In parallel, to manage tariff impact, the cell and upstream ALMM transition should be ring-fenced to government and PSU-linked procurement, or to a defined annual allocation (for example, 25–50 GW), while open-access and competitively tendered private projects retain flexibility to procure least-cost modules during the scale-up period. The phased approach gives investors certainty (an assured market for compliant domestic product) while allowing time to build capacity in stages. It leverages the existing ALMM framework to progressively deepen local content starting from modules (ongoing) to cells (2026), and thereafter to wafers and polysilicon between 2028–2030. Clear timelines will guide industry investment, for example, manufacturers would know that by 2028 only an ALMM-approved domestic wafer will qualify a module as 'Made in India', incentivizing them to integrate backwards and to ease lingering concerns of developers worrying about near-term cost and availability; the ALMM timetable should be reviewed annually by an MNRE-industry panel, with the option to recalibrate deadlines if capacity lags or prices spike. Clear but adjustable milestones thus give investors certainty, support India's build-rate targets, and balance the interests of both camps.
- *Harmonized Fiscal and Regulatory Support for ESG-Compliant Upstream Investments*— To spur the upstream segment (polysilicon, ingot, wafer), the government should roll out blended fiscal incentives, with a special focus on facilities that meet high ESG standards. These could include tax breaks, viability gap funding, accelerated depreciation, for new plants, conditional on using renewable energy in production, recycling waste, and other ESG metrics. The aim is to make India a hub for green silicon and other inputs. For instance, polysilicon refining being energy-intensive, incentives can be tied to using solar and/or wind power for those plants, so that Indian polysilicon is ultra-low carbon. Central and state incentives must be harmonized to present a unified package, e.g., combining the central PLI scheme (which offers production subsidies for integrated solar factories) with state-level capital subsidies or land facilitation, so that upstream investors see a clear, attractive RoI. This will support projects like the planned 10 GW polysilicon plant by 2027–28, and encourage new entrants, while ensuring these new factories are world-class in sustainability, a growing requirement for global solar supply chains.
- *Biennial Incentive-Performance Review Mechanism*— Implement a biennial review of all major solar manufacturing support schemes (PLI, ALMM enforcement, import duties, etc.), tied to milestones in capacity addition and ESG

performance. Every two years, a joint committee of MNRE, Ministry of Finance, and industry experts should evaluate some key factors Are the capacity targets on track? Are beneficiaries meeting localization and ESG commitments for example, percentage of renewable energy usage, pollution control, labour standards, etc. Based on this, policies can be tweaked—for example, if domestic cell production is lagging, the review might recommend extending higher tariffs on cell imports for 2 more years, or if certain firms aren't achieving the specified capacity, their incentive disbursements could be reallocated. Conversely, if the industry is ahead of targets or module prices have reached parity, the government could consider scaling back protections to reduce costs for developers. This feedback loop will ensure policies remain adaptive, cost-effective, and focused on outcomes (such as reaching specific GW of integrated capacity before 2030 or certifying all new plants for ISO environmental standards). Importantly, tying the review to ESG metrics means that a company's performance on factors like energy efficiency, emissions, and workplace safety could influence its continued eligibility for subsidies–encouraging manufacturers to build not just capacity, but quality capacity aligned with India's sustainable growth vision.

Together, this integrated policy roadmap phasing in local content requirements upstream, aligning incentives with green goals, and rigorously monitoring progress, will create a stable yet dynamic policy environment. It signals long-term commitment to the domestic PV ecosystem (de-risking big investments in mining, materials, and fabs) while retaining flexibility to adjust course. The policy framework should transition India from heavy import reliance to a position where domestic producers meet most of the nation's needs and compete globally, all underpinned by strong compliance with ESG norms.

4.2. Financing and Risk-Sharing Instruments

Achieving the scale and technological depth envisioned for India's PV manufacturing will require huge capital investments from mega polysilicon plants and wafer fabrication facility (fab) to new equipment for cell lines. Mobilizing this capital at an affordable cost is a major challenge, especially given high interest rates and the evolving tech risks. To address financing constraints, a set of financing and risk-sharing instruments is proposed.

