Report | May 2026

Advancing Solar Cell Manufacturing in India

Bridging Gaps in Cell Technology and Lowering Manufacturing Costs

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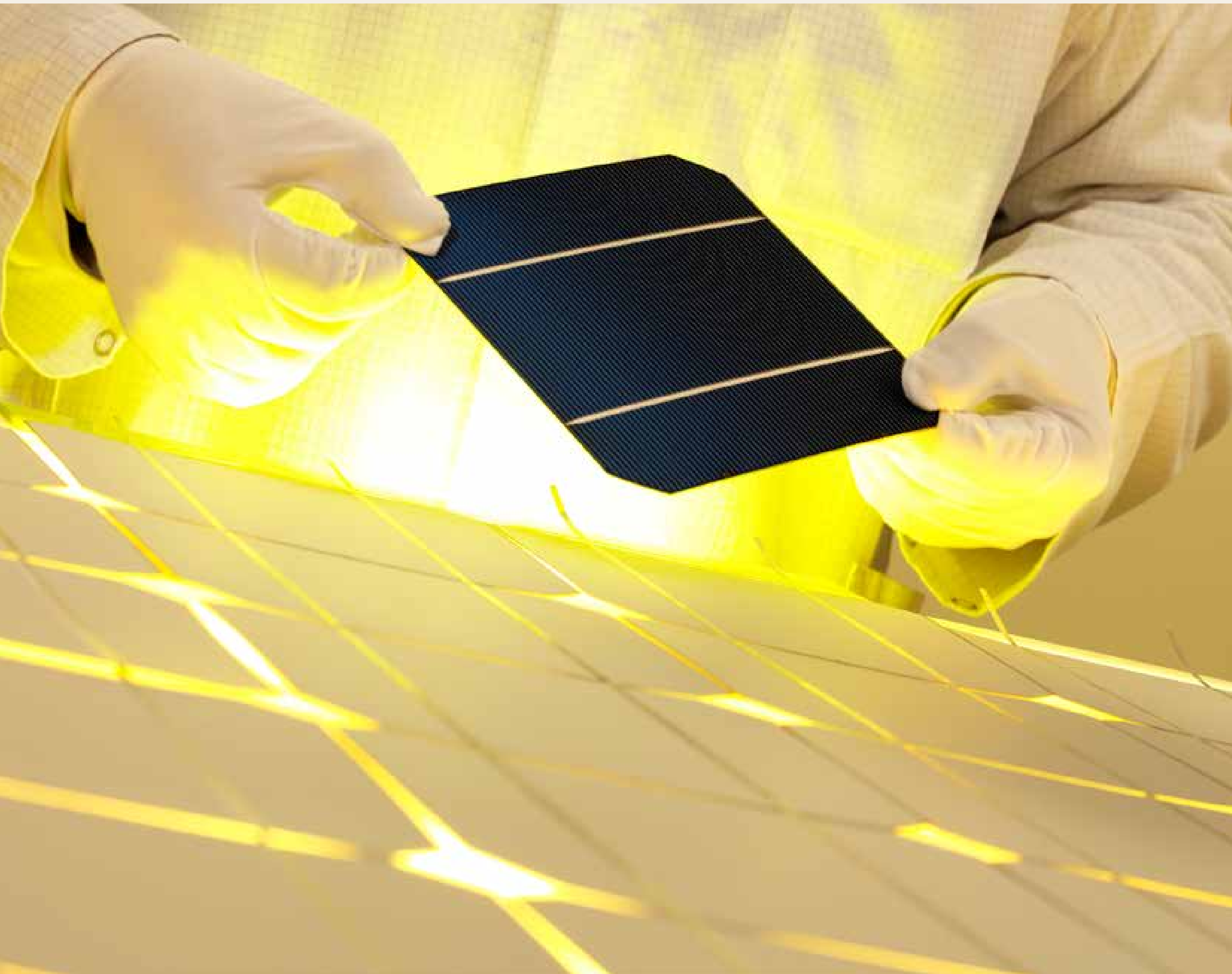

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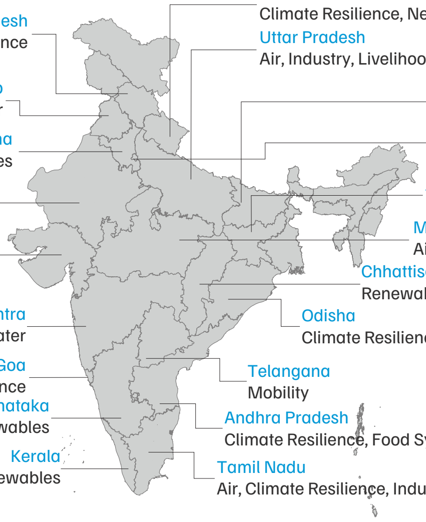


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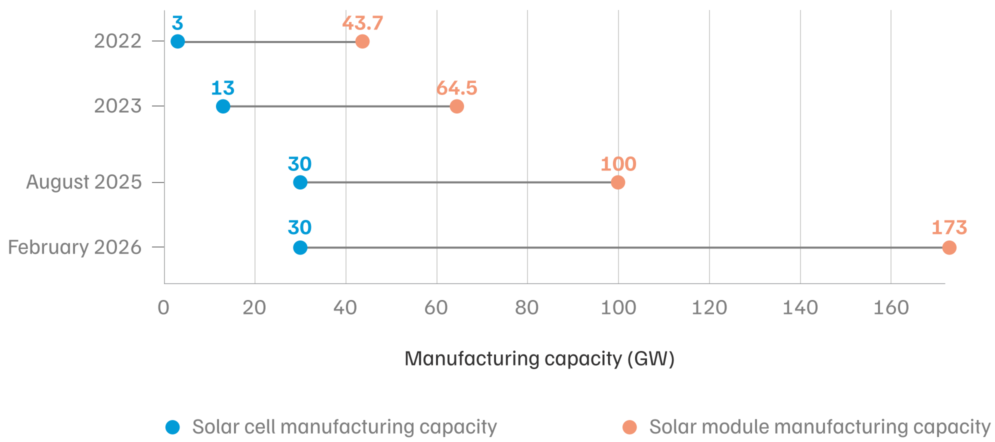
Executive summary

India has rapidly expanded its solar energy deployment over the past decade, emerging as one of the world's largest and fastest-growing markets. However, this growth in deployment has not matched the growth of domestic manufacturing across the supply chain. Such a mismatch risks creating supply chain vulnerabilities in downstream segments, such as module manufacturing and deployment, due to continued import dependence (Premier Energies 2024; Vikram Solar 2024; Waaree Energies 2024a). As of March 2026, solar module manufacturing is the most established supply chain segment in the Indian solar PV industry, with a manufacturing capacity of 173 GW (MNRE 2026b). In comparison, nameplate solar cell manufacturing capacity is only ~30 GW, forming only 20 per cent of the module manufacturing capacity (authors' analysis from Waaree Energies 2025; MNRE 2025a; Sinovoltaics 2025; ETEnergyWorld 2024; MNRE 2026a). For the remaining 80 per cent, module manufacturing would have to depend on imported cells primarily from China. Figure ES1 demonstrates the gap in growth between module and cell manufacturing.

Figure ES1. Module manufacturing capacity has outpaced cell manufacturing capacity by more than five times, creating high demand for new cell production



Source: Authors' analysis

Scaling up solar cell manufacturing is thus necessary to solve this issue and improve supply chain resilience. Such scaling up is also critical for increasing domestic value addition through solar manufacturing, as nearly 60 per cent (InfoLink Consulting 2025c) of the solar module cost is attributable to the solar cells.

However, domestic solar cell manufacturers face a global landscape marked by declining prices and rapidly evolving technology—the global cell technology landscape has shifted, with PERC (passivated emitter rear contact) being replaced by TOPCon (tunnel oxide passivated contact) as the commercially dominant technology within two years (2023 to 2025). In contrast to this evolution, domestic solar cell manufacturing remains PERC-based, and faces higher manufacturing costs compared to Chinese counterparts. As a result, domestic solar cell manufacturing faces risks of technology lock-in and lack of cost competitiveness.

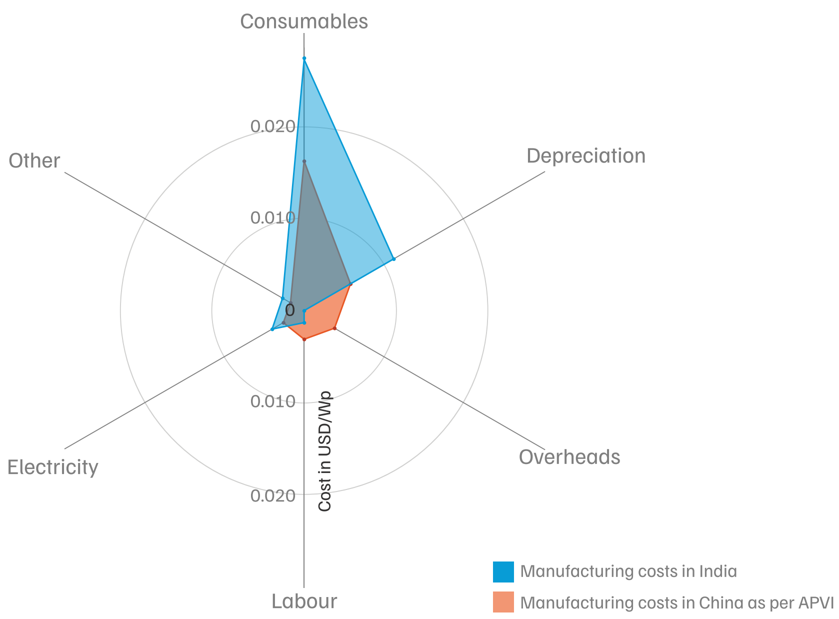
Hence, vertical integration into solar cell manufacturing must be accompanied by the development of technological capabilities and the reduction of manufacturing costs to build long-term competitiveness. **The objective of this report is to identify the key priority areas and strategic interventions that should be targeted by policymakers and domestic solar manufacturers to achieve this twin goal.**

This study adopts a techno-economic lens to arrive at the key findings, drawing from secondary literature and stakeholder consultations. Further, the interventions have been mapped by considering domestic policies, actions taken by other nations, and their relevance to the identified gaps.

Key findings

1. **Domestic solar cell manufacturing struggles with high capital expenditure and high consumable costs:** Capital expenditure for domestic manufacturers is nearly 109 per cent (Premier Energies 2024; Waaree Energies 2024a; Vikram Solar 2024; APVI 2024) higher than that of Chinese counterparts. This is due to smaller production scales and limited access to subsidised infrastructure. Presently, the ***Production-Linked Incentive (PLI) scheme*** provides fiscal support to enlisted domestic cell manufacturers after manufacturing facilities are set up and sales are made. However, the high upfront capex has been a roadblock in the execution of this scheme. Further, key consumables—such as silver paste itself—contribute at least 20 per cent (APVI 2024) of the solar cell manufacturing cost, for TOPCon cell technologies. Chinese manufacturers benefit from subsidised, local silver paste supplies, whereas Indian manufacturers face higher costs due to import duties, contributing to the cost-of-manufacturing disparity. Such high manufacturing costs, as showcased in Figure ES2, lead to limited expansion of cell manufacturing capacity.

Figure ES2. Higher costs in consumables and depreciation make cell manufacturing ~40% more expensive in India than China



Source: Authors' analysis

2. **Import dependency for solar cell machinery creates technology lock-ins:** Machinery for cell manufacturing is imported, and there is a lack of domestic equipment manufacturing. The technological knowhow for carrying out machinery setup and process optimisation rests with the equipment suppliers. As a result, domestic manufacturers depend on foreign equipment suppliers to provide this knowhow. Due to the lack of localised knowledge, manufacturers struggle to switch to high-efficiency cell technologies in a timely manner, as process optimisation for newer advanced lines takes longer than previous setups. Newer TOPCon production lines take nearly 12 months for process optimisation, when compared to PERC lines which take nearly 7–8 months. As a result, domestic cell manufacturing is still PERC-centric, whereas TOPCon accounts for 29 per cent of the domestic solar cell manufacturing capacity (Sinovoltaics 2025).

3. **Domestic manufacturers face a lack of skilled professionals and upskilling capability required for process optimisation of equipment:** Solar cell manufacturing requires low-skilled operator roles for day-to-day operation of machinery, and high-skilled process engineers responsible for process control and optimisation of the overall production. The skills required by process engineers are highly equipment- and process-specific. These include troubleshooting process performance, evaluating process settings and stability of new cell production models, and deciding process conditions and material consumption specifications. Domestic manufacturers face both a lack of such skilled professionals and upskilling capabilities, leading to the industry remaining dependent on hiring foreign technical expertise. Only a few manufacturers have dedicated training centres; the rest depend on equipment providers training the engineers.

> Structural constraints—cost, import dependence, and weak innovation—limit India's solar cell manufacturing competitiveness.

4. **Weak domestic R&D capacity threatens long-term competitiveness:** Commercial solar cell technologies have rapidly evolved due to investment in research and development (R&D) globally, but similar domestic private investments in indigenous R&D, pilot-scale manufacturing, or process innovation have been largely absent. Domestic manufacturers spend a maximum of 0.1 per cent of their total revenue on R&D (Vikram Solar 2024), whereas Chinese manufacturers can spend from 2 per cent (Taiyang News 2025c) up to nearly 6 per cent of their total revenue on R&D (LONGi 2024). Similarly, public investment in solar PV R&D in India since 2014 has been approximately USD 13 million (MNRE 2024b), significantly lower than allocations in the US and Japan, along with weak industry participation in the government-allocated research grants for R&D. Further changes in the global cell technology landscape are expected through rise in market shares of presently commercialised technologies—heterojunction (HJT) and Back Contact (BC) cells—and commercialisation of alternate technologies such as tandem-perovskites. Lagging domestic R&D would lead to technology lock-ins, and inhibit solar cell manufacturers' ability to adapt in a timely manner to such a changing technology market.

Key recommendations

1. **MNRE could develop shared infrastructure for machinery localisation, cell technology development, and upfront capital-cost reduction:** A national framework should be created to bridge the gap between laboratory research, pilot-scale validation, and commercial deployment. The key priorities are as follows.

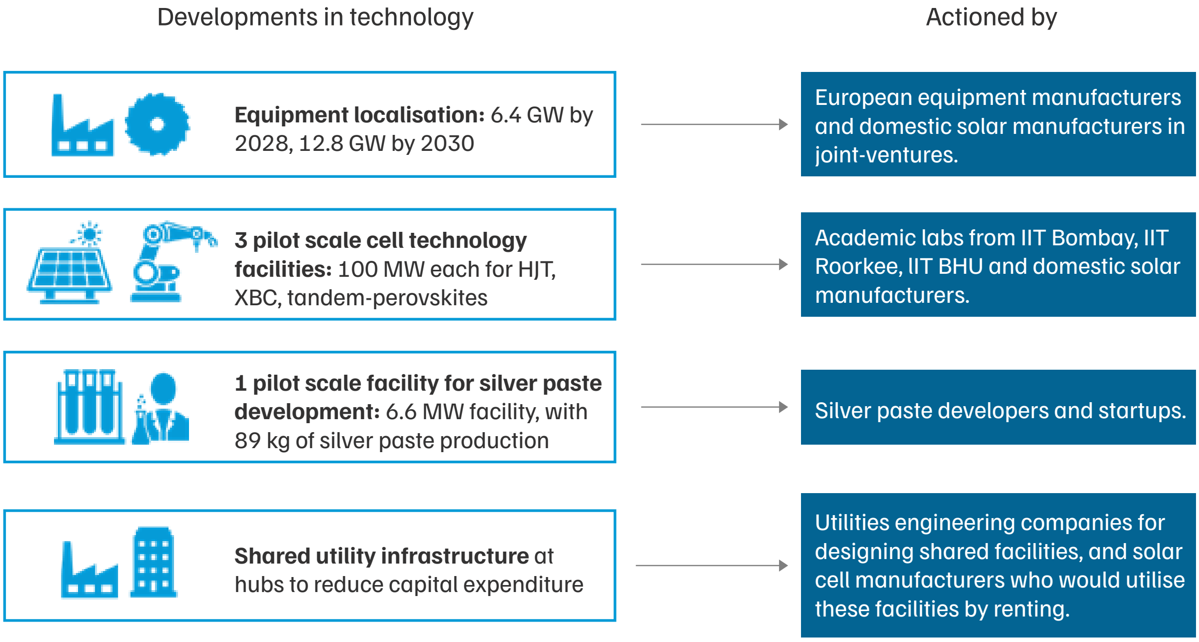
- **Support indigenisation of manufacturing equipment and critical inputs** through a shared hub, anchored by centres of excellence (CoE), leading academic institutions, and experienced technology partners (acting as spokes). Such hubs should house capital-intensive infrastructure for advanced cell technologies, equipment development, and materials research. These include diffusion furnaces, chemical vapour deposition chambers, etc. The **Ministry of New and Renewable Energy (MNRE)** should collaborate with the **Ministry of Heavy Industries (MHI)** to design and implement this model. The MHI may also introduce a dedicated 'capital goods for solar cell manufacturing programme' under its *National Capital Goods Policy.*

- **Establish pilot manufacturing to stay in line with market trends.** The **MNRE**, in collaboration with the **Ministry of Science and Technology (MST)**, academic institutions like **IIT Bombay**, **IIT BHU** and **IIT Roorkee**, and domestic solar cell manufacturers should collaborate to establish pilot-scale manufacturing facilities. By 2030, at least three pilot-scale cell manufacturing facilities covering TOPCon/XBC, HJT, and tandem-perovskite technologies should be operational. The objective should be to ensure that around 20 per cent of new cell capacity by 2030 is based on high-efficiency technologies beyond conventional TOPCon. Parallel efforts should promote pilot-scale development of critical inputs such as silver and hybrid metal pastes. The pilot-scale facilities would act as individual hubs, and research activities would be actioned by spokes such as the academic institutions and domestic solar cell manufacturers.