- *Sovereign 'Green PV Bonds' with Interest Subsidy*— The government can launch sovereign green bonds earmarked specifically for solar manufacturing and infrastructure, raising debt at attractive rates to on-lend or invest in the sector. India has already seen success with sovereign green bonds for renewable energy projects, which attracted investors at lower yields due to the green premium.[113] A dedicated 'Green PV Bond' could finance a pool of low-interest loans for setting up factories or procuring high-tech equipment. For example, if the government raises funds at ~7% via such bonds (as in recent green bond issues), it could on-lend to manufacturers at, say 4–5%, covering the interest differential as an interest subvention. This dramatically lowers the cost of capital for domestic players, providing a level playing field with Chinese competitors who benefit from ultra-cheap state financing. The bonds would appeal to ESG-focused domestic and global investors, and the proceeds can be managed by a national renewable energy bank or Indian Renewable Energy Development Agency (IREDA). In essence, the sovereign takes on some financing burden (backed by its credit rating) not only to provide loans to the industry at a cheaper rate but also to de-risk them, recognizing solar PV manufacturing as infrastructure industry of national importance.
- *Blended Finance through NIIF and DFIs with Risk Mitigation Tools*— A blended finance approach can pool in public as well as private investment. The National Investment and Infrastructure Fund (NIIF), backed by government and foreign investors, can create a solar manufacturing fund that co-invests equity in large projects (e.g., a polysilicon or solar glass plant) alongside private firms. This reduces the equity risk for private investors. Similarly, Indian development finance institutions (DFIs) and global ones (World Bank's IFC, Asian Development Bank, etc.) can provide patient capital or guarantees. The blending of concessional and commercial funds will share risks for instance, first-loss capital from a climate fund can insure other investors against technology failure or market downturns. Additionally, specialized tools should be offered to

mitigate specific risks a cross-currency hedge facility (possibly through RBI or SBI) to protect manufacturers taking foreign loans for equipment purchases against rupee depreciation, and integration of carbon credit revenues to improve project viability. For the latter, if a new manufacturing facility uses 100% renewable power and thus significantly cuts carbon footprint, it could generate carbon credits or certificates that are monetizable a framework could allow the facility to sell these to voluntarily offset buyers or into any future carbon market, providing extra income. By packaging loans/equity with such enhancements, the effective financing cost comes down and investors will be keener to back capital-intensive, longer-payback ventures. An example structure could be a new wafer fab receiving 30% equity from NIIF (with sovereign anchor), 50% debt from banks/DFIs at concessional rates, and 20% equity from the private promoter; currency risk on foreign machinery is hedged by a government facility and the project is eligible for earning green credits for any exported emissions savings. This kind of comprehensive financing bouquet solution will be able to tackle the twin problems of high cost of capital and perceived risk, which currently hinder upstream solar investments in India. In addition, the government can explore credit guarantees for equipment leasing programmes (so smaller manufacturers can lease advanced tools instead of heavy upfront purchases) and work with insurance companies to create products that insure against policy changes or power supply disruptions for factories.

Overall, these financing instruments will ensure well-conceived projects do not falter due to lack of affordable finance. They shift part of the risk to actors better able to bear it (sovereign, international finance), unlock larger pools of capital, and in return, bind the industry to national goals (through conditions on ESG, domestic sourcing of machinery, etc., attached to the funding). With sustainable financing pipelines in place, India's PV manufacturing can scale rapidly to meet the 2030 and beyond targets without being stymied by funding hurdles.

4.3. R&D and Innovation Clusters

To sustain competitiveness beyond just scale and cost, India must foster a culture of innovation in solar manufacturing. As the industry races towards higher efficiencies (TOPCon, heterojunction, Interdigitated Back Contact (IBC), tandem cells) and improved processes, a coordinated R&D ecosystem will ensure India's manufacturers are technology leaders, not laggards or followers. Establishing innovation clusters and shared R&D infrastructure is recommended to drive this forward.

❖ *Semiconductor Mission and its Linkage to Solar*— India launched the India Semiconductor Mission in 2021 with an aim to establish semiconductor fabs and display fabs in the country (with an outlay of ₹76,000 crore (~$10 billion) incentive package.[114] While semiconductors (chips) are a distinct sector, there is an overlap in the foundational technology and supply chain with solar PV, particularly at the polysilicon and wafer stage. Producing electronic-grade polysilicon and silicon wafers for chips is even more demanding than for solar; success in that domain could have spill-over benefits to solar. For instance, if a silicon purification plant is set up for semiconductor-grade silicon, off-spec or lower-grade output could potentially be used for solar-grade polysilicon. Moreover, the ecosystem of suppliers (chemicals, gases, crystal-growing equipment, precision tooling) that develops around a semiconductor fab can also support solar wafer and cell manufacturing, which use same analogous processes (crystal growth for ingots, slicing, diffusion furnaces, etc.). The solar industry must seek synergies with semiconductor sector one example is to explore setting up common manufacturing clusters where both semiconductor and solar factories can share infrastructure. Additionally, skills developed under the semiconductor programme (such as ultra-clean manufacturing practices, metrology, automation) will enrich the talent pool available to solar manufacturers.