- **Establish shared utility infrastructure that can be rented by multiple solar cell manufacturers**, leading to a reduction in capital expenditure for solar cell manufacturing. This would help manufacturers scale-up fast and achieve cost-competitiveness. The **MNRE** can act as a nodal agency, bringing together manufacturers, utility companies, and state-level stakeholders. **State Industrial Development Corporations (SIDCs)** can co-finance and build shared utilities such as chillers, compressors, diesel generators, gas cabinets, chemical delivery systems, etcetera. The shared utility facilities would act as individual hubs, with individual solar cell manufacturers acting like spokes and carrying out manufacturing.

2. **MNRE could offer one-time capital subsidy to PLI winners to bridge capital expenditure gaps:** Based upon our calculation, a one-time capital subsidy of 15 per cent would assist in bridging the capital expenditure gaps between Chinese manufacturers and domestic PLI winners. Execution of the PLI-allocated manufacturing capacity would double the solar cell manufacturing capacity, from nearly 30 GW to 60 GW.

Figure ES3. Framework for developing machinery, technology, materials, and reducing upfront manufacturing costs



Source: Authors' analysis

3. **MNRE could develop skilling programmes and training centres to upskill process engineers and build domestic technological capacity:** Scaling solar cell manufacturing will require a substantial increase in skilled process engineers and technicians. Dedicated training centres should be established in key manufacturing states, supported by industry partnerships and specialised curricula targeting process optimisation, equipment handling, and advanced cell technologies. The **MNRE**, in collaboration with the **All India Council for Technical Education (AICTE)**, can take charge of curriculum and courses development, while the **Ministry of Education (MoE)** and **Ministry of Skill Development and Entrepreneurship (MSDE)** can then serve as stakeholders responsible for implementing the courses through establishing the dedicated training centres.

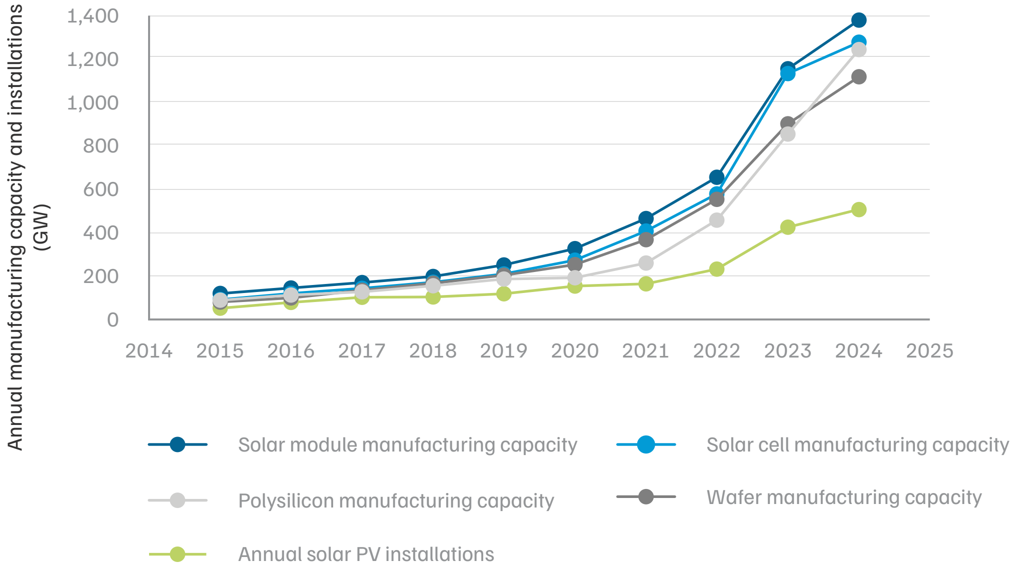
4. **Ministry of Commerce and Industry (MoCI) could push for strategic asset acquisition and technology transfer in trade policy:** MoCI can negotiate easing of regulations for acquisition of distressed foreign manufacturing assets and intellectual property through trade and investment negotiations. This will push private players to acquire distressed companies. Such acquisitions can accelerate technology upgrading, reduce capital costs, and enable faster entry into advanced cell technologies without duplicating global R&D investments.

By shifting policy focus from module-led expansion towards technology-driven, vertically integrated solar cell manufacturing, India can stabilise its domestic manufacturing base, reduce strategic vulnerabilities, and position itself as a competitive player in a diversifying global solar value chain. Timely and coordinated action across policy, industry, and academia will be critical to ensuring that today's manufacturing scale translates into durable industrial leadership over the next decade.

1. Overview of the solar cell manufacturing sector

The global transition to renewable energy has positioned solar photovoltaic (PV) technology as a cornerstone in addressing the trilemma of balancing energy security, affordability, and environmental sustainability. Unlike fossil fuels, disruptions in the supply of renewable energy technologies such as solar PV do not immediately affect a country's energy system, contributing to energy security (IEA 2024). The levelised cost of electricity (LCOE) of solar PV was around USD 61 per megawatt-hour (MWh) in 2024, much lower than LCOE from fossil fuel sources like coal, which is around USD 118 per MWh in 2024 (Lazard 2024), showcasing its affordability. Along with this, solar PV systems do not directly emit greenhouse gases during energy generation, making them an ideal alternative to fossil fuels for reducing carbon emissions.

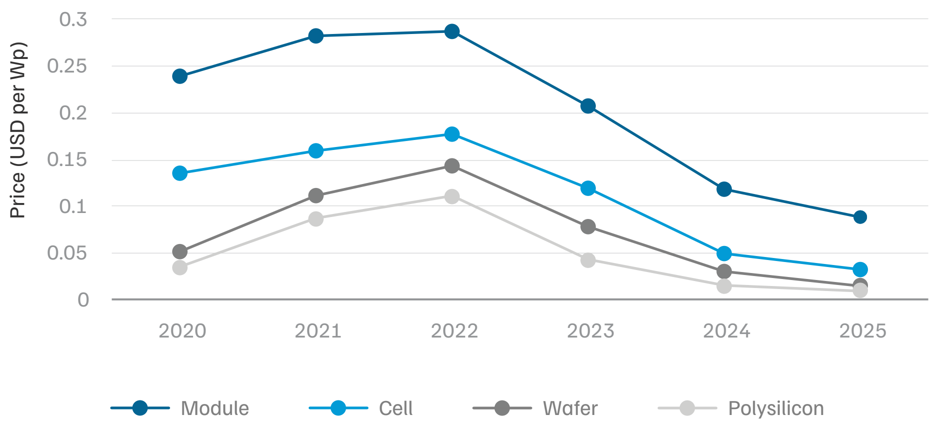
Figure 1. Globally solar PV manufacturing capacity has outpaced deployment, resulting in oversupply



Source: Authors' analysis based on IEA 2025b

Solar PV installations have surged worldwide, with annual solar PV installations rising from 51.8 gigawatts (GW) in 2015 to an estimated 507.2 GW in 2024 (IEA 2025b). This has been driven by rising solar PV module manufacturing capacity, which has grown from nearly 120 GW in 2015 to 1,379 GW in 2024 (IEA 2025b), as shown in Figure 1. While manufacturing capacity has grown to support higher deployment, annual solar PV deployment remains less than half of total capacity across the solar supply chain. This imbalance has led to oversupply, driving down average market prices for each component, as shown in Figure 2.

Figure 2. Globally prices across the solar PV supply chain have declined drastically in recent years



Source: Authors' analysis based on Rethink Energy 2024b; InfoLink Consulting 2025c

Manufacturing growth is largely driven by Chinese producers who, by capitalising on government incentives, have achieved economies of scale, resulting in the solar PV supply chain becoming heavily concentrated in China. Out of the total global manufacturing capacity, 92 per cent of polysilicon production, 98 per cent of ingot and wafer production, 91.8 per cent of solar cell manufacturing capacity, and 84.6 per cent of solar module assembling capacity are located in China (SolarPower Europe 2025). Despite the manufacturing overcapacity in China, the declining prices have also affected profitability of Chinese manufacturers such as Jinko Solar, LONGi, JA Solar, and Trina Solar, who are locked in fierce competition to retain market share amidst the issue of manufacturing overcapacity. The fall in polysilicon prices, while reducing the cost of production, has undervalued the inventories of Chinese manufacturers. This has led to heavy investment in technological innovations to outperform peers in terms of efficiency and manufacturing costs. The development of such technological innovations has been captured in the next subsection.

1.1 A dynamic market: Solar cell efficiencies rise due to ever-evolving technology market

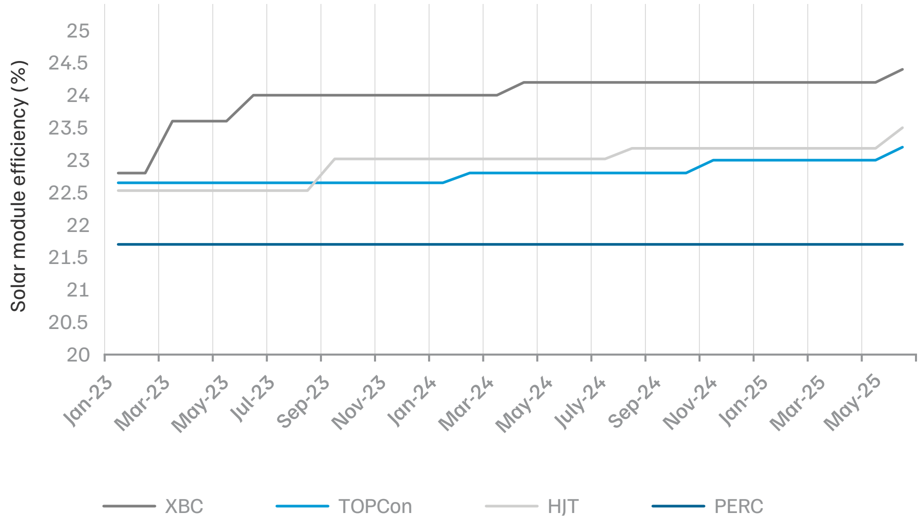
Solar PV technology can be categorised as either silicon-based or thin-film-based. Globally, silicon-based solar PV is the dominant technology, with a market share of nearly 97.5 per cent, while thin-film technologies make up the rest (Fraunhofer ISE 2024). The supply chain for silicon-based solar PV modules consists of producing polysilicon from metallurgical grade silicon, melting polysilicon to make ingots, slicing them into wafers, utilising the wafers to make solar cells, and assembling the solar cells into modules using bill-of-material (BOM) components such as solar glass, encapsulant materials such as ethylene vinyl acetate sheet (EVA) and polyolefin elastomer (POE), backsheets and junction boxes. Due to its prevalence, this report exclusively focuses on silicon-based PV technology.

> Rapid R&D and commercialisation have led to solar cell efficiencies rising from 21.7% in January 2023, to 24.5% in June 2025, across different evolving technologies globally.

Solar cell technologies are constantly evolving in terms of efficiency, costs, and market share. Among silicon-based cells, the different cell technologies that have been commercialised are passivated emitter rear contact (PERC), tunnel oxide passivated contact (TOPCon), heterojunction (HJT), and different variants of Back Contact (BC) on either TOPCon or HJT, termed as XBC. There have been changes in wafer technology too, with the industry shifting from multi-crystalline wafers to monocrystalline wafers. The commercialisation and gradual development of these different cell technologies have been reflected in increasing photovoltaic conversion efficiencies. The photovoltaic conversion efficiency refers to the percentage of incident solar energy a solar cell or module can convert into electrical energy, and it has risen from a meagre 14 per cent in 1977 to nearly 27.8 per cent in 2025 (Green et al. 2025). The improvements in photovoltaic conversion efficiency offered by advanced solar cell designs contribute to a lower LCOE (Wang et al. 2011) which acts as an incentive for the industry to focus on manufacturing and adopting these solar cell technologies.

Global manufacturers are pushing for continuous technological innovation to push efficiencies up for solar cell technologies, and this is captured in Figure 3.

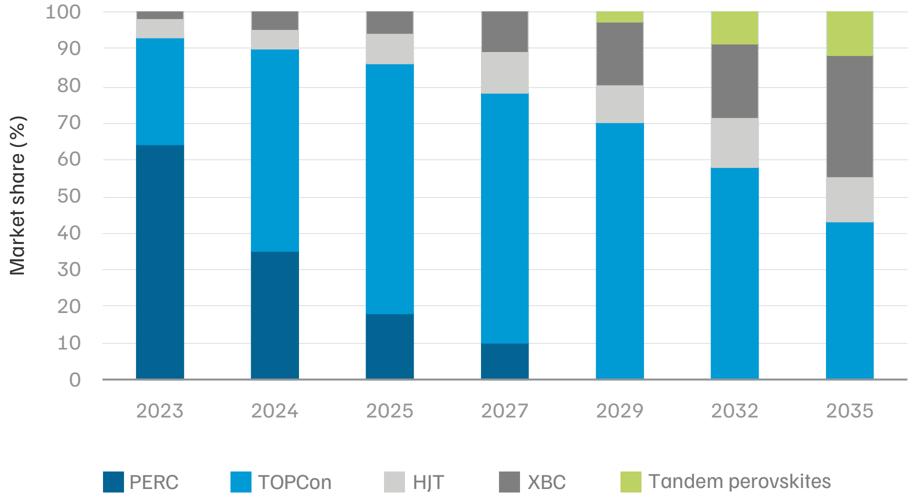
Figure 3. TOPCon, HJT, and XBC modules show rising efficiencies, while PERC modules have stagnated



Source: Taiyang News 2025

PERC, which dominated the global market till 2023, appears to be the most stagnant technology in terms of efficiency improvement. Since 2023, TOPCon has taken over as the leading commercially available technology, with an estimated market share of nearly 60 per cent (VDMA 2025). This has been due to both the higher efficiencies promised by it, and its similar manufacturing cost to PERC. This evolution in market share is captured in Figure 4. While HJT and XBC exhibit higher cell efficiencies than TOPCon, they have low market shares due to their higher manufacturing costs. However, they are predicted to grow in the future, making up nearly 50 per cent of the global market post 2030 (VDMA 2025).

Figure 4. Solar cell technology landscape is poised to shift beyond TOPCon towards HJT, XBC, and tandem perovskites in the near future



Source: VDMA 2025

The eventual rise of HJT and XBC cell technologies is predicated on their achieving cost competitiveness with TOPCon. Beyond the current commercially available technologies, alternative technologies such as tandem perovskites are also predicted to enter the global market post 2030. Tandem perovskites have the potential for solar cell efficiencies higher than conventional silicon-based solar cells (PV Magazine 2024), and are yet to reach maturity.

The change in market share for each technology thus depends on their efficiencies, their scale of maturity, and how complex the manufacturing process is. The transition from PERC to TOPCon was facilitated by the similarities in their manufacturing processes, and similar capital expenditure—the average capital expenditure for PERC and TOPCon are USD 34.5 million per GW (CRISIL 2024) and USD 33.5 million per GW (CRISIL 2024; APVI 2024), respectively. In contrast, while HJT has fewer process steps, it has a much higher average capital expenditure, at USD 72 million per GW (CRISIL 2024).

Compared with silicon-based solar cells, the futuristic tandem perovskite cells are estimated to have lower production costs. The capital expenditure for setting up a perovskite manufacturing plant is estimated to be one-fifth of the capital expenditure required for a silicon solar manufacturing plant (Rethink Energy 2024a). Further, perovskite manufacturing processes operate at much lower temperatures than conventional silicon solar manufacturing, meaning lower energy consumption and operating costs (Mitsui & Co Global Strategic Studies Institute 2024). Lower energy consumption also entails a lower emissions profile associated with perovskite manufacturing. Further technical details and description of all the solar cell technologies mentioned (PERC, TOPCon, HJT, Back Contact, and perovskite) are provided in Annexure 3.

The historical and predicted changes in market share reveal the dynamic nature of solar cell technology, with Chinese manufacturers focusing on technological breakthroughs to increase conversion efficiency, while optimising for cost. Indian manufacturers thus must now contend with this dynamic technology landscape while competing with historically low market prices. The next subsection will detail how the domestic solar PV sector has evolved in terms of deployment, manufacturing, and technology.

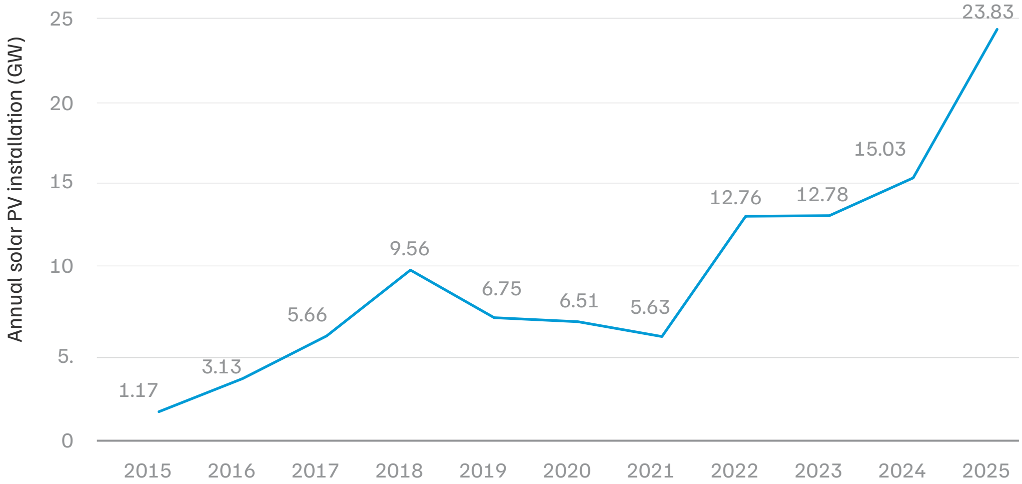
1.2 How has India fared within this sector?

The Government of India has set a Nationally Determined Contribution (NDC) target of achieving 500 GW of cumulative electric power generation from non-fossil fuel sources by 2030, and solar photovoltaic sources are expected to contribute 292 GW (over 50 per cent) to this target (CEA 2023).

Supply-side policies such as ***Production-Linked Incentive (PLI) scheme*** have incentivised domestic manufacturers to carry out vertical integration across the solar PV supply chain. Demand-side policies include domestic content requirement (DCR) schemes such as *Pradhan Mantri Kisan Urja Suraksha evam Uthaan Mahabhiyan* (PM-KUSUM) and *Pradhan Mantri-Surya Ghar Muft Bijli Yojana*, which require domestic solar cells and modules to be used for rooftop solar PV installations and distributed renewable energy installations.

Additionally, similar to the *Approved List of Models and Manufacturers* (ALMM) *List I*, which acts as a non-tariff barrier for domestic modules against imports, the government plans to implement the ALMM List-II from June 2026 to create demand for domestic cells (MNRE 2024a).

Figure 5. Annual solar PV installations have grown, but consistency is required to meet the NDC target

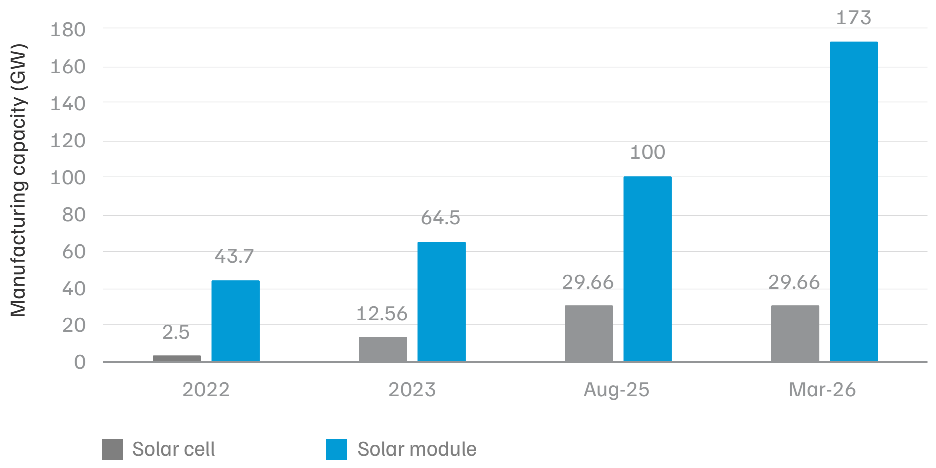


Source: MNRE 2025d

As of February 2026, India's installed solar capacity stands at 140.60 GW (MNRE 2025c), and the annual solar PV installation in FY 2025 was 23.83 GW, as given in Figure 5. Thus, around 151.4 GW needs to be installed over the next four years to meet the NDC target, which entails an annual average deployment of nearly 37.85 GW.

While deployment rates are short of the required installations, module manufacturing capacity enlisted in ALMM List-I reached 173 GW in March 2026 (MNRE 2026b). However, 80 per cent of this would be dependent on imported solar cells from China as the domestic solar cell manufacturing capacity stands at 29.66 GW (Waaree Energies 2025; MNRE 2025a; Sinovoltaics 2025; ETEnergyWorld 2024; MNRE 2026a), as shown in Figure 6. This gap in the domestic module and cell manufacturing capacity needs to be bridged in a timely fashion to reduce industry's exposure to supply chain vulnerabilities, as well as ensure compliance with upcoming policy mandates like the *ALMM List-II.*

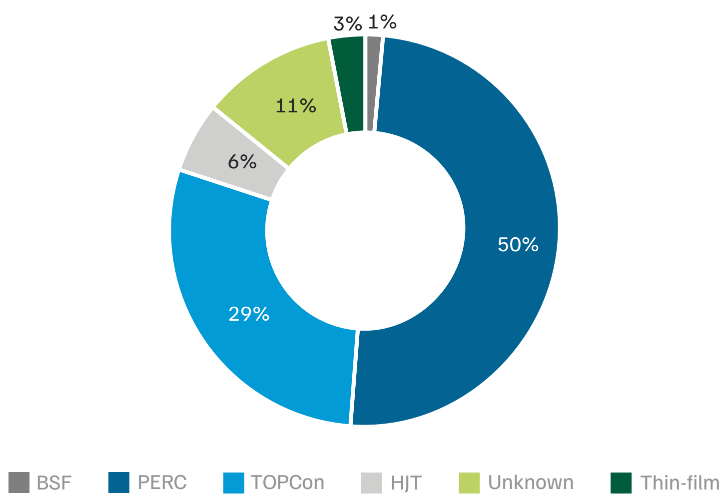
Figure 6. India's module manufacturing has outpaced cell capacity, creating strong demand for new cell production



Sources: MERCOM India 2023b, MERCOM India 2025d, Sinovoltaics 2024, Sinovoltaics 2025, Waaree Energies 2025, ETEnergyWorld 2024

Domestic cell manufacturing is mainly PERC-based, with a few manufacturers producing TOPCon. Previously dominant BSF (back surface field) solar cell technology, has very minor production share now. A breakdown of the manufacturing capacities for different cell technologies has been provided in Figure 7.

Figure 7. PERC-based cell manufacturing remains dominant in India, only 29% geared towards TOPCon



Source: Authors' analysis from Sinovoltaics 2025

Out of 29.66 GW of solar cell manufacturing capacity, BSF accounts for 0.43 GW, PERC for 14.76 GW, TOPCon for 8.5 GW, HJT for 1.72 GW, thin-film (cadmium telluride) for 3.3 GW, while around 0.9 GW is unknown—not clarified by solar cell manufacturers. A detailed manufacturer-wise breakdown is provided in Annexure 1. Recognising the global trend of the rising importance of TOPCon, several Indian manufacturers have announced expansion plans to set up TOPCon-based manufacturing facilities—amounting to nearly 22 GW—by March 2027. A detailed manufacturer-wise breakdown of such expansion plans has been provided in Annexure 2.

The government has also imposed a Basic Custom Duty of 20 per cent and Agriculture Infrastructure Development Cess (AIDC) of 7.5 per cent on imported solar cells, to protect domestic cell manufacturing (Ministry of Finance 2025). Further, on 29 September 2025, the Directorate General of Trade Remedies (DGTR) recommended anti-dumping duties up to 30 per cent on imported Chinese solar cells (DGTR 2025). If the ADD is levied, the cumulative tariff of 57.5 per cent would lead to an increase in the price of imported cells from USD 0.039 per Wp (InfoLink Consulting 2025b) to nearly USD 0.06 per Wp, which is near the lower end of the domestic solar cell price (nearly USD 0.07 per Wp), as of November 2025 (CRISIL 2025). While the duties make imported Chinese solar cells comparable to domestic solar cells in terms of price, domestic solar cell manufacturing remains more expensive than Chinese cells, and the removal of duties would ultimately lead to non-competitiveness. Therefore, domestic solar cell manufacturing currently faces a twin-problem of higher manufacturing costs and a lag in adoption of current mainstay solar cell technology.

57.5% import tariffs on imported solar cells have narrowed the gap with domestic market prices – yet, higher production costs and technology adoption lag constrain capacity expansion and competitiveness.

1.3 Twin problem of high manufacturing costs and technology lag

To reap the benefits of indigenisation, the twin problems of higher manufacturing costs and technological lag must be addressed, and for that, their causes must be identified. The research objective of this report is to identify what causes these two problems and identify strategic interventions that policymakers and domestic manufacturers can carry out that would solve them. Due to the dominance of silicon-based solar cell technology (97.5 per cent of the total market share worldwide), the report focuses on costs, components, technology, and machinery aspects of silicon-based solar cell manufacturing only.

Overcoming these challenges will help the domestic manufacturing industry achieve indigenisation of solar cell manufacturing, leading to supply chain resilience. Furthermore, this would enable Indian manufacturers to capitalise on the prevailing ‘China Plus One’ sentiment in international markets, and become a significant player in diversifying global solar supply chains. This would help domestic manufacturers to expand their export markets. Historically, more than 97 per cent of India’s solar exports across FY 2023, FY 2024, and FY 2025, have been geared towards the United States (Sharma, Gulia and Garg 2024). However, due to 18 per cent tariffs being levied on Indian exports to the USA (Ministry of Commerce 2026), along with ongoing anti-dumping duties (ADD) and countervailing duties on Indian solar cells and modules by the US Department of Commerce and US International Trade Commission (USITC) (USITC 2025), this export market has now come under threat. Vertical integration, starting with the production of solar cells, would also aid in the creation of new jobs, stimulate investment, and create market opportunities.

We carried out a comprehensive literature review to identify the current solar cell technology landscape. This included identifying the cost-drivers of solar cell manufacturing in Chapter 2, and identifying key technological issues for domestic solar cell manufacturers in Chapter 3. We further complemented findings from the literature review with stakeholder consultations, and identified the specific factors contributing to high domestic manufacturing costs and persistent technological lag. Finally, we have provided key recommendations that will help policymakers and stakeholders navigate these challenges to establish a resilient and future-proof solar cell manufacturing industry. We drew up these recommendations by considering existing domestic policies, comparing what policy measures other nations have taken, and the key gaps identified from the analysis.

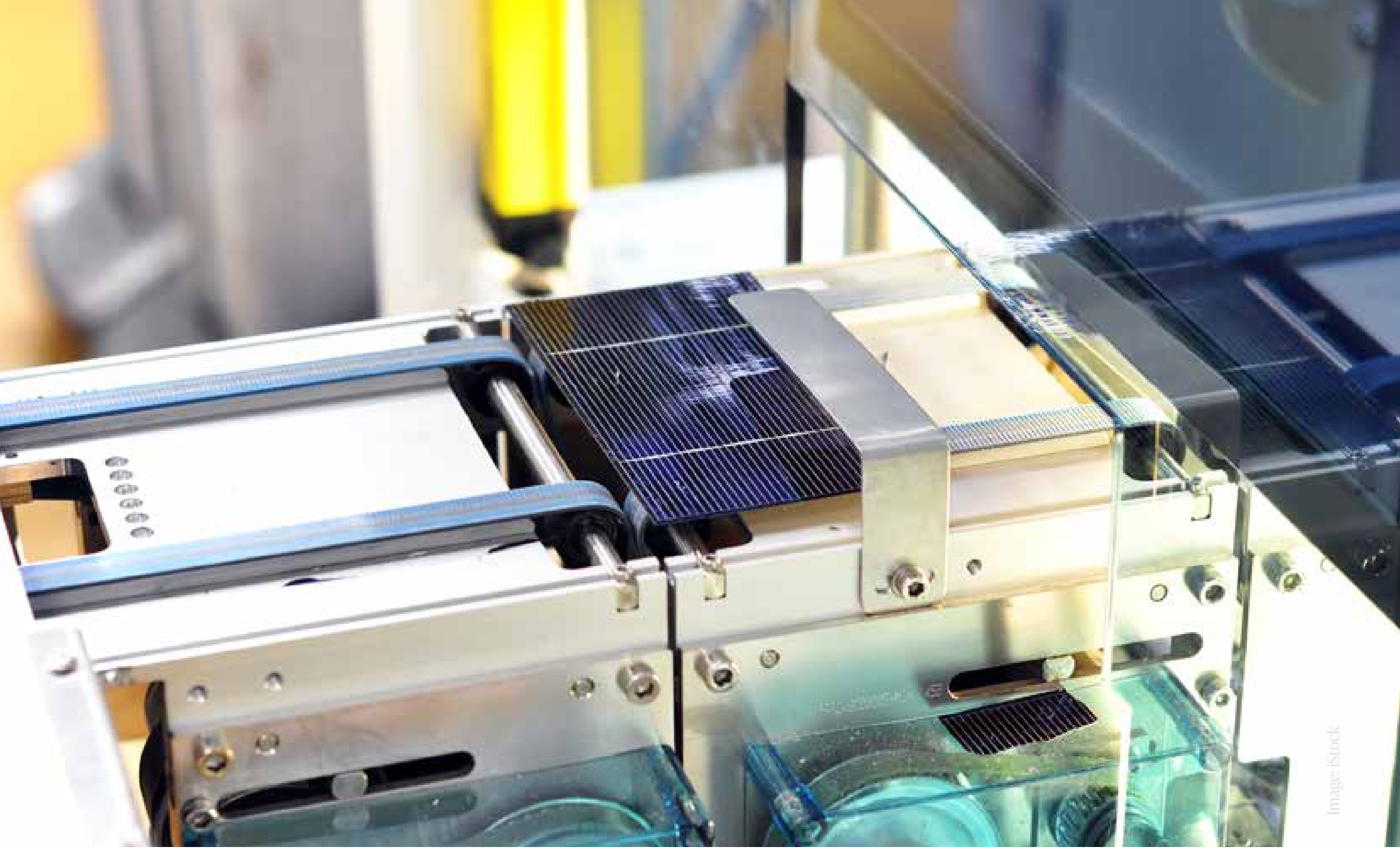


Image: iStock

2. Price pressures for domestic solar cell manufacturing

Prices for components across the solar supply chain have hit historic lows, as detailed in Figure 2. Market prices of Chinese solar cells were around USD 0.038 per Wp (Infolink Consulting 2025c) in November 2025, much cheaper than domestically manufactured solar cells, which can have market prices as high as USD 0.07 per Wp. Even after the implementation of a total of 57.5 per cent of duty (BCD and ADD) on imported solar cells, the price of imported solar cells is in the range of 0.06 USD per Wp, which is still cheaper than the price range of domestic solar cells. The market price of solar cells is determined by both supply and demand, and the production cost of solar cells. As 91.8 per cent of global solar cell manufacturing capacity is concentrated in China, the supply side price dynamics are influenced by Chinese manufacturers.

However, this pricing regime is beginning to shift. China's decision to phase out value-added-tax (VAT) export rebates for solar wafers, cells, and modules from 1 April 2026, after an earlier cut in late 2024, has already raised export and domestic pricing along the entire supply chain, and is shifting sourcing and trade patterns worldwide. China previously reduced the export tax rebate for PV products to 9 per cent from 13 per cent in December 2024, as part of its broader efforts to curb overcapacity and deflationary price wars amid international trade tensions (PV Magazine

2025a; Reuters 2026). Spot-price data now reflects this, with rise in mono-PERC cell prices to averages near USD 0.047 to 0.056 per Wp (InfoLink Consulting 2025c). It is expected that cell prices will increase along with modules once rebates are removed. Project equipment and panel procurement costs are also expected to increase by 9 to 15 per cent (MERCOM India 2025a) in the short term.

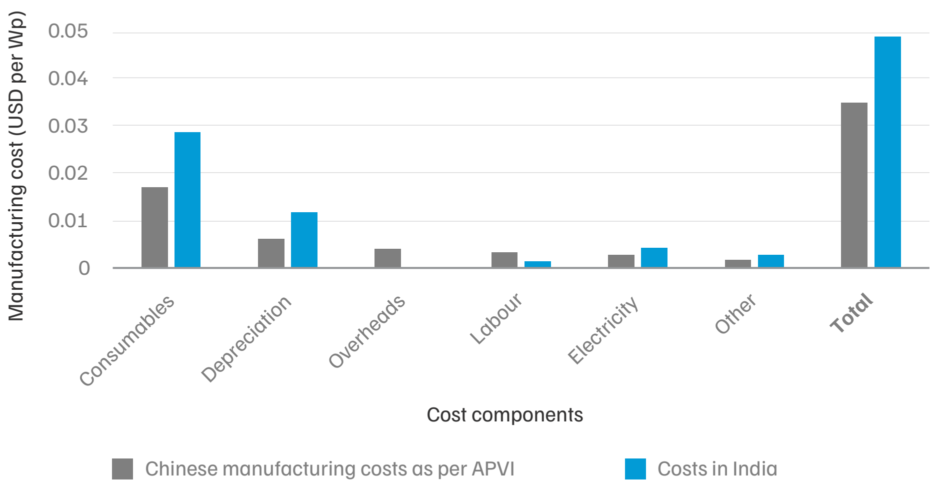
While these developments may narrow the price differential at the margin, the structural gap between Chinese and Indian manufacturing costs remains substantial. For Indian manufacturers to compete sustainably, irrespective of short-term price corrections driven by Chinese policy, it is essential to reduce domestic production costs. This makes it imperative to systematically analyse and elucidate the differences in the cost structures of solar cell manufacturing in India and China. The subsequent sections, therefore, break down the key drivers of production cost in both geographies.