❖ *Shared Advanced Pilot Fabs for Next-Gen Technologies*— The government, in partnership with industry and academia, may set up one or more pilot fabrication facilities (fabs) focused on emerging PV technologies for example, Interdigitated Back Contact (IBC) solar cells and perovskite-silicon tandem cells. These would be like centres of excellence where new processes can be developed and tested at, say, 100 MW scale before commercial scaling. Individual companies might find it too risky or expensive to invest in pilot lines for unproven tech; a shared facility (possibly at a national lab or an innovation park) fills the gap. Participants (domestic manufacturers, start-ups, university researchers) could access the pilot fab to experiment with HJT, IBC cell deposition techniques, new transparent conductive oxides, tandem cell stacking processes, etc. The pilot line provides prototyping, testing, and training de-risking the leap to mass production. For instance, a 50 MW pilot line for tandem perovskite-silicon cells could be awarded through an open, outcome-based competition. Proposals may be evaluated on verifiable R&D milestones, cost-sharing commitments, and a clear scale-up roadmap. This competitive, performance-driven approach would ensure that the pilot is led by the team most likely to deliver results. This mirrors successful models abroad such as in Belgium which offers semiconductor pilot fabs, or the US DOE's consortia but tailored to solar.[115,116] India could have these pilot fabs producing cells with higher efficiency, enabling local firms to gain know-how before investing in full-scale IBC lines. Such clusters will also help develop process engineers and technicians skilled in these new technologies, feeding the workforce pipeline.

- *Public–Private Consortia for PV Equipment & Materials R&D*— Given the current import dependence on manufacturing equipment, India needs its own development of critical tools and materials. It is proposed that forming consortia can bring together equipment makers, PV companies, and research institutes to collaborate on R&D projects. For example, a Solar Equipment Innovation Consortium could focus on developing an indigenous PECVD reactor for thin-film deposition, or a new wire-saw technology for wafering. Members might include established Indian engineering firms (e.g., BEL, BHEL, or semi-equipment firms, startups, and technical institutes. The government can co-fund these projects through the Anusandhan National Research Foundation (ANRF) once an independent performance audit has assessed the tangible outcomes of MNRE's existing renewable energy R&D scheme, thereby letting ANRF manage merit-based R&D grants while MNRE focuses on policy and programme oversight. The goal is to achieve at least a few homegrown tool prototypes by 2028 such as an India-made tabber-stringer or automated quality inspection system that can be commercialized. Additionally, R&D efforts should target materials recycling and circularity for instance, a consortium on solar module recycling to develop processes for extracting silicon, silver, and glass from end-of-life panels. MNRE has already identified PV recycling as a priority and is supporting research in recovery of critical materials.[117] Building on that, a partnership between industry (module manufacturers who will have waste) and national labs can pilot recycling plants. By creating these innovation networks, India leverages collective expertise and sharing of costs/benefits. Breakthroughs from consortia say a successful kerf-less wafer slicing technique or efficient silver recovery method would be diffused to all consortium members, uplifting the entire industry's capability.
- *Innovation Cluster Hubs*—The government can accelerate technology diffusion by designating Solar Manufacturing Technology Parks in PV-heavy states such as Gujarat and Tamil Nadu. Each park would co-locate start-up incubators, accredited testing-and-certification laboratories, shared ISO-class clean rooms, reliability chambers, and open-access pilot fabs run by industry–research consortia. Such one-stop ecosystems shrink the distance between laboratory discovery and market-ready product while giving suppliers, equipment makers, and cell/module manufacturers a neutral platform to iterate together. Global precedents, including Germany's Solar Valley, the FortZED clean-energy district in Colorado, and Denmark's Energy Cluster show that well-equipped hubs draw foreign R&D investment and raise regional competitiveness.[118,119,120] With targeted incentives, India's parks can play the same role attracting international firms to base research teams locally while domestic firms and institutes provide continuous scientific support, driving gains in efficiency, throughput and sustainability across the solar value chain.

Through these measures, India can cultivate a domestic innovation pipeline, as it's not just manufacturing volume that has grown, but also the intellectual property and advanced skills within India. The country would be producing next-generation solar cells (maybe even exporting HJT or tandem modules), refining its own manufacturing equipment designs, and recycling materials at scale. This reduces long-term dependence on foreign technology, and positions India as a source of solar tech solutions (for instance, selling an indigenously developed low-cost cell equipment to other emerging markets). The investment in R&D and clusters now will in essence, future-proof India's solar industry for the coming technological leaps.