2.1 Breaking down cost drivers of Chinese and Indian solar cell manufacturing

The first difference between domestic and Chinese manufacturing set-up is the level of vertical integration. Leading Chinese manufacturers are vertically integrated across wafer, cell, and module production (InfoLink Consulting 2023), while Indian solar cell manufacturers have to depend on imported wafers. As Chinese manufacturers are vertically integrated, their cost of manufacturing solar cells does not include the cost of wafer sourcing.

The cost of manufacturing solar cells includes costs due to capital expenditure (which, when accounted for across the lifetime of a manufacturing facility, are termed as depreciation), consumables (such as wafer, silver paste, and other chemicals), labour, electricity, overheads, and other costs, such as maintenance of the manufacturing facility, overheads such as R&D, and costs due to shipping and tariffs (APVI 2024). Figure 8 provides a comparison of cost-of-manufacturing TOPCon solar cells in Chinese and Indian manufacturing set-ups. Given that TOPCon is the currently dominant solar cell technology and is expected to have a market share of at least 50 per cent till 2030, cost of manufacturing estimations for Chinese and Indian set-ups are based on TOPCon solar cell technology (VDMA 2025).

Figure 8. Higher consumable and capital costs make solar cell manufacturing in India more expensive than China



Source: Authors' analysis from APVI 2024; Stakeholder consultations; Premier Energies 2024; Vikram Solar 2024 and Waaree Energies 2024a

Consumables for the Indian estimate include both wafer and silver paste, while consumables for the China estimate include only silver paste. Other consumables, such as the chemicals in which wafers are dipped, form a very miniscule portion of the total costs, and hence are not included in the calculation. Further, depreciation for capital expenditure for Chinese set-ups is based upon literature, while depreciation for Indian manufacturing set-ups is calculated on the basis of capital expenditure estimation announced by Indian manufacturers in their draft red-herring prospectus (DRHP) documents. The depreciation calculation is shown in Annexure 5.

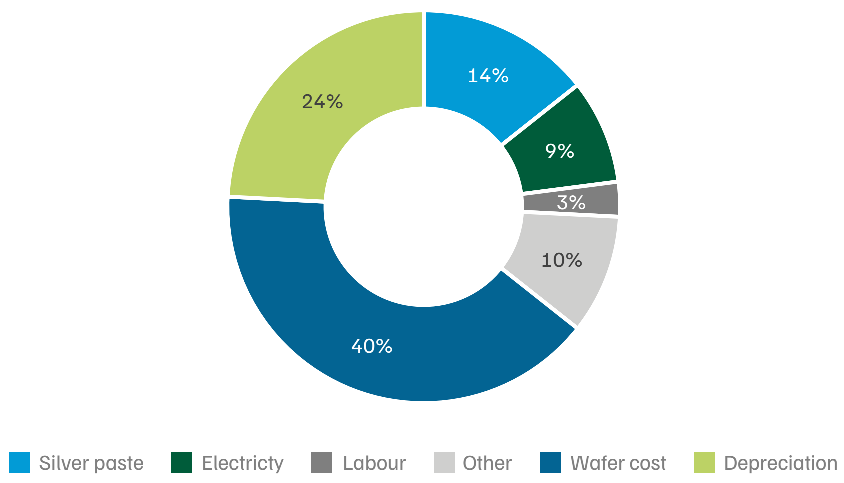
Consumables and capital expenditure are the major cost drivers that make Indian solar cell manufacturing more expensive than Chinese solar cell manufacturing. The next sections will explore the reasons behind this.

2.2 Cost attributed to various consumables

1. Wafer

For domestic solar cell manufacturing, wafer consumption is the highest cost driver, as shown in Figure 9. Domestic cell manufacturers depend on imported wafers, predominantly from China, which has 95 per cent of the global wafer manufacturing capacity (IEA 2024). The concentration of wafer manufacturing in China makes it vulnerable to disruption, and entails that a majority of the value addition for the domestic solar supply chain is situated outside. For example, a 7.7-magnitude earthquake on the Richter scale hit Myanmar on 28 March 2025, affecting China's wafer production areas, particularly regions like Sichuan, Ningxia, Yunnan, and Inner Mongolia (InfoLink Consulting 2025b). The earthquake caused equipment issues such as wire breaks and furnace explosions, affecting production output, supply-demand balance, and thus leading to a 5–10 per cent increase in wafer price (JA Solar Tech 2025). Policy changes, including the lapse of the BCD exemption on imported silicon inputs and un-diffused wafers from 1 April 2026 will impact the cost of imports, leading to a direct cost escalation for Indian solar cell manufacturers (Ministry of Finance 2026). The measure compresses profit margins and structurally favors vertically integrated domestic producers with wafer capacity.

Figure 9. Wafer and silver paste are the primary cost drivers amongst consumables



Source: Authors' analysis from stakeholder estimates; Vikram Solar 2024, Premier Energies 2024

Wafer sizes have kept increasing, with a predicted market shift from M10 wafers, which have a dimension of 182 mm x 182 mm, towards G12 wafers and G12 rectangular wafers, which have a dimension of 210 mm x 210 mm and 210 mm x 182 mm, respectively (VDMA 2025). The shift to larger and rectangular wafers has led to greater power output of solar cells, and provided flexibility for manufacturers to produce solar cells of varying sizes, tailored to their module size requirements. Due to rapid changes in wafer size and shape, and changes to equipment required to process the wafers, manufacturers face uncertainty (VDMA 2025).

2. Silver paste

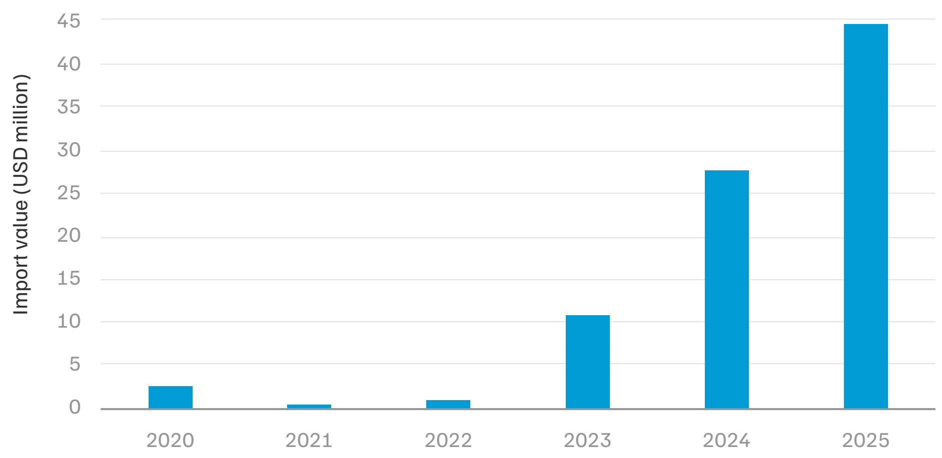
Silver paste is made using silver particles, glass frit, and an organic binder, and is produced by mixing, rolling pulp, and other processes (Maysun Solar 2023b). The process of making silver paste requires optimisation of the size and shape of silver paste particles, and has strong intellectual property protections (CEEW 2022). For a TOPCon solar cell, keeping aside the cost of importing wafers, silver paste consumption can contribute at least 20 per cent of the entire cost outside China (APVI 2024).

Import dependence for silver paste

Domestic manufacturers are completely import-dependent for sourcing silver paste from a few regions like China, Hong Kong, Taiwan and Singapore[1], predominantly under two HS codes[2]: 71069290 and 71159010 (Ministry of Commerce 2025). The total value of commodities imported under these two HS codes are showcased in Figure 10 and Figure 11. The description of each of the HS codes are:

- 71159010: Other articles of precious metal or metal clad with precious metal.
- 71069290: Silver (including silver plated with gold or platinum), unwrought, semi-manufactured, or powder form.

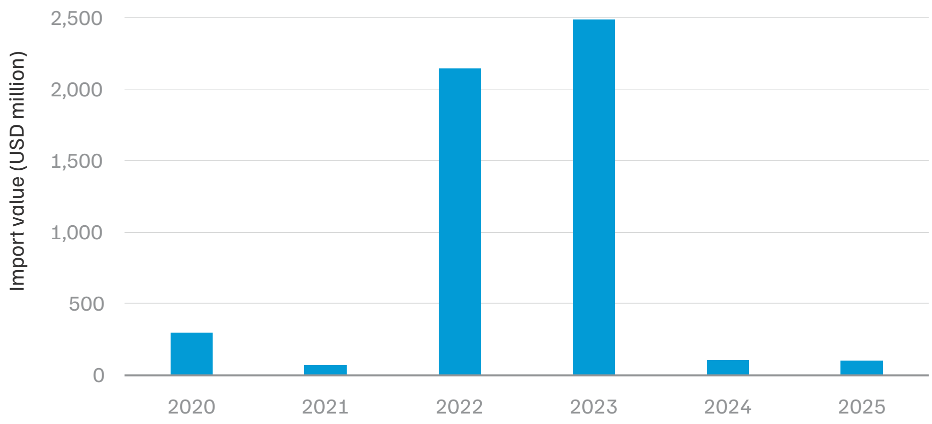
Figure 10. USD 88 million worth of total commodities have been imported under HS code 71159010 over six years



Source: Ministry of Commerce 2025

1. According to stakeholder consultations.
2. The Harmonised Commodity Description and Coding System, generally referred to as 'Harmonised System' or simply 'HS' is a multipurpose international product nomenclature developed by the World Customs Organization (WCO). It comprises more than 5,000 commodity groups, each identified by an eight-digit code, arranged in a legal and logical structure, and is supported by well-defined rules to achieve uniform classification (World Customs Organization 2025).

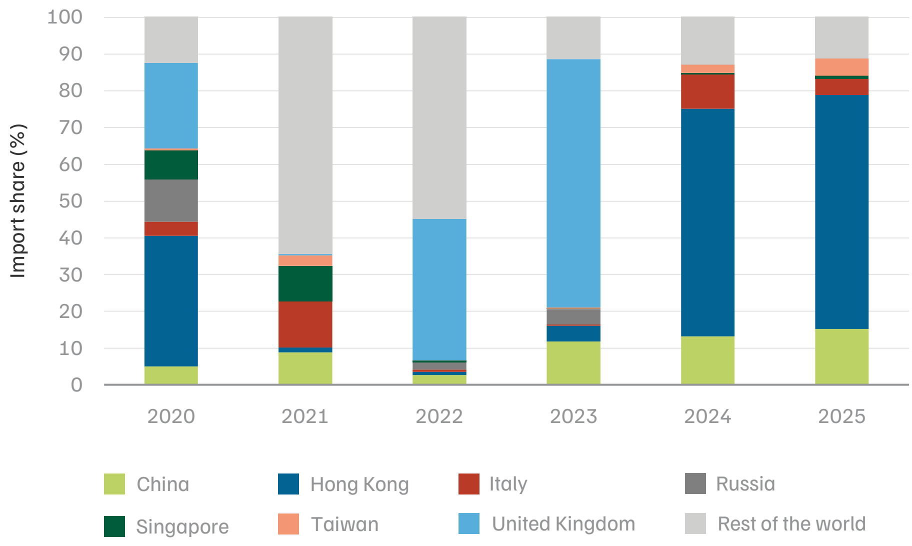
Figure 11. USD 5211 million worth of total commodities have been imported under HS code 71069290



Source: Ministry of Commerce 2025

Analysis of import share changes across years for commodities under both HS codes reveals that imports under HS code 71069290 are distributed across multiple countries, as shown in Figure 12. This suggests that the HS code encompasses a range of commodities beyond silver paste. Given that silver paste is primarily sourced from China, the presence of significant import shares from other countries indicates the inclusion of other materials under this classification.

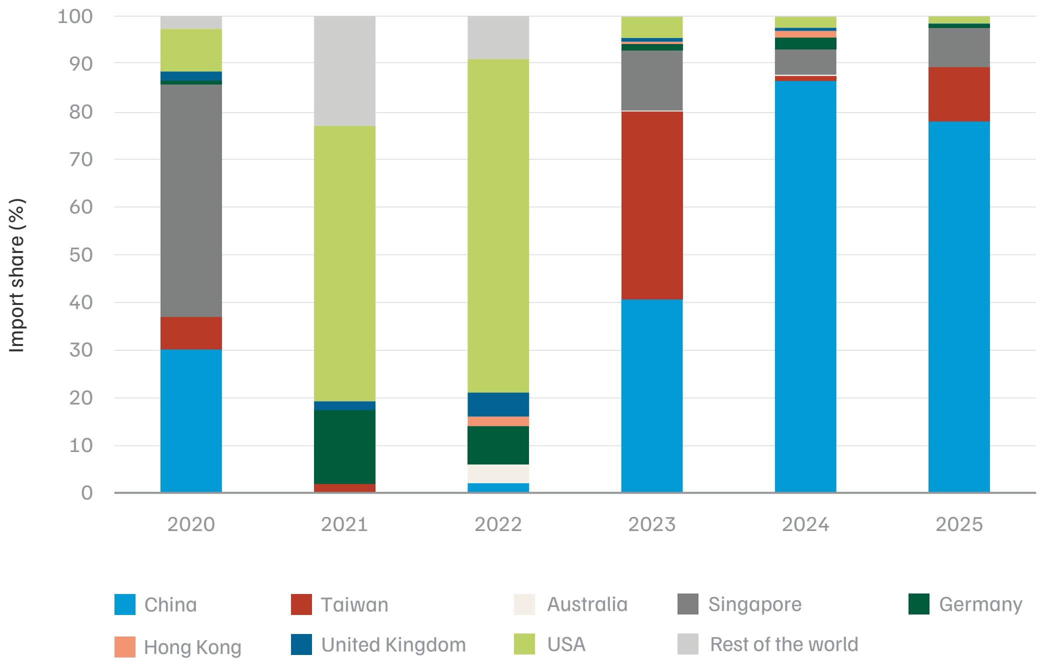
Figure 12. Imports for commodities under HS Code 71069290 are spread out over multiple countries



Source: Ministry of Commerce 2025

In comparison, imports under HS code 71159010 have consistently been dominated by China over the years, as illustrated in Figure 13.

Figure 13. China has been the most significant source of imports for HS Code 71159010



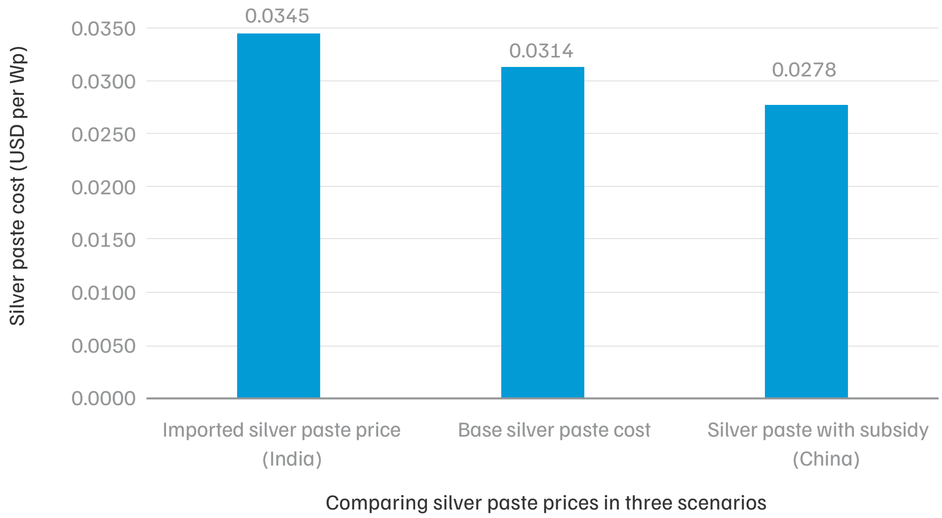
Source: Ministry of Commerce 2025

Overall, the difference in import volume and import share between the two HS codes signals a lack of clarity in classifying conductive silver paste into HS codes, which causes a lack of traceability of silver paste imports for solar PV manufacturing.

Cost contribution of silver paste to solar cell manufacturing

As of February 2026, front-side silver paste for fingerprinting, front-side silver paste for busbars, and rear-side silver paste were priced at USD 2,473 per kg (Shanghai Metals Market 2025b), USD 2,566 per kg (Shanghai Metals Market 2025a), and USD 1,712 per kg (Shanghai Metals Market 2025c), respectively. For Indian solar cell manufacturers, silver paste effectively costs 24 per cent more than Chinese competitors. This is due to a combined effect of import duties on silver paste, and subsidies granted to Chinese manufacturers upon sourcing silver paste from Chinese players. Assuming a 13.5 mg per Wp (VDMA 2025) consumption of silver paste for TOPCon solar cell, the base cost contributed by silver paste alone for cell manufacturing is USD 0.0314 per Wp. Further, silver paste imported to India under the two HS codes is subject to a 10 per cent customs duty (Central Board of Indirect Taxes and Customs 2025), raising costs to USD 0.0345 per Wp. In comparison, Chinese manufacturers benefit from subsidies of approximately 11.5 per cent on silver paste sourced domestically (APVI 2024), reducing their effective cost to USD 0.0278 per Wp. A comparison of these silver paste costs, base price and post-duty cost in India, and subsidised cost in China, is presented in Figure 14.

Figure 14. Chinese cell makers benefit from subsidised silver paste, Indian manufacturers face higher costs due to import duties



Source: Authors' analysis from Shanghai Metals Market 2025a; Shanghai Metals Market 2025b, Shanghai Metals Market 2025c and VDMA 2025

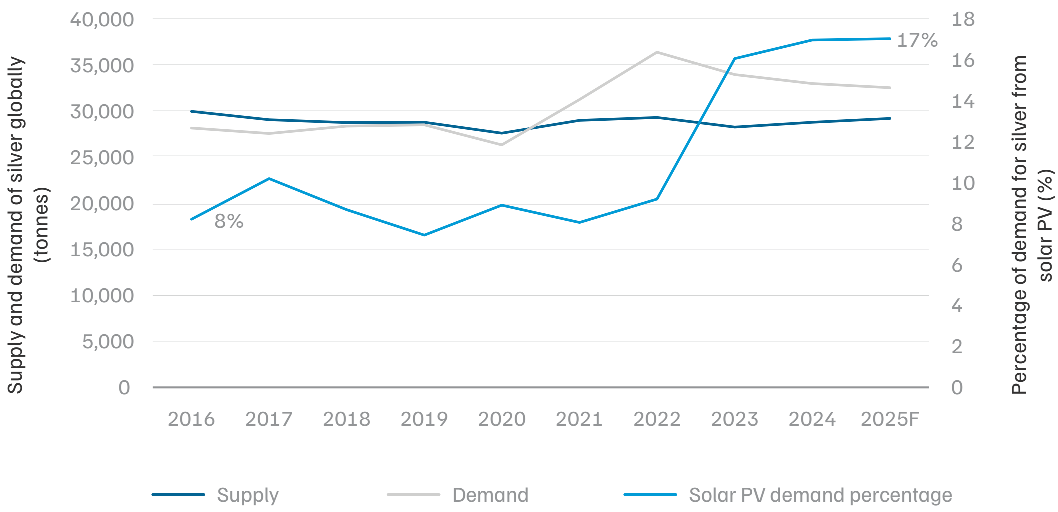
The removal of import customs duty on silver paste can bring the cost differential between Indian and Chinese players down from 24 per cent to 13 per cent.

Rising silver demand due to solar PV

Apart from rise in silver costs due to import dependence, there is a demand-supply imbalance, leading to rise in prices. At the end of 2025, total silver demand across various applications was 32,554 tonnes, eclipsing total silver supply at the end of 2025, which was 29,217 tonnes (The Silver Institute 2025). Further, silver demand from solar PV applications reached 17 per cent of total demand in 2025, rising from 8 per cent in 2016, as shown in Figure 15.

Rising silver demand from solar PV manufacturing has contributed to broader demand-supply imbalance

Figure 15. Global silver demand has eclipsed supply; rising demand from solar PV a key factor



Source: The Silver Institute 2025

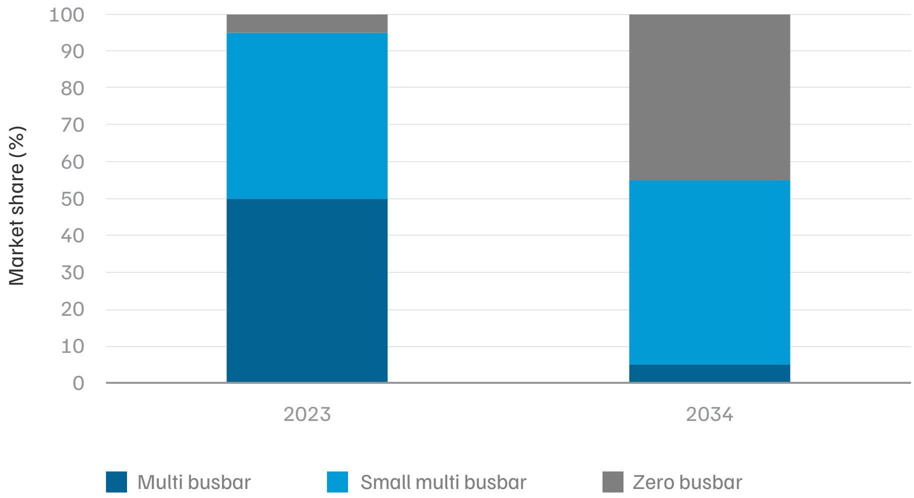
Figure 15 shows silver demand overtaking the supply, coinciding with the rise in silver demand from solar PV, which may entail a potential risk from rising silver prices. A long-term solution would be to either reduce silver paste consumption, or explore alternative materials to lower costs.

Technological advances in the reduction of silver paste consumption

One of the technical advances underway is the shift from multi busbar (MBB) technologies, which consist of nine busbars per solar cell of the thickness of 0.3 to 0.4 mm, to smart multi busbars (SMBB), which consist of 16 to 20 busbars per solar cell, enabling the usage of finer busbars of the thickness of 0.24 mm (Maysun Solar 2023a). Finer busbars reduce silver paste use, minimise shading, and lower electrical resistance, leading to lower costs and higher efficiency. A further shift from SMBB to zero busbar (0BB) technology is expected, as it eliminates the need for busbars by connecting the silver fingers with the ribbons attached to the modules, further reducing silver consumption, shading, and electrical resistance. Zero busbar technology can reduce silver paste consumption by 30 per cent, but is currently in the early stages of industrialisation, optimising the exact process of connecting the ribbons to the silver fingers (Maysun Solar 2024).

Assuming a silver consumption of 13.5 mg per Wp for TOPCon, a 30 per cent reduction through 0BB technology will lead to a reduction in silver consumption to 9.45 mg per Wp. This leads to a 30 per cent reduction in silver paste cost, pushing it down to USD 0.0242 per Wp and USD 0.019 per Wp for Indian and Chinese players respectively. However, R&D for such technologies are being led by Chinese manufacturers; Indian manufacturers lag behind in research and development due to a lack of industry and academia collaboration, a lack of R&D investment, and focus on scaling up commercialised technologies.

Figure 16. Busbar technologies that reduce silver paste consumption are likely to gain market share



Source: VDMA 2025

The market share for both SMBB and 0BB technologies is expected to increase from approximately 45 and 5 per cent respectively in 2024 to approximately 50 and 45 per cent in 2035 (VDMA 2025), with a decrease in the market share for MBB technologies from 50 to nearly 5 per cent in 2034 (VDMA 2025), as shown in Figure 16. Implementing advanced busbar technology in domestic cell manufacturing requires sourcing suitable equipment as well as developing the technical expertise to operate it. Chinese manufacturers are a step ahead in commercialising such technologies due to their close collaboration with their equipment suppliers, thus ensuring higher performance and, in this particular case, lower costs.

Another novel method of reducing silver paste consumption is replacing silver paste with a mixture of silver and copper paste (Taiyang News 2023a). In such pastes, copper particles are coated with silver, reducing the amount of silver required. These pastes, now entering commercialisation, are primarily aimed at HJT solar cells, which consume more silver than TOPCon cells (Taiyang News 2023a). Currently, hybrid silver and copper paste metallisation ratios of 20 per cent and 70 per cent are commercially available for HJT solar cell manufacturing (Taiyang News 2025a).

> Adopting novel technological innovations such as 0BB and hybrid silver-copper pastes, can reduce silver consumption by 30% and 80% respectively.

3. Chemical consumables

The chemical consumables used in solar cell manufacturing consist of hydrochloric acid (HCl), hydrogen fluoride (HF), nitric acid (HNO_3), potassium hydroxide (KOH), deionised water, and gases such as Diborane (B_2H_6) and Silane (SiH_4). Hydrochloric acid, hydrogen fluoride, nitric acid, and potassium hydroxide are used in surface damage etching and texturing, the initial steps of solar cell manufacturing. Chemicals such as deionised water are required in edge isolation, performed after emitter formation through diffusion (Taiyang News 2023b). Chemical gases like diborane and silane are used as feedstock material for emitter formation and passivation layer deposition. According to stakeholders, these gases are imported from outside, stored in bottling plants, and then transported to manufacturing facilities in tankers. Transportation and storage of these chemicals increase the indirect costs through warehousing and tanker requirements, creating a logistical challenge. For example, silane is an explosive chemical which must be stored offsite, and transported at USD 0.09 per km per tonne. This cost gets embedded into the overall manufacturing cost.

2.3 Indian solar cell manufacturing requires nearly twice the capex of China

Table 1 compares the capital expenditure[3] estimated from analysing the DRHP documents of two domestic manufacturers, Vikram Solar (Vikram Solar 2024) and Premier Energies (Premier Energies 2024). The original tables have been attached in Annexure 4.

Table 1: Comparing cost of establishing solar cell manufacturing facilities in India

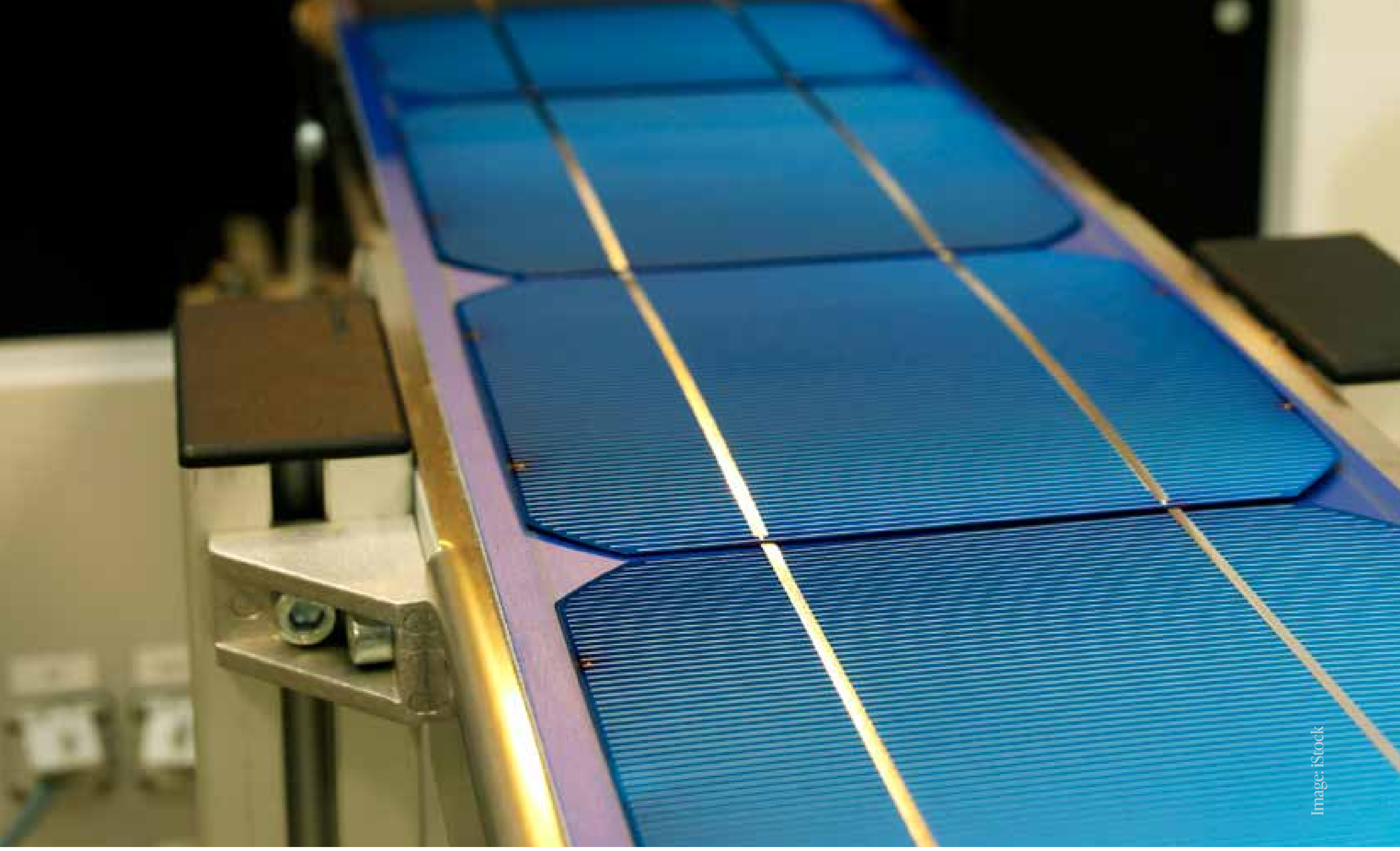
Particulars	Vikram Solar expenditure (USD million /GW)	Premier Energies expenditure (USD million /GW)
Land and site development	0.8	0
Building and civil works	5.3	4.1
Plant, machinery, equipment, and utilities	59.8	55.6
Miscellaneous (fixed assets, pre-operative expenses)	1.8	1.9
Design, engineering, and project management	0	0.7
Interest during construction	2.0	6.2
Contingency cost	1.4	1.4
Total	**71.1**	**70.0**

Source: Vikram Solar 2024, Premier Energies 2024

3. The numbers originally were mentioned in INR million; they have been converted to USD million for uniformity.

From Table 1, the average capital expenditure for establishing TOPCon cell manufacturing facilities is around USD 70 million per GW. In China, estimated capital expenditure for TOPCon cell manufacturing facilities can range from USD 25 million per GW (APVI 2024) to an average of USD 42 million per GW (CRISIL 2024). Thus an average of USD 33.5 million per GW of capital expenditure can be considered, which is nearly 48 per cent of India's capex. Hence, Indian manufacturers require almost double the capital expenditure to set up solar cell manufacturing facilities compared to Chinese manufacturers. As the capital expenditure incurred for equipment and machinery significantly varies in India and China, the depreciation calculated based on their useful life under the straight-line method will also significantly vary. As depreciation is a revenue expenditure, it will affect the profitability of the company.

Stakeholder consultations reveal that the lower capital expenditure in China is due to the country's larger manufacturing facilities, with dozens of GWs (Renewable Energy Institute 2024), leading them to reach economies of scale quicker. India's largest solar cell manufacturing capacity is 5.4 GW, and the average size of a facility is around 2 GW (Sinovoltaics 2024), leading to longer time to achieve profitability. Additionally, Chinese manufacturers benefit from lower infrastructure costs, lower equipment costs sourced from Chinese manufacturers with no shipping costs, and subsidies for capital expenditure for building, civil works, and land, all of which reduce capital expenditure.



3. Technological outlook on domestic solar cell manufacturing

Indian manufacturers face another key challenge—slower adoption of advanced technologies compared to their global and Chinese counterparts. Only 29 per cent of the domestic solar cell manufacturing capacity is geared towards producing TOPCon solar cell technology, which is the current dominant cell technology. Recognising this, several domestic cell manufacturers have announced expansions for TOPCon solar cells (mentioned in Annexure 2), along with one manufacturer focusing on producing HJT solar cells. While announcements have been made, Indian manufacturers have to select and optimise the right equipment. Along with this, they have to train and retain a skilled workforce to execute the production process, and overall support research and development for alternative cell technologies. These are key factors in adapting to the changing landscape of solar cell technology.

3.1 Cell manufacturing equipment

For importing cell manufacturing machinery, there are two methods of sourcing: either importing the entire cell line from one equipment manufacturer in a 'turnkey mode', or importing the machinery required for each manufacturing process step separately through 'cherry-picked mode'. Each mode of importing equipment offers unique advantages and challenges, as detailed in Table 2.

Table 2: Differences in the two modes of sourcing cell manufacturing equipment.

Turnkey mode	Cherry-picked mode
• 25 to 30 per cent more expensive than cherry-picked mode. • More straightforward to optimise. • Equipment suppliers provide the technical knowhow for installation, optimisation and operation of the equipment.	• Longer optimisation time due to difficulties in interlinking and matching the throughput of equipment sourced from different suppliers. • Often requires assistance from consultants such as RCT Solutions GmbH for equipment selection, equipment output and production ramp up, as they have the technical knowhow.

Source: APVI 2024, and stakeholder consultations

Chinese manufacturers work in close collaboration with local equipment manufacturers, and thus possess the technical knowhow to keep manufacturing and innovating high-efficiency cells. In contrast, for the Indian solar industry, the technical knowhow to optimise and operate the equipment is primarily limited to the equipment providers (who are predominantly Chinese), which makes domestic solar cell manufacturers dependent on them for both equipment and knowledge. Thus, the absence of indigenous equipment production capability contributes to the lag in technical knowhow of Indian solar cell manufacturing.

3.2 Impact of dynamic changes in global cell technology on domestic manufacturing

The solar cell technology landscape is rapidly changing, with ever-increasing efficiency levels and reducing costs. While domestic manufacturers are focusing on manufacturing TOPCon cells, other cell technologies like HJT and Back Contact cells offer unique advantages, if commercialised. However, these cell technologies also pose unique barriers to commercialisation, due to the complexity of manufacturing processes and the cost of consumables required. Table 3 provides an overview of the challenges and advantages offered by commercial production of TOPCon, HJT, and Back Contact cells.