4.4. Workforce and Social Infrastructure

A robust manufacturing ecosystem is not only about machines and policies, but also about people. Skilled human capital and supportive social infrastructure are critical enablers for scaling up the solar PV manufacturing industry. India needs to develop lakhs of technicians, engineers, and researchers for the sector, and ensure the industry's growth is inclusive and worker friendly. Key recommendations are as follows:

- *PV-Semiconductor Skill Council & 10-Year Workforce Roadmap*— Set up a Solar PV and Semiconductor Skill Council under the National Skill Development Corporation to tackle the shop-floor and mid-skill needs specific to manufacturing equipment operation, clean-room protocol, preventive maintenance, inline quality monitoring needs that differ markedly from those of EPC or installation crews. The council would (i) assess annual demand for technicians, supervisors and production engineers; (ii) accredit modular, industry-led training delivered through ITIs, polytechnics and corporate academies; and (iii) publish a rolling 10-year skills roadmap linked to India's capacity-addition milestones. Curricula for degree-level roles process engineers, materials scientists, R&D personnel would remain under AICTE and university jurisdiction, developed in partnership with the same manufacturers to ensure classroom learning tracks emerging technologies such as tandem-cell deposition or kerf-less wafer handling. Certified training centres co-located with innovation clusters and industrial parks can provide hands-on modules, while the council leverages the existing Skill Council for Green Jobs for standards and assessment frameworks, adding deeper manufacturing content and continuous updates as process technologies evolve. A target could be set to train say, 50,000 technicians and 5,000 engineers over the next decade specifically for PV manufacturing. The roadmap should also anticipate future needs and start the training well in advance for producing the same; if automation and data analytics will be big (Industry 4.0), courses on manufacturing IT systems and machine learning for yield improvement can be included. Incentives can be given to companies to take on apprentices and upskill them as part of PLI commitments. Essentially, this ensures a steady talent pipeline so that labour shortage or skill gaps do not become a bottleneck. A coordinated effort will translate that into a competitive edge on the factory floor (where Indian engineers already excel at frugal engineering and process optimization). By 2030, the aim is to have a sizeable cohort of world-class Indian experts in cell process engineering, equipment design, and plant management, reducing reliance on foreign experts.
- *Women-Inclusive Employment Targets*— The expansion of manufacturing should be an opportunity to boost women's participation in the industrial workforce. Currently, women comprise only ~20% of India's formal manufacturing workforce, a figure that has remained stagnant for about two decades.[121] It is recommended that government incentives such as PLI disbursements, interest subventions, etc., be linked to women-inclusive hiring practices. For example, firms could be required to gradually increase the proportion of women in shop-floor roles to at least 20%, 25%, and 30% in a phased manner, as a prerequisite for receiving full benefits. These targets are ambitious yet attainable, some electronic factories in states like Tamil Nadu already have over 40% female workforce.[113] The policy could be structured as a baseline requirement (say, minimum 15% women employees) plus additional bonus incentives for exceeding thresholds (e.g., an extra 1% subsidy if women are >30% of workforce). Parallelly, support facilities like on-site crèches, safe transport for women on night shifts, and mentorship programmes should be encouraged via guidelines or part-funding. By making the solar manufacturing boom inclusive, India not only addresses gender equity but also expands its labour pool tapping into the often-underutilized talent and productivity of women. Studies indicate that higher female participation can significantly raise manufacturing output, this is economically prudent too.[122] Moreover, a diverse workforce tends to be more innovative and stable. Thus, by 2030, seeing women technicians running a coating machine or leading a production shift in a solar fab should be commonplace, supported by policy-driven inclusion.
- *Worker Welfare-Industrial Housing and Safety Standards*— Many new PV manufacturing facilities would arise in electronics manufacturing clusters or special economic zones. It is vital to provide social infrastructure for workers to ensure productivity and well-being. Establishing industrial housing norms is recommended for instance, requiring or

incentivizing companies (or industrial park developers) to build dormitories or affordable housing for migrant workers near the factory site. This model, common in East Asia's manufacturing hubs, can be adapted to Indian conditions. It will help attract skilled workers from across the country to remote fab locations. Additionally, enforceable safety and labour benchmarks should be part of the ecosystem. This includes rigorous implementation of occupational health and safety (OHS) protocols regular safety drills, proper protective equipment (PPE) for handling chemicals in cell fabs, adherence to fire safety, etc. The government can mandate annual safety audits for facilities receiving its incentives and publish a solar industry safety report to ensure transparency. Health insurance and accident insurance for all workers should be standard potentially negotiated at group rates through industry associations. By proactively creating a safe and supportive work environment, the industry will not face labour shortages or community resistance. It would also tie into ESG commitments a factory that meets global safety standards and provides decent worker housing would score better with ESG-conscious investors or buyers.