Table 3: HJT and XBC cells offer advantages, but TOPCon is a commercially viable option

Cell technology	Challenges faced	Advantages upon commercialisation
TOPCon	• Longer commissioning time (12 months) vs PERC (7–8 months) due to more process steps. • Upgradation costs from PERC: USD 14.66–19.58 million per GW according to stakeholders. • Larger cleanroom size required: 10–12 square metres per line vs 7–8 square metres per line for PERC.	• Shares many manufacturing steps with PERC, easier to upgrade. • Mature technology with fast scaling-up once optimised.
HJT	• Entirely different process flow; fewer steps with high initial capex. • High opex due to stronger cleanroom requirements, usage of targets in PVD process, vacuum-based equipment, higher silver paste consumption, and usage of rare earth material such as Indium. • Lack of both domestic commercial manufacturing and domestic R&D	• Higher efficiency and bi-faciality, better temperature sensitivity, ideal for deployment in Indian climates. • Supports thinner wafers (90 micrometres vs 130 micrometres for TOPCon), thus has potential for cost-saving.
XBC	• More complex than TOPCon or HJT due to rear-side contact architecture. • Difficult to achieve cost-competitiveness due to lower yields. • Difficult optimisation process.	• Highest efficiency ceiling. • Compatible with both TOPCon and HJT cell technology.

Source: Authors' analysis from stakeholder consultations

In addition to the complex cell design and manufacturing process for cell technologies, domestic manufacturers also face the challenge of keeping pace with rapid innovations by Chinese manufacturers across all three cell technologies. An example of this is the recent standardised metallisation process in TOPCon solar cells, called laser enhanced contact optimisation (LECO), which leads to an absolute efficiency increase of 0.5 per cent and demonstrates better reliability on exposure to sodium chloride (salt or NaCl) (Wu et al. 2024). Innovations—such as edge passivation deposition (EPD) which involves deposition of passivation layers on the edges formed after half-cutting of cells, leading to an efficiency gain of around 0.15 per cent (Li et al. 2022), are also in the process of being commercialised and standardised. Other innovations underway include development of copper and silver paste hybrids to reduce the cost of HJT and XBC cells.

Domestic solar cell manufacturers thus face challenges in executing the complex manufacturing processes of HJT and XBC, and in adapting to the rapid innovations currently occurring across all three solar cell technologies. These challenges are a cause of concern, as they can widen the existing gap between Indian and Chinese solar cell manufacturing. Connected to this theme, there arises a question of the kind of labour needed to operate and optimise the equipment, and how domestic manufacturers fare in this regard. This shall be explored in the next subsection.

3.3 Skills and labour

Two kinds of job roles are required for solar cell manufacturing: operators and process engineers. Operators are responsible for the day-to-day operation of machinery and must follow a specific set of instructions provided by the manufacturers. Operator roles require a ‘low-skilled’ workforce, easy to source for manufacturers. In contrast, according to stakeholders, it is process engineers whose hiring, training, and retention are difficult for domestic solar cell manufacturers.

A process engineer must have qualifications in mechanical, chemical, or electrical engineering, and requires additional training to carry out the required process control. International job listings by solar cell manufacturers show that a process engineer’s main responsibility is to carry out process management, new cell product integration, cell process and material development, and cell process standardisation (Qcells 2025). In Table 4, the skills and responsibilities required by domestic and foreign solar manufacturers have been listed.

Table 4: Skill requirements by domestic manufacturers are less complex than for foreign makers

Skills required by domestic solar manufacturers	**Skills required by foreign solar manufacturers**		
	Cell process management	**Cell process or material development**	**Cell process standardisation**
Process improvement skills	Troubleshooting process performance	Evaluating process setting and stability of new cell production models	Providing and training standard operating procedures
Six sigma methodology and statistical software	Improving cost of cell material	Researching foundational processes and materials through market intelligence, analysis and characterisation	Deciding specification of process condition, material model and consumption, cell product performance and quality
Process knowledge and experience in operating equipment and carrying out process related to wet chemistry, thermal diffusion, and metallisation	Optimising process conditions	Developing and testing the mass production reliability of proprietary processes and materials	Defining related cell process standard documents such as parameter sheets and bill of materials
	Training and evaluating performance of technicians	Managing procedures of new solar cell model and testing for mass production.	Establishing standard process environment for quality control, and modifying cell process for performance and quality requirements

Source: Authors' analysis from job listing published by Qcells and ReNew

Stakeholders have highlighted the need for training to upskill process engineers, but the training requirements are not standardised, as they are prone to changing along with a shift in cell technology and equipment. Due to the absence of indigenous equipment manufacturing, the knowledge base for operating and optimising often lags, and manufacturers have to depend on foreign technicians and experts to provide training. As domestic manufacturers import equipment from China, they depend on Chinese technicians to carry out training. For example, Waaree's 5.4 GW cell manufacturing capacity at Chikhli in Gujarat requires around 30 Chinese technicians to optimise the manufacturing process. Dependence on Chinese technicians poses a vulnerability for solar manufacturing in India, as visa approval delays are a common issue. Similar challenges in the electronics sector led to an estimated USD 15 billion in production losses between 2020 and 2024 (Economic Times 2024). As domestic solar cell manufacturing scales up, such visa-related disruptions may pose risks of similar disruptions.

Further, solar manufacturing faces a high attrition rate of skilled professionals (Reuters 2024). High attrition rates cause production delays and raise operational costs for domestic manufacturers due to frequent hiring and upskilling needs. As it is, the manufacturing sector faces competition in retaining workforce, especially for skilled roles, due to better pay, flexible work environments, and career growth opportunities in other sectors (TeamLease 2024).

3.4 TOPCon maturity and IP issues

Much of the core innovation around TOPCon technology is held by global and Chinese firms, raising concerns about patent barriers and licencing costs. Intellectual property constraints arising from this make a solar manufacturer vulnerable to potential infringements or restricted access to proprietary manufacturing processes. Solar manufacturers within China and globally, have filed patent infringement lawsuits, limiting the scope of technology transfer, increasing costs, and creating a delay in scaling. From April 2024 to February 2025, around 24 instances of patent infringement lawsuits have been filed worldwide by solar manufacturers against each other, concentrated mainly in the USA and the European Union. A brief summary of all the lawsuits filed has been mentioned in the Annexure 6.

Chinese manufacturers like Trina Solar and JinkoSolar have already filed lawsuits in the USA against domestic cell and module manufacturers Adani and Waaree. With emerging TOPCon capacity, Indian manufacturers risk entering a fiercely contested global market for cell technology, competitive advantage, and market share. If such patent infringement lawsuits are successful, the defendant manufacturer may be forced to cease production of the particular cell technology in question, destroy inventory, and compensate for financial losses (PV Magazine 2025b). Previous cases show that the damages sought by the claimant company can be as high as USD 147 million (PV Magazine 2025b), along with market restrictions in the jurisdictions where the lawsuits have been filed.

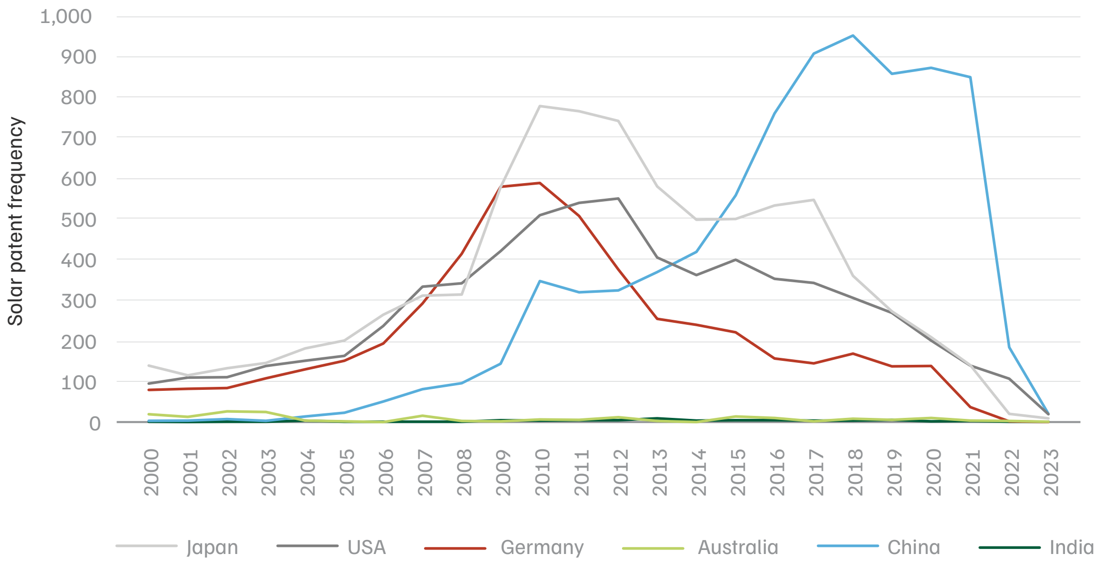
In FY 2023, FY 2024, and FY 2025, a respective 97, 99, and 97 per cent of domestic modules exported were to the USA, with the leading manufacturers, Waaree and Adani, exporting around 53 and 68 per cent of their total respective production (Ministry of Commerce 2025; Sharma, Gulia, and Garg 2024). As export is concentrated in one country along with revenue generation and investments by domestic manufacturers, IP-related disputes create an uncertain environment. Despite TOPCon being a low-hanging fruit for domestic manufacturers due to their lower capital and operational expenditure, manufacturers have to prepare for impending lawsuits. Successful lawsuits could restrict export markets for Indian solar manufacturers, resulting in revenue loss and missed opportunities to diversify their customer base. Revenue loss may hinder the future growth of domestic solar cell manufacturing, leading to manufacturers only catering to the domestic demand.

Rising IP issues and litigation cases in mature TOPCon technologies across the world can limit export markets for Indian cell manufacturers.

3.5 R&D for solar cell technology and manufacturing

Research and development (R&D) targeting solar PV is lagging in India. At an industry level, domestic solar cell manufacturers spend around 0.1 per cent of their total revenue on R&D (Vikram Solar 2024), whereas Chinese manufacturers can spend from 2 per cent (Taiyang News 2025c) up to nearly 6 per cent of their total revenue on R&D (LONGi 2024). Along with expenditure, patent data trends are also an indicator of the R&D ecosystem of a country for any particular sector. Figure 17 shows that the frequency of solar PV patents being registered in India is much lower than other countries, reflecting a weak R&D ecosystem.

Figure 17. India's low solar patent numbers signal an underperforming R&D sector



Source: IEA 2025a

It is essential to solve for the lagging R&D infrastructure, as evidenced by limited private spending and lower solar patent numbers, for scaling up domestic cell manufacturing. A thriving R&D sector would help the industry catch up with the global technology landscape, while also driving indigenous innovations that improve efficiency and reduce costs. To support R&D efforts, there has been a history of policy action taken by the Government of India. The impact of such initiatives, in comparison to the policy efforts of other nations, is highlighted in the next section.

Government support for research and development in India

Public funding for solar R&D in India is available through research grant programmes, funded by both the MNRE and the Department of Science and Technology (DST). This contrasts with how energy ministries lead the management of solar research and development funding in other technology-leading nations (CEEW 2022).

The MNRE funds research and development through the *Renewable Energy-Research and Technology Development* (RE-RTD) programme. Under this, projects from academic institutions, research institutes, government and non-profit research organisations are eligible for financial support of up to 100 per cent of the total cost. Financial support for private institutes, private research organisations, start-ups, entrepreneurs, and manufacturing units is restricted to 50 per cent (MNRE 2024b).

MNRE first implemented the RE-RTD programme from 2017–18 to 2019–20 (MNRE 2020). Under this programme, there were 14 projects focusing on solar PV, and eight of these projects were related to solar cell technology development. Although these projects were conducted at the lab scale and led by academic institutions, they have not been translated into industry-level applications despite successful evaluations. MNRE further announced the continuation of the scheme from 2020–21 to 2025–26 (MNRE 2023). In total, around USD 13 million (INR 1.11 billion) (MNRE 2025b), has been invested through this programme, with 225 total publications, seven filed patents, 10 new products developed, and 13 current ongoing projects. Of the ongoing projects, five are focused on solar PV. Only two out of those five projects focus on lab-scale solar cell development. Public funding for solar PV lags comprehensively in India compared to countries such as Japan and the United States. For example, as of August 2023, Japan's '*Project for Developing Next Generation Solar Cells*' has a budget of USD 420 million to support industrial efforts for the development and commercialisation of perovskite technology (Renewable Energy Institute 2024). The US, too, has previously allocated funding of USD 72 million just for solar PV research and development under their overall solar technologies research program, for one year (IEA 2021). Indian public funding thus has been disbursed over 9 years, yet is much less than the single year allocation for R&D by these countries.

Further, there is a lack of industry participation in the Indian solar R&D landscape. Of the projects being funded under MNRE's RE-RTD programme, only one project had an industry partner, BHEL. In comparison to this, industry participation is higher in the R&D ecosystem of other nations. For example, several Japanese companies, such as Aisin, EneCoat, Kaneka, Sekisui Chemical, and Toshiba, have benefited from the policy support for R&D. Sekisui Chemical, in particular, is responsible for carrying out innovations in the perovskite manufacturing processes by creating roll-to-roll processes (Renewable Energy Institute 2024).

Existing domestic lab-scale initiatives also face challenges in accessing the finance necessary to set up pilot scale lines, necessary for commercialisation and industrial-scale R&D. Stakeholders have mentioned that getting access to funds for scaling up has been a challenge for even initiatives based in academia, due to the complex process involved in getting approval for financing for research grants.

> Weak industry participation and limited public funding for solar R&D hinders commercialisation and scale-up of new technologies.

Image: iStock

4. Identifying hurdles and barriers

Domestic solar cell manufacturing faces the following challenges, based on the analysis carried out in this report.

1. **Domestic solar cell manufacturers are unable to compete with Chinese solar cells, due to their lower price and higher technology levels.** Overcapacity in China has led to lower prices of solar cells and modules. While wafers are largely imported, cost of manufacturing both cells and modules is higher in India compared to China, leading to extreme competition in both domestic and export markets.

2. **Domestic manufacturers are at risk of IP issues arising from recent patent litigations between global manufacturers for TOPCon solar cell technology.** This introduces risk for export competitiveness for TOPCon, which is otherwise the low-hanging fruit for scaling up and advancing domestic solar cell technology, as most of the patent litigations have occurred in the USA and Europe.

3. **Domestic manufacturers face higher production** costs due to the following reasons.

    - **High capital expenditure to set up manufacturing facilities:** Domestic manufacturers face nearly twice the capital expenditure compared to Chinese manufacturers. This is a result of Chinese manufacturers benefiting from capex subsidies for land, building and equipment, support for ancillary infrastructure, and subsidised energy cost.

    - **Expected increase in price of silver paste:** Silver paste contributes to around 20 per cent of the manufacturing cost, and due to supply-demand imbalance, the prices are expected to increase. Further, domestic manufacturers pay import duties on silver paste, while Chinese manufacturers can access subsidised silver pastes. Hence, domestic manufacturers face a higher cost for sourcing silver paste.

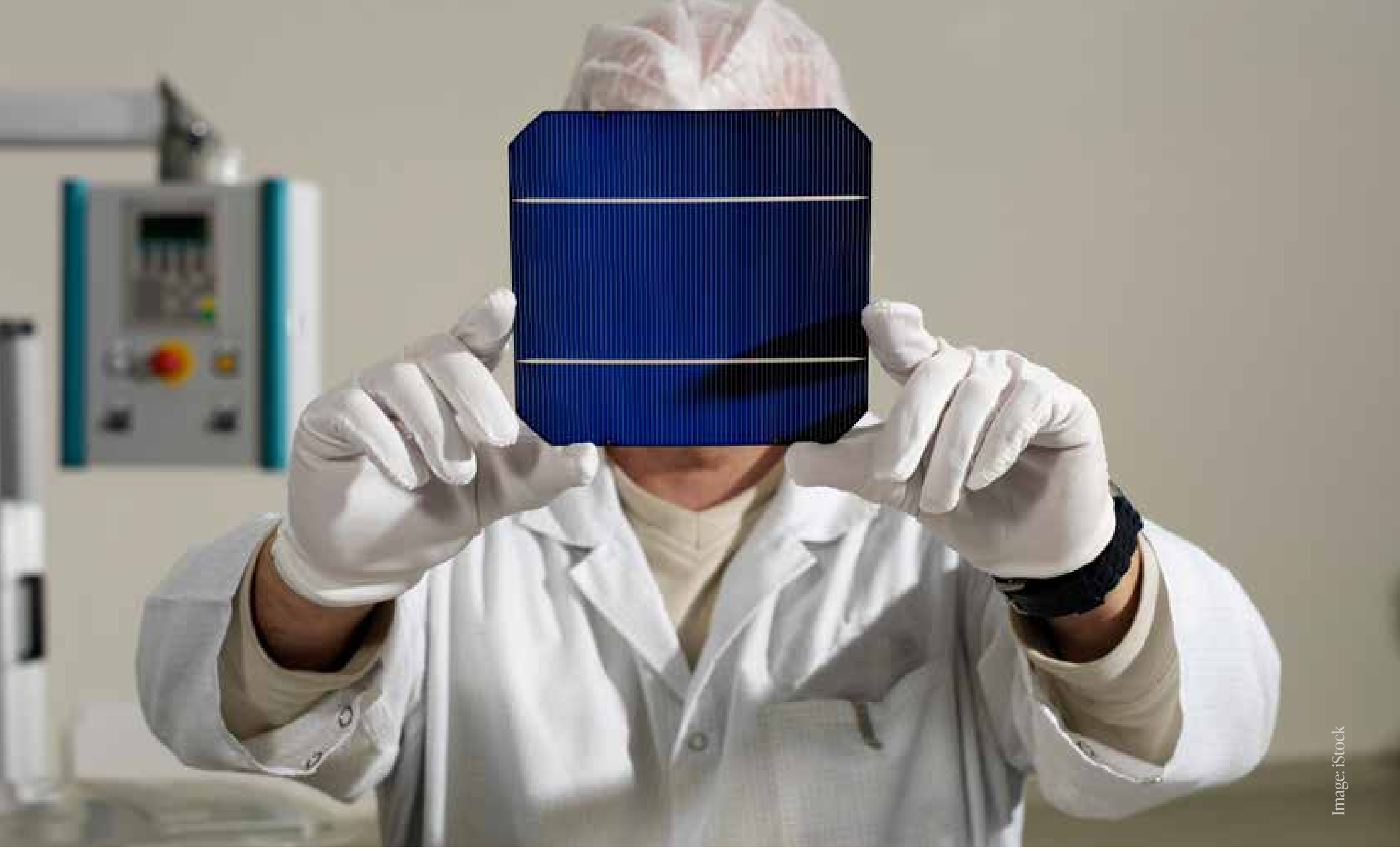
4. **High import dependence on China for silver paste and wafer:** While wafer costs have remained low, they are the highest contributor to solar cell manufacturing cost. The import dependence on a single country makes the supply chain vulnerable to price shocks through disruptions. Similarly, silver paste forms a major share of the cost of manufacturing. Although there are import duties levied on silver paste, it is not classified under a unique HS code. Without this, levying and collection of duties becomes difficult, as does the calculation of actual import dependence.

5. **Domestic manufacturers struggle to adapt to the technological know-how of the Chinese solar cell manufacturers.** This is due to the following reasons:

    - **Domestic cell manufacturers are dependent on foreign equipment suppliers** (predominantly Chinese) for importing, installation, and the technical knowhow of the cell manufacturing process. This lack of technological knowhow prevents manufacturers from indigenous innovation and contributes to the technology lag in comparison with global and Chinese solar cell manufacturing. The dependence on imported machinery also leads to vulnerabilities arising from delay in shipping of machinery, rise in freight charges, and delays due to port congestion and non-availability of containers (Vikram Solar 2024).

    - **The lack of technical knowhow leads to difficulty in training and upskilling workers such as process engineers.** In the current scenario, only the equipment providers have the technical knowhow required to optimise and operate equipment and processes specific to cell manufacturing, and then impart this to the solar cell manufacturer. Only a few domestic manufacturers have dedicated facilities for training, and the rest depend on training arranged by equipment providers. This leads to delays in manufacturing solar cells with targeted efficiencies. Along with this, domestic manufacturers depend on Chinese technicians, who face visa approval issues, to provide technical supervision on the shop floor. Further, solar manufacturers face higher attrition rates of around 20 per cent compared to 10.6 per cent in the rest of the manufacturing sector.

    - **Overall lack of targeted R&D for solar cell technologies.** MNRE's total investment in R&D through the *RE-RTD* has been USD 13 million since 2014, much lower than investments by other technology-forward nations like the USA and Japan, which have allocated USD 72 million and USD 420 million for solar PV, respectively. Lack of more public funding prevents academic institutions from availing grants necessary for setting up larger pilot-scale manufacturing facilities required for the commercialisation of laboratory-scale advances. Further, domestic solar cell manufacturers spend at most 0.1 per cent of their total revenue on R&D, much less than Chinese solar cell manufacturers, who can spend anywhere between two to six per cent of their total revenue on R&D, showcasing a lack of industry participation in R&D.



5. Recommendations and conclusion

The challenges portrayed in the previous chapter elucidate how domestic solar cell manufacturing is at risk of technological lag and non-competitiveness in terms of price. To address these challenges, we put forward four recommendations. These are drawn up for a period of 10 years, from 2026 to 2035, as estimated changes in market share are available till 2035 from literature (VDMA 2025).

5.1 MNRE could develop shared infrastructure for machinery localisation, cell technology development, and upfront capital cost reduction

Developing shared infrastructure for solar cell technology development would help in supporting indigenisation of solar cell manufacturing equipment, accelerating lab-scale innovations for solar cells and metallic pastes to commercial-scale manufacturing, and reducing capital expenditure associated with commercial-scale cell production.

Shared infrastructure can consist of expensive equipment such as advanced deposition tools, metrology equipment, reliability test facilities, and utility infrastructure, that individual firms or universities may not be able to easily afford. Firms would leverage processes, machinery, and technology developed through shared infrastructure, scaling them from pilot to commercial production. Such a framework will allow industries to participate in R&D without each firm spending on R&D individually, provide timely feedback on manufacturability, yield, and cost, and ultimately shorten the time period between proof-of-concept and commercial production.

The framework would enable the following four recommendations, that feed into the overall targeted roadmap that has been sketched out.

- Indigenisation of machinery and capital goods, with hubs being constituted by the centres of excellence approved by the Ministry of Heavy Industries (MHI), such as Central Manufacturing Technology Institute, IIT Madras, and Scientific and Industrial Testing and Research Centre (Si'Tarc). These hubs would be complemented by European equipment suppliers, who would localise their production in India to access the domestic solar cell market, and spokes would be made up of firms entering into partnerships with these equipment manufacturers, thus gaining access to the R&D carried out at the centre of excellence and knowledge-transfer from the equipment manufacturers.

- Establishing pilot-scale lines for cell technology development, with institutions that have a track record of solar cell R&D, such as IIT Bombay, IIT Roorkee and IIT BHU, serving as academic partners in the hubs for lab-scale to pilot-scale R&D. Hub creation would require the creation of pilot-scale lines dedicated to each cell technology, while spokes would consist of solar cell manufacturers.

- Establishing lab and pilot-scale initiatives for potential silver paste and metal paste production in India, with hubs being utilised to set up lab-scale development, with targeted pilot-scale development in the future.

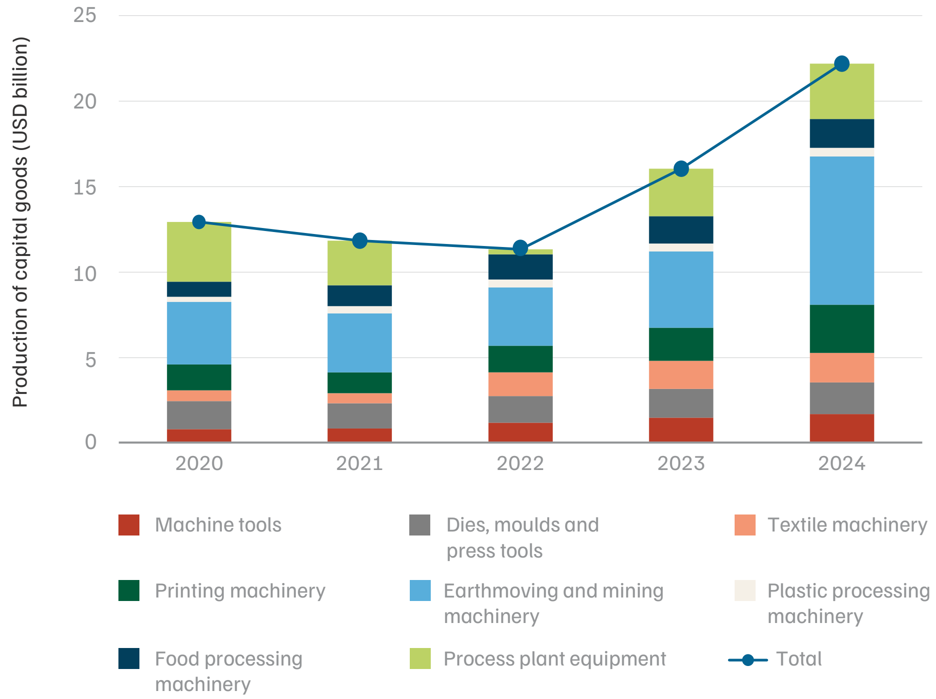
- Establishing shared utility infrastructure for scaling up solar cell manufacturing, with hubs housing such shared facilities, and spokes being made up of manufacturers who would share such facilities.

Further analysis of the investment needed, the targets, and additional policy support for these have been explained in the next sub-sections.

Indigenise machinery and capital goods for domestic solar cell production

Along with creation of shared infrastructure, the MNRE, in collaboration with the MHI, can establish a dedicated 'capital goods for solar cell manufacturing' programme under the *National Capital Goods Policy*. The *National Capital Goods Policy* was established to boost the production of essential capital goods, such as machinery and equipment, across industries. In the fiscal year 2024–25, INR 184 crore or USD 21 million was allocated for the schemes being supported by the *National Capital Goods Policy*. Out of this, INR 134.55 crore or USD 15.8 million were released for utilisation in sub-schemes (Press Information Bureau 2025), which consisted of setting up centres of excellence and common engineering facilities, augmenting existing testing and certification centres, etc.

Figure 18. Due to favourable policy support, capital goods production across all subsectors has increased, with total production increasing by 72%



Source: Press Information Bureau 2025

Due to such policy support, the production across all the eight different sectors has increased between the fiscal years 2019–20 and 2023–24 from USD 12.71 billion to USD 21.87 billion, as shown in Figure 18. Similar to these sectors, key equipment required in solar cell manufacturing, such as wet chemical tools, diffusion furnaces such as PECVD, LPCVD, ALD and PVD, and screen printers, can be included in the scheme by creating a separate sub-section under capital goods.

Stakeholders stated that one entire equipment line can produce 1.2 GW of solar cells annually. Given 30 GW of solar cell manufacturing is currently present, this would require production capacity of at least 25 equipment lines. Estimates suggest that an additional 86 GW of solar cell manufacturing capacity maybe commissioned by 2030 (PV Tech 2025), which would require nearly 70 equipment lines. Hence, a total of 95 equipment lines of production capability may be required. Domestic solar cell manufacturers spend an average of USD 41.5 million for sourcing one equipment line (Premier Energies 2024; Vikram Solar 2024), ensuring a market opportunity for local equipment producers from USD 1 billion to USD 4 billion.

A comprehensive EU-India free-trade agreement was concluded on 27 January 2026 (European Commission 2026). The agreement creates a platform to speed up supply-chain diversification, bilateral clean-tech manufacturing, and bankable European investments into India's fast-growing solar market, supporting both equipment trade and joint technology development. The growth of Indian solar cell manufacturing presents a USD 1 billion to USD 4 billion market opportunity for solar cell equipment, incentivising foreign technology leaders in equipment manufacturing to set up production in India, and thus facilitating technology transfer. For the EU, accessing India's rapidly expanding module capacity offers a non-Chinese supply source for certain components. For India, easier access to European high-quality balance-of-system (BOS) equipment and specialised components (high-efficiency cells, industrial PV glass, smart inverters) will support larger, higher-value projects.

India should strategically leverage the Memorandum of Understanding signed by National Solar Energy Federation of India (NSEFI) and SolarPower Europe (NSEFI 2025) to accelerate solar cell manufacturing equipment localisation and technology transfer. The platform can be used to attract European equipment manufacturers to establish production facilities in India, supported by structured knowledge-exchange and regulatory facilitation. To ensure market uptake, the government should introduce a preferential sourcing mechanism for domestically manufactured solar cell equipment, aligned with the PLI framework, enabling PLI-supported manufacturers to procure localised machinery. This would simultaneously increase domestic value addition, reduce import dependence, and create a viable market for local equipment manufacturers.

Establish pilot manufacturing centres through industry-academia collaboration

To compete in international markets, it is important for Indian solar cell manufacturing to become a technology leader from 2030 onwards. Given the predicted rise in market shares of high-efficiency technologies such as XBC and HJT, and the potential commercialisation of perovskites post-2030, policy support for research and development for these technologies would be crucial. The policy support should consist of the creation of at least one pilot-scale (100 MW) cell manufacturing centre for each cell technology, led by premier academic institutions and solar cell manufacturers, to accelerate the commercialisation of advanced technologies. Localising foreign equipment will support the initiative by providing equipment for pilot lines, and aiding the development of new machinery for next-generation technologies.

Indian academia and manufacturers have shown interest in development and eventual commercialisation of tandem-perovskites. In December 2024, Waaree announced a strategic CSR relationship with IIT Bombay for R&D on perovskite solar cell technology (Waaree Energies 2024b), while in September 2022, Reliance acquired a 20 per cent stake in Caelux, a US-based enterprise that works on R&D and the commercialisation of solar perovskite technologies (MERCOM India 2023a). Further, in 2023, a perovskite start-up from IIT BHU called P3C acquired fund-raising of USD 250,000, with a further commitment of USD 3 million on a successful trial. The start-up seeks to demonstrate and develop flexible perovskite solar cells (Perovskite-info 2023). Despite the presence of R&D interest across academia and industry, no pilot mass production lines have been commissioned. In the absence of swift action, the Indian solar industry may fall behind other countries and China. Hence, prudent policy action that leads to establishing the first pilot perovskite facilities is essential.

Box 1. Tongwei Solar's research and development approach

Tongwei Solar led the list of top-five solar cell suppliers in 2024, based on the volume of solar cells shipped as external cells (InfoLink Consulting 2025a). To drive continuous innovation, Tongwei Solar has set up a global R&D centre in Chengdu, China, covering 270,000 m^2, with over a third dedicated to R&D workshops. The facility, costing around USD 568.9 million (2.86 per cent of 2023 revenue), includes multiple pilot lines for testing and scaling new cell technologies—an approach common among Chinese manufacturers. In this facility, Tongwei houses pilot lines dedicated to its patented TOPCon technology 'TNC', its patented back contact technology 'TBC', an R&D centre for modules, and an HJT and perovskite GW scale lab (Taiyang News 2025). Thus, the company focuses on R&D across different cell technologies: TOPCon, HJT, BC and perovskite/tandem cell technologies.

Tongwei Solar's R&D efforts have driven innovative combinations of the present cell technologies, achieving cell efficiencies as high as 26.6 per cent and 27 per cent for cell technologies like Back Contact and HJT. Even in the dominant TOPCon segment, Tongwei continue to push boundaries, setting a record of 25.28 per cent module-level efficiency. Tongwei has achieved this through manufacturing innovations such as tubular PECVD passivation layer deposition, screen printing, and EPT passivation layer techniques (Taiyang News 2025c).

According to stakeholder consultations, establishing one pilot scale facility of a 100 MW can require USD 100 million. Hence, the establishment of three pilot-scale cell manufacturing facilities may require around USD 300 million, and this would have to be funded by the domestic industry. In return for funding the establishment of pilot-scale facilities, successful technologies can be picked up for commercial production by industry players through patent-sharing or IP-sharing agreements. MNRE could act as a nodal agency, bringing industry players and the academia under the same umbrella. MNRE can further select the manufacturers who would contribute to financing pilot schemes and patent-sharing agreements, on the basis of those who have experienced revenue growth and showcase interest in adapting new solar technologies. Lab-scale activities related to tandem-perovskite solar cell development are taking place in India, and such a platform may help in eventual commercial production of these solar cell technologies. For example, a lab-scale tandem perovskite solar cell with 30 per cent efficiency was developed by ART-PV (Advanced Renewable Tandem Photovoltaics), a start-up incubated at IIT Bombay under the National Centre for Photovoltaic Research and Education (NCPRE) (Taiyang News 2025b). The relevant ministries should also leverage the EU-India agreement to co-fund pilot lines for advanced cell architectures, joint certification labs to mutually-recognise performance and reliability testing.

Policy action taken in this regard should support the development of solar cell technologies in the following phases:

1. 2026-2030: Development and scaling up of advanced high-efficiency solar cell technologies such as HJT and/or XBC should be prioritised. XBC can be given a higher preference as it can be produced using the TOPCon solar cell architecture. The ideal technology share for additional domestic solar cell manufacturing can be 80 per cent TOPCon and 20 per cent XBC, since most predictions put the market share of XBC or HJT reaching 20 per cent globally (Taiyang News 2025) by 2030.

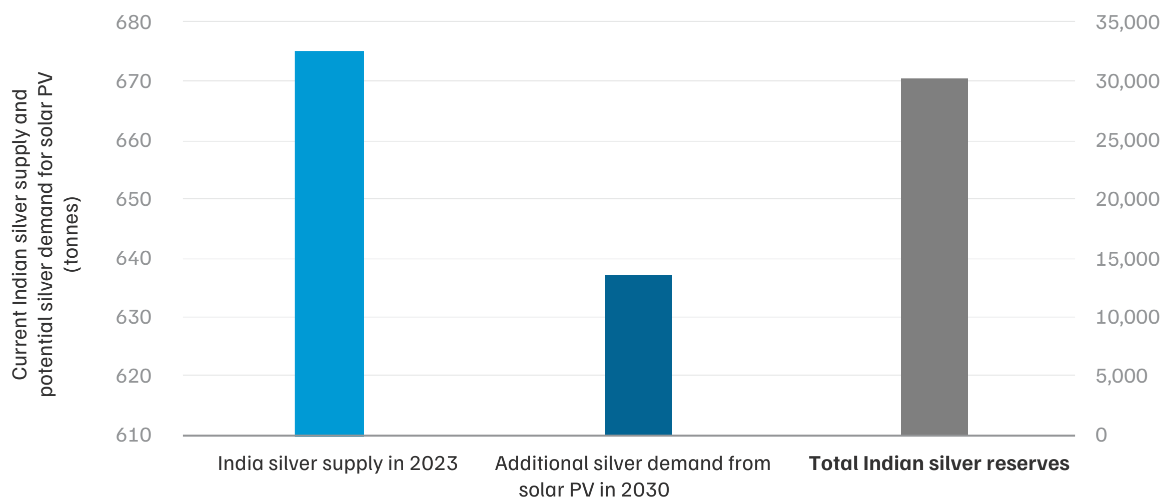
2. 2026-2035: Commercialisation of alternate solar cell technology, such as tandem-perovskite.