Investing in human capital and social infrastructure is investing in the longevity and quality of the PV manufacturing drive. A skilled, inclusive, and well-supported workforce will drive higher yields, lower defect rates, and innovation on the shop floor. At the same time, ensuring the benefits of industry growth (jobs, training, improved livelihoods) reach a broad section of society will make the clean energy transition just and equitable a key principle as India shifts workers from traditional industries into new economy jobs.

4.5. Cross-Cutting Enablers

Beyond the core pillars of policy, finance, innovation, and workforce, several cross-cutting enablers need to be in place to accelerate the ecosystem's progress and ensure its resilience. These are overarching measures that impact all parts of the value chain.

- *Circular Economy & EPR Implementation*— As India's solar installations grow, so will solar waste in coming decades. To be ahead of curve in this aspect, a strong circularity regime is crucial. India has already amended e-waste management rules in 2022 to cover solar PV modules, requiring producers to take responsibility for end-of-life panels.[117] Now, enforcement and scaling of Extended Producer Responsibility (EPR) is key. Manufacturers should design products with recyclability in mind and invest in recycling facilities. The government can set progressive targets for PV waste recycling for example, ensuring at least 30% of end-of-life modules are collected and recycled by 2032, moving towards 100% by 2047. Establishing a few regional solar e-waste recycling centres by 2028, possibly via PPP mode, would be a practical step. These centres can start by processing manufacturing scrap and defective modules (which will grow as factories expand) and later handle field returns. Recovered materials like glass, aluminium, and silicon can re-enter the supply chain, reducing the need for fresh raw imports. International collaboration can help to bring technology and knowledge transfer to India. By embracing circular economy principles, the solar industry will lower its environmental footprint and recover valuable materials (silver, copper, high-purity silicon) that make the upstream supply less resource-constrained. Over time, a robust recycling ecosystem will also create jobs and new businesses (in recycling tech, secondary materials markets), reinforcing the sustainability of the PV manufacturing boom.
- *Industry 4.0 and Digitalization*— To boost productivity and quality, Indian PV manufacturing should fully leverage Industry 4.0 technologies automation, data analytics, and machine learning. Early adoption of these can be a force-multiplier for catching up with established global players. For example, manufacturers can deploy AI/ML for yield improvement, analysing sensor data from production lines to predict equipment maintenance, optimize process parameters, and reduce defect rates. The government and industry bodies should create knowledge-sharing platforms on digital best practices possibly an Industry 4.0 for PV workshop series or pilot projects funded to demonstrate smart manufacturing. Additionally, implementing advanced Manufacturing Execution Systems (MES) and digital twins in factories will allow real-time monitoring and quick adjustments, leading to higher throughput and consistency. As

part of cross-cutting support, the government could provide grants or tax credits for SMEs in the solar supply chain to digitalize (for instance, a small EVA film maker could get support to install an MES or QC automation). Embracing Industry 4.0 will help offset some of India's current disadvantages in scale even if our factories are smaller than that of China, they can be smarter, thus efficient. In the long run, the vision is that Indian fabs are not labour-intensive in a negative sense but rather augmented by technology robots handling wafer loading, machine vision inspecting cells at micron precision, and a central data dashboard where engineers use analytics to drive continual improvement. This will improve global competitiveness (higher quality, lower unit costs) and attract tech-savvy young talent into manufacturing careers.