    - By 2030: Establishment of at least 1 pilot facility of 100 MW scale, which may require an investment of around USD 100 million. 2030-2035: Establishing more pilot-scale lines and commercialising pilot-scale advancements. Targeted tandem-perovskite solar cells should have efficiencies more than 30 per cent.

Establish lab- and pilot-scale initiatives for potential silver paste production in India

India's total silver supply and reserves are sufficient to meet additional silver demand from solar PV in 2030, as showcased in Figure 19, if silver paste production is localised and commercialised. Therefore, strong policy support for pilot-scale activity can set the stage for the commercialisation of domestic silver paste production. Additionally, reducing silver paste usage through developing either copper-silver paste hybrids or innovative metallisation methods such as smart busbar and zero busbar metallisation, can be a way forward for reducing cost-of-manufacturing. These technologies can be developed only after building domestic silver paste manufacturing capability.

Figure 19. Indian silver supply and reserves can meet demand from solar cell manufacturing



Source: The Silver Institute 2025, Ministry of Mines 2022

A pilot-scale facility capable of developing and testing silver pastes with 99 per cent accuracy, 95 per cent confidence interval, and a population ratio of 50 per cent, would require a testing sample size of around 2,256.25 solar cells[4] per day, which is equivalent to 18,050 W of solar cells per day (as one solar cell has wattage of 8 Wp). Thus, a pilot-scale facility of the scale of 6.6 MW per year[5] and production capability of 89 kg[6] silver paste per year (as the average silver paste consumption for TOPCon solar cells is 13.5 mg per Wp) would be required for research and development of indigenous silver paste. Such pilot-scale facilities would allow for testing of the final product over multiple production cycles, enabling industrial process validation.

Lab-scale activity is currently present for development of silver paste, as evidenced by the presence of 'AnyD', a lab-scale start-up that develops conductive silver paste for PV applications, among other things. This start-up was established at IIT Bombay in 2023 (AnyD Materials 2023). Upon determining the technology and financial requirements, pilot-scale centres co-led by industry and academia should be established to scale up and commercialisation. MNRE, along with industry players, can create a financing mechanism for indigenous silver paste production. In the long term, support should be extended to R&D on silver-copper paste hybrids to reduce manufacturing costs.

Action taken by industry, academia, and policymakers for indigenous silver paste development should thus contribute to the following achievements.

1. **2026–2028**: Establishment of pilot-scale activity related to silver-paste development of the scale of 89 kg silver paste production per year.

2. **2028–2035**: Utilisation of pilot-scale activity for the development of silver and copper paste hybrids.

    - **2028–2030**: Targeted achievement of silver-copper paste hybrids with ratios ranging from 50:50, 40:60, 30:70, and 20:80, with a maximum efficiency loss of 0.1 per cent.

    - **2030–2035**: Adoption and scaling up of indigenous silver paste production.

Alongside the development of indigenous silver paste, a distinct HS code should be established for imported silver paste used in solar cell manufacturing, and import duties should be eliminated in the short term to help reduce manufacturing costs. From 2026 to 2028, the HS code classification should be clarified, and import duty on silver paste should be removed entirely. By 2030, duties can be gradually reintroduced, starting with a 5 per cent rate in 2028, increasing to 10 per cent by 2030. From 2030 to 2035, the 10 per cent import duty should be maintained to provide continued support and protection for domestic silver paste production, encouraging long-term self-reliance.

Create industrial parks co-located with hubs for equipment localisation and shared utility facilities for scaling up solar cell manufacturing

Shared infrastructure for capital machinery localisation can be further mobilised to create an industrial ecosystem. Industrial parks, where equipment would be localised by European equipment manufacturers and domestic solar cell manufacturers, can provide equipment at lower costs to domestic manufacturers. This would be balanced on the equipment manufacturer's side by a long-term partnership agreement that ensures providing products at a lower cost does not affect their market opportunity.

4. Sample size is calculated as such: $n=t^2 \times p(1-p)/m^2$, where n is the minimum sample size required, t is the confidence level at a certain percentage, p is the estimate of proportion of solar cells testing positive for the desired characteristic and m is the margin of error.
5. 6.6 MW per year = 18,050 W of cells per day x 365 days in a year
6. 89 kg of silver paste production per year = 6.6 MW per year x 13.5 mg per Wp

The industrial parks can be located in already existing clusters of solar manufacturing, in states like Gujarat or Tamil Nadu. They should also house shared utility facilities accessible to solar cell manufacturers. Such utilities would include chillers, compressors, diesel generators, gas cabinets, chemical delivery systems, a centralised ultra-pure water plant, compressed dry air systems, effluent treatment plants capable of handling aggregate chemical loads, a high-capacity substation to provide electricity to multiple facilities, and process cooling water systems. Utilities can contribute 30 to 40 per cent of the total capital expenditure of setting up solar cell manufacturing facilities (Vikram Solar 2024; Premier Energies 2024). Shifting to an operational model where manufacturers pay only connection charges and usage fees, rather than capital expenditure, would help them scale-up faster, access economies of scale, and produce solar cells competitively.

Similar support for shared facilities for other industrial sectors already exists in India, including for electronic component manufacturing (MeitY 2020), textiles (Ministry of Textiles 2025), MSMEs (Ministry of Micro Small and Medium Enterprises 2022), and food processing parks (Ministry of Food Processing Industries 2020). State industrial development corporations under state governments can co-finance and build shared utilities and provide regulatory fast-tracks for establishing industrial parks, while MNRE can act as a central nodal body to oversee the strategic framing of the scheme. Special Purpose Vehicles and private developers would execute and operate such facilities, and recover the shared utility costs via connection fees and usage tariffs under PPP models.

5.2 MNRE could offer one-time capital subsidy to PLI winners to bridge capital expenditure gaps

A total of 48.30 GW of solar cell manufacturing has been enlisted under PLI tranches I and II, out of which 17.62 GW of solar cell manufacturing has already been established (Biswas and Kale 2025). While the production-linked incentive (PLI) scheme does give financial support for domestic solar manufacturing (MNRE 2022), it is a post-production and post-sales incentive based on the performance of solar modules, and hence does not help manufacturers bridge the upfront capital expenditure gap. To ensure the establishment of the remaining 30.68 GW of solar cell manufacturing capacity, one-time capital subsidy should be provided to PLI-enlisted manufacturers. This would add on to the nearly ~ 30 GW of present solar cell manufacturing capacity — hence execution of PLI-supported projects can double the solar cell manufacturing capacity to nearly 60 GW.

There has been a precedent set for capital subsidies in other domestic industries. The *Modified Special Incentive Package Scheme* (M-SIPS) offered capital subsidies of up to 25 per cent to promote domestic electronics manufacturing, including solar PV components (MeitY 2019). This significantly reduced the upfront capital investment and encouraged manufacturers to expand their value chain. Further, the *Electronic Component Manufacturing Scheme* (ECMS), introduced by the Ministry of Electronics and Information Technology (MeitY 2026), combined production incentives and capex subsidies.

The PLI-supported manufacturers should be given a capital goods subsidy of 15 per cent. The disbursement of the PLI is dependent on the number of sales, local value addition, and the technology of the modules sold (on grounds of efficiency and temperature coefficient), by a particular manufacturer. For an average manufacturing facility of 2 GW, assuming a utilisation rate[7] of 30 per cent, the total amount disbursed through PLI (for the sale of modules of efficiencies more than

> A 15% capex subsidy to PLI-enlisted projects would fast track cost-competitiveness and ensure execution.

7. The utilisation rate of capacity for a given technology is typically derived by dividing actual production by the maximum rate capacity over a full year.

21.5 per cent) is at nearly USD 51.1 million, calculated in Annexure 7. This is with the assumption that all the modules that are produced at the assumed utilisation rate are sold. The capex for the same manufacturing facility will be USD 140 million, as the capex per GW is USD 70 million, as shown in Table 1. Hence, out of the 140 million, a PLI support manufacturer has to spend only USD 88.9 million in setting up a 2 GW project, entailing a capital expenditure of USD 44.45 million per GW. This is still not enough to lower capital expenditure to Chinese levels, which is around USD 33.5 million per GW, with a differential of nearly USD 11 million per GW. This differential is nearly 15 per cent of the per GW capex, hence such a subsidy would assist in bridging the gap. The subsidy can be provided to the manufacturer over five years, as that is the depreciation time for the production equipment for solar cell manufacturing (APVI 2024).

Targeted support towards only PLI-enlisted manufacturers is recommended as they have already committed towards establishment of manufacturing capacity. For non-PLI enlisted manufacturers, the previous recommendation of capex reduction through shared utility and equipment infrastructure is applicable.

5.3 MoCI should push for strategic asset acquisition and technology transfer in trade policy

Several manufacturers of equipment and machinery across the world are in financial distress, with largely negative EBITDA (Earnings Before Interest, Taxes, Depreciation, and Amortisation) and reduced cash balances. Indian firms such as Waaree and Reliance have taken advantage of such situations to acquire manufacturers like Meyer Burger (MERCOM India 2025b) and REC silicon (Ornate Solar 2021), respectively, which has enabled technology transfer.

These firms, despite financial instability, possess advanced cell and module technology knowhow, state-of-the-art manufacturing machinery, and well-established production facilities that can be acquired at a fraction of their original cost during insolvency or restructuring proceedings. By acquiring such assets, Indian companies can rapidly upgrade their technological capabilities without the heavy capital expenditure normally required for new R&D or high-cost equipment leasing. Such actions can help support the creation of pilot-scale lines, similar to how Reliance is operating the sole HJT solar cell manufacturing facility, after its acquisition (MERCOM India 2025c). MoCI can negotiate easing of regulations for the acquisition of distressed foreign manufacturing assets and intellectual property through trade and investment negotiations. This will push private players to acquire distressed companies. Such acquisitions can accelerate technology upgrading, reduce capital costs, and enable faster entry into advanced cell technologies without duplicating global R&D investments.

This approach not only reduces the per-unit cost of solar cell manufacturing but also accelerates domestic production of high-efficiency modules under initiatives like Make in India and the PLI scheme. Moreover, leveraging the existing R&D knowledge and patents of these distressed firms can help Indian manufacturers achieve global quality benchmarks while driving cost competitiveness across the value chain. In the long run, such strategic acquisitions could position India as a hub for integrated, low-cost, high-efficiency solar manufacturing, reducing dependence on imports and strengthening its role in the global renewable energy market.

Trade and investment negotiations can include provisions to facilitate technology transfer, investment cooperation and investor protections that make cross-border acquisitions (including of distressed firms) easier. Most countries regulate mergers and acquisitions through insolvency and bankruptcy laws, foreign investment or merger control regulations, and competition laws. In most cases, there should be no restriction in acquiring foreign assets through court-supervised sale process subject to disclosure and approval by insolvency administrators. While such is the case, incorporating clauses in trade and investment agreements can simplify the process.

5.4 MNRE could develop skilling programmes and training centres to upskill process engineers and build domestic technological capacity

National curriculum and courses targeting skill development across the various levels of expertise should be developed in coordination with industry stakeholders, educational institutions, and the government. Such skill development training centres can be located in states which are already solar manufacturing hubs, such as Gujarat and Tamil Nadu. Industry stakeholders such as foreign equipment manufacturers can be specifically targeted to impart training and contribute to course developments related to tooling, process optimisation and process engineering.

Programmes with varying durations should be developed, targeting different participant profiles. These can include short-term certificate courses for upskilling existing employees and Bachelor's or Master's programmes for imparting advanced knowledge of process optimisation and process engineering, thus training future process engineers. The MNRE, in collaboration with the All-India Council for Technical Education (AICTE), can take charge of the development of the curriculum and courses. The Ministry of Education (MoE) and the Ministry of Skill Development and Entrepreneurship (MSDE) can then serve as the stakeholders responsible for implementing the courses in selected academic institutions across the country.

Further upskilling can be implemented by cross-border, systemic skill training. Similar activities have been carried out in the automobile manufacturing industry through a memorandum of cooperation (MoC) on *Manufacturing Skill Transfer Promotion Programme*, signed in 2016 between the MSDE and Japan's Ministry of Economy, Trade and Industry (METI), carried out by Maruti Suzuki (Maruti Suzuki 2021). MNRE can similarly leverage existing bilateral agreements with countries such as Germany, which have expertise in solar manufacturing due to the presence of R&D organisations such as Fraunhofer ISE and ISC Konstanz, and equipment suppliers like Rena.

MNRE could develop skilling programs and training centres...

Conclusion

In conclusion, India's solar cell manufacturing sector faces a global landscape shaped by falling prices, rapid technological shifts, and evolving trade dynamics. Our analysis underscores that while India has made significant progress through policy instruments such as the PLI, ALMM mandates, and tariff protections, structural challenges persist in technology indigenisation, cost-competitiveness, and ecosystem readiness. Addressing these gaps requires a coordinated, multi-dimensional strategy that integrates industrial policy, trade diplomacy, research and development, and skill creation.

Our proposed recommendations align with this strategy and interlink with each other. Together, these recommendations form an integrated industrial strategy anchored in a national framework that links research, manufacturing, capital goods, skills, and trade policy into a single execution framework. Shared national hubs create the backbone for machinery localisation, pilot manufacturing of advanced cell technologies, and metallisation R&D, while firm-led spokes translate these innovations into gigawatt-scale production. Building shared utility facilities at such hubs would also enable reduction of capital expenditure incurred by domestic manufacturers, helping them become cost-competitive. A targeted capital subsidy would ensure that PLI-enlisted manufacturers can complete planned capacity additions. Parallel investments in specialised skill development ensure that process capability keeps pace with technological ambition. In combination, these measures transform the domestic solar cell manufacturing ecosystem from purely capacity expansion into a coordinated, technology-led industrial system capable of sustained global competitiveness.

Acronyms

0BB	zero busbar
ADD	anti-dumping duty
ADE	atmospheric dry etching
AICTE	All India Council for Technical Education
AIDC	*Agriculture Infrastructure Development Cess*
ALD	atomic layer deposition
ALMM	Approved List of Models and Manufacturers
APVI	Australian Photovoltaic Institute
ART-PV	Advanced Renewable Tandem-Photovoltaics
BC	back contact
BCD	basic customs duty
BOM	bill of materials
BOS	balance of system
B_2H_6	diborane
CEA	Central Electricity Authority
CoE	centre of excellence
CSR	corporate social responsibility
CVD	chemical vapour deposition
DCAM	detailed cost analysis model
DCR	domestic content requirement
DGTR	Directorate General of Trade Remedies
DI	deionised
DRHP	draft red-herring prospectus
DST	Department of Science and Technology
EBITDA	earnings before interest, taxes, depreciation, and amortisation
ECMS	*Electronic Component Manufacturing Scheme*
EPD	edge passivation deposition
EVA	ethylene vinyl acetate
FY	financial year
GW	gigawatt
HCl	hydrochloric acid
HF	Hydrogen fluoride
HJT	heterojunction
HNO_3	nitric acid
HS	harmonised system
IEA	International Energy Agency
IIT	Indian Institute of Technology
IP	intellectual property
ITRPV	International Technology Roadmap for Photovoltaics
KOH	potassium hydroxide
LCOE	levelised cost of electricity
LECO	laser enhanced contact optimisation
LPCVD	low-pressure chemical vapour deposition
MBB	multi busbar
MeitY	Ministry of Electronics and Information Technology
METI	Ministry of Economy, Trade and Industry (Japan)
MHI	Ministry of Heavy Industries
MNRE	Ministry of New and Renewable Energy
MoE	Ministry of Education
MoCI	Ministry of Commerce and Industry
M-SIPS	*Modified Special Incentive Package Scheme*
MSDE	Ministry of Skill Development and Entrepreneurship
MST	Ministry of Science and Technology
MWh	megawatt-hour

NCPRE	National Centre for Photovoltaic Research and Education
NDC	Nationally Determined Contribution
NREL	National Renewable Energy Laboratory
NSEFI	National Solar Energy Federation of India
PECVD	plasma-enhanced chemical vapour deposition
PERC	passivated emitter rear contact
PLI	production-linked incentive
PM-KUSUM	*Pradhan Mantri Kisan Urja Surakasha evam Utthaan Mahabhiyaan*
POE	polyolefin elastomer
PV	photovoltaic
PVD	physical vapour deposition
RE-RTD	*Renewable Energy – Research and Technology Development*
R&D	Research and development
SIDCs	State Industrial Development Corporations
SiH_4	silane
SMBB	smart multi busbar
TOPCon	tunnel oxide passivated contact
USITC	United States International Trade Commission
VAT	Value Added Tax
VDMA	Verband Deutscher Maschinen und Anlagenbau (German Engineering Federation)
Wp	Watt-peak
XBC	Back contact solar cell technology variant

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Aarathi Srinivasan works as a Programme Associate with the Technology Futures team at The Council. Her work focuses on trade negotiations, tracking global policies, and analysing trends related to international trade of clean energy technology and critical minerals. She has prior experience working across thematic areas including ESG, air pollution, and macro-level taxation policy analysis.

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