- *Tariff and ALMM Timeline Coordination*— India's use of import tariffs (Basic Customs Duty of 20% on modules and 25% on cells) and the ALMM (which restricts government projects to approved domestic models) has given a boost to domestic manufacturing. However, these measures need expansion and well thought calibration over time to balance industry support with project costs. A clear, coordinated timeline should be drawn such that as and when domestic capacities come online, any adjustments to tariffs or expansion of ALMM criteria are well-communicated and synchronized. For instance, the cell duty and the mandate for local cells (ALMM for cells by 2026) should work in tandem the 20% cell import duty might be maintained through 2026 to protect nascent cell manufacturers, but if by mid-2027 domestic cell supply meets demand (due to the new mandate), the duty structure could be reviewed to avoid excessive cost burden on any remaining imports needed. Similarly, as wafer/poly ALMM kicks in by 2028–29, the government might introduce or raise import duty on those items gradually to encourage self-reliance, but only once domestic production can support it. Coordination also means giving the solar project developers a predictable roadmap e.g., announcing that module and cell import duties will remain until 2028 and then taper to 20% by 2030 as local supply stabilizes in line with ALMM covering more components. Such predictability would help developers factor in costs and prevent policy shocks, while still ensuring the intent, fostering local industries is met. By aligning tariffs, ALMM, and other tools like production incentives on a synchronized timeline, India can avoid gaps or overlaps, e.g., avoid a scenario where tariffs are removed too early (hurting industry before it's ready) or kept too long (making solar power costlier than necessary). The end goal by 2030 is a soft-landing where Indian manufacturers are competitive enough that high tariffs or strict mandates can be relaxed without harming them, allowing a more open market with India as a confident player.

By synthesizing insights from India's current PV landscape and the state of its manufacturing apparatus, it's clear that an ecosystem approach is needed for the way forward. The recommendations made herein span policy, finance, innovation, and workforce development, reflecting the multifaceted effort required. The Indian government and industry have already ignited the solar manufacturing engine–capacity is rising, and supportive policies are in place. The task now is to steer this momentum strategically–build the missing upstream links, ensure financing isn't a roadblock, cultivate innovation at home, and empower the workforce that will ultimately make 'Make in India' a reality. If these recommendations are pursued in earnest, by 2030 India can evolve from being one of the world's largest solar markets to also becoming a global manufacturing powerhouse in solar–competitive, self-reliant, environmentally sustainable, and socially inclusive. The coming years are a critical window of opportunity to set the foundation for that future. The way forward is clear; it requires continued collaborative action from policymakers, industry captains, financiers, and the scientific community to turn these recommendations into on-ground outcomes, ensuring India's solar revolution shines not just in gigawatts installed, but also in gigawatts made in India.

APPENDIX

Appendix- A

Estimated CAPEX Breakdown for a 10 GW TOPCon Manufacturing Plant (2025) [17]

TABLE A.1 Comparative Upfront Capital Cost Structure of Integrated Solar PV Manufacturing (China Tier-1 Cluster vs India/ EU/US New Build, 2025)

Cost Head (upfront)	China-Mainland "Tier-1 cluster" 2025 Average $ million per GW	10 GW total ($ bn)	India / EU / US new build 2025 Average $ million per GW	10 GW Total ($ bn)	Key Cost Drivers
Polysilicon reactors & utilities	80	0.80	120	1.20	Capex/kt poly in China has fallen below $9 kg-cap with 120 kilo tonnes/year[115]
Ingot + wire saw wafering	40	0.40	60	0.60	Large DSS/CCZ furnaces & 3 GW diamond-wire lines quoted at $35–40 m/GW by Jingyuntong/ Jinggong (2024 tenders)[123]; EU tooling list price c.$55 m/GW [124]
PERC / TOPCon cell line (diffusion, PECVD/ALD, metallization, QC)[123]	70	0.70	100	1.00	Chinese turnkey TOPCon line bid in 2024 at ¥510 m ≈ $70 m/GW[125]
Module assembly (stringer, lamination, test)	18	0.18	28	0.28	Jinchen turnkey 1 GW mono-glass line FOB Tianjin $15-20 m; India expansions cost $18.1 million GW/ year[126,127]
Building, clean-room & infra (~20% of equipment)[127]	42	0.42	62	0.62	Land + civil work lower in Chinese provincial parks; higher compliance/EPC rates outside China

Cost Head (upfront)	China-Mainland "Tier-1 cluster" 2025 Average $ million per GW	10 GW total ($ bn)	India / EU / US new build 2025 Average $ million per GW	10 GW Total ($ bn)	Key Cost Drivers
Engineering, project management, spares (≈10 %)	21	0.21	31	0.31	Vendor-financed EPC teams commonplace in China; overseas builds pay higher mobilization
Total direct CAPEX	271 m/GW	≈ 2.71 bn	401 m/GW	≈ 4.01 bn	This can vary widely depending upon the import duties
Fully-loaded project outlay (Duties, Freight, customs & Contingency / working capital)	≈ $2.9 bn		≈ $4.4 bn		

Source: Author's analysis and compilation based on industry tender disclosures, equipment vendor quotations, and published cost benchmarks and secondary literature.

Note: Total CAPEX (billion $) required for a 10 GW manufacturing facility, by region is based on a vertically integrated facility producing ~23% efficient TOPCon modules with polysilicon yield assumes modern granular processes; wafer thickness ~150µm. Totals are the sum of all cost components. Figures are rounded to two decimal places, excludes land acquisition (~$5-10M/GW extra in India/US). The cost estimates presented in this table are the author's analysis, derived from a synthesis of publicly available industry disclosures, equipment vendor quotations, tender data, and secondary literature. The figures represent indicative 2025 averages under typical market conditions and are intended for comparative assessment across geographies rather than as definitive project costs. Actual capital expenditure may vary depending on plant scale, technology configuration, localization level, import duties, financing structure, and regulatory requirements.

Appendix- B

The Comparative Indicators Illustrate Circular-Economy Aspects of Different PV Technologies[75,88]

TABLE B.1 Material Composition, Hazard Profile, and End-of-Life Recycling Considerations for Major Solar PV Technologies

Technology (Module type)	Key Material Composition (estimates)	Notable Hazardous or Rare Materials	Recyclability & Recovery Potential	Waste Management Considerations
c-Si PERC/ mono-facial	~75% glass, 10% aluminium frame, 6–10% polymers, 3–5% silicon cells; copper wiring; silver ~0.05%.	Lead (in solder, often ≤0.1% – being phased out); small silver content.	Bulk recycling feasible: >85% by weight (glass, aluminium, copper) recoverable. Silicon can be reclaimed (downcycled or potentially reused); silver extraction possible with chemical processes. Overall high EoL recovery potential by mass, but low by value unless silver is recovered.	Avoid breakage to prevent lead leachate. Modules classified as e-waste; can be processed by general PV recycling lines. Extended producer responsibility (EPR) programmes can ensure high collection rates.
c-Si bifacial / bifacial PERC	Similar to above but often glass-glass (no polymer backsheet); ~80% glass, rest similar.	Same as PERC (lead/ silver); bifacial have no additional toxics.	Slightly higher recyclability by weight because of glass-glass design (no backsheet to discard). Both glass sheets can be recovered as cullet. Otherwise, same recovery pathways as PERC.	Glass-glass modules require shredding or thermal peeling to separate encapsulant. Absence of frame simplifies some handling. Need to recycle junction box plastics as well.
c-Si TOPCon	Very similar to PERC (glass, aluminium, etc.) May have transparent conductive oxide layer.	No new hazardous elements: (some use thin nickel/copper plating on cells instead of silver)	Same as PERC. If Ni/Cu plating replaces some Ag, module contains more base metal (copper) which is recyclable. Overall recycling identical to PERC.[128]	No special issues if polymer backsheet is replaced with glass (some TOPCon are bifacial), see bifacial considerations.
c-Si HJT	Glass, aluminium frame (often), dual-glass encapsulation, silver fingers. Additional: transparent oxide layers (usually ITO = Indium Tin Oxide); amorphous Si layers.	Indium (in ITO coatings); Tin (in ITO); no significant lead (many use lead-free solder).	High bulk recyclability (glass, metal). Indium/Tin could be recovered by specialized process (not currently standard). Silver content similar or slightly less than PERC (since HJT uses fewer busbars but still Ag grid).	HJT cells delaminate similarly to other c-Si in shredding. ITO glass recycling could piggyback on LCD recycling methods to reclaim indium if volumes justify. Ensure dedicated processing to capture indium/tin dust if panels are smelted.

Technology (Module type)	Key Material Composition (estimates)	Notable Hazardous or Rare Materials	Recyclability & Recovery Potential	Waste Management Considerations
c-Si IBC	Materials akin to PERC (glass, frame, etc.) Back-contact design uses more silver and copper on rear.	Silver (up to ~3x PERC amount in older IBC); no extra toxics.	Bulk recyclability same as PERC. Extra silver makes recovery economically more attractive – recycling processes could recover a few times more Ag per module. Silicon cells can be recovered similarly.	Handling of IBC is same as other silicon modules. Ensure silver-rich cell fragments are routed to precious metal recovery to capitalize on value.
CdTe Thin-Film	~95% glass (two sheets), ~5% plastics (encapsulant, edge seal), <0.1% Cd and Te semiconductor. No aluminium frame typically (may have mounting strip).	Cadmium (toxic heavy metal); Tellurium (rare metalloid, not toxic but valuable); small amount of lead in solder ribbons (lead-free used in newer models).	Very high recycling potential: ~90% of Cd and Te can be recovered and reused in new modules; ~90% of glass can be recovered for reuse. First Solar's commercial process achieves these rates. Even without specialized facilities, panels must be treated as hazardous waste if not recycled, due to Cd.	EPR is crucial – take-back programmes needed to prevent any Cd-Te going to landfill. Recycling requires controlled environment: shredding and chemical leaching steps to capture Cd/Te. Given economic value of Te, recycling often pays off if volume is there. Storage of broken modules must avoid water contact to prevent Cd leachate.
CIGS Thin-Film	Glass ~90%+, remainder encapsulant, trace metals (Cu, In, Ga, Se, with Mo electrodes; small Cd in buffer). Often frameless.	Indium, Gallium (scarce/valuable); Selenium; Cadmium (few mg from buffer layer).	Moderate recycling potential: glass and metal (frame if any) easily recovered. Indium and Ga can be recovered (>95% in lab tests) via hydrometallurgy, but no large-scale plant yet. Some general e-waste smelters can capture indium from bulk processing. Copper is low quantity but recoverable. Selenium likely lost in high-temp processes (needs specific capture methods).	CIGS should be processed in e-waste facilities capable of handling heavy metal fumes (selenium, cadmium). Indium recovery may become economically important if CIGS volumes grow (indium supply constraints). Until dedicated recycling is common, ensure CIGS panels are at least collected and sent to smelters or specialized recyclers, not regular landfills.

Technology (Module type)	Key Material Composition (estimates)	Notable Hazardous or Rare Materials	Recyclability & Recovery Potential	Waste Management Considerations
Perovskite (single junction)	Glass (front, possibly back), transparent conductive oxide (ITO or FTO), metal electrodes (gold in lab cells, likely aluminium or carbon in commercial), perovskite semiconductor (~500 nm coating), encapsulant.	Lead (in most efficient perovskites, e.g., methylammonium lead iodide); Organic solvents and halides; if lead-free perovskite, then Tin (Sn) which is also toxic in groundwater.	Unknown full-scale potential yet in principle glass and metal electrodes are recyclable as usual. Lead could be recovered by dissolving the perovskite (since it readily dissolves) and precipitating Pb – similar to lead-acid battery recycling chemistry. Because perovskite layers are extremely thin, mass of lead is low, but leaching is a concern if not handled. The value in recycling perovskites will be mainly avoiding pollution rather than recovering high-value material (lead is cheap but hazardous). If using gold electrodes (lab devices), gold would certainly be recovered, but commercial devices will avoid gold for cost.	Strong need for safe EoL handling due to soluble lead. Likely will be categorized as hazardous e-waste. Modules should be encapsulated well during use to prevent any lead leakage even if cracked. At EoL, expect specialized recycling where panels might be shredded and soaked in solution to extract lead. Could piggyback on existing lead glass (CRT) recycling or battery recycling infrastructure for material recovery.
Silicon-Perovskite Tandem	Combination of c-Si (bottom cell) and perovskite (top cell). Thus includes all materials of a silicon module plus the added perovskite layer and possibly an extra glass or encapsulant layer in between.	Lead (from perovskite); Indium (from additional TCO layers); small additional number of other metals from interconnections.	Potentially recyclable, but complex. One concept is to separate the tandem into its two sub-cells at EoL. For e.g., delaminate the perovskite top layer from the silicon wafer. This will likely require new processes (e.g., a chemical that dissolves the intermediate layer without harming silicon). Once separated, the silicon cell can go through standard silicon recycling, and the perovskite part can be treated as perovskite above. If not separated, tandem modules might be shredded whole, which complicates material recovery (mixes lead with silicon waste). Designing for disassembly (e.g., using a sacrificial release layer) will greatly enhance recyclability.	Ensuring no lead leakage is doubly important here broken tandem panels could release Pb and also make silicon unrecoverable if contaminated. Policy may need to set guidelines for tandem PV EoL given the dual-material nature. Manufacturers are encouraged to provide take-back and perhaps even modular designs where the perovskite layer can be replaced or upgraded mid-life (which would reduce waste and allow partial reuse of the silicon component).

Source: Author's analysis and compilation based on peer-reviewed literature and industry disclosures, including lifecycle studies and manufacturer-led recycling programmes.
Note: 'Hazardous' here denotes elements regulated for safe disposal (lead, cadmium), while valuable denotes scarce materials worth recycling (Ag, In, Te). All percentages are approximate for representative commercial modules.

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