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Making India a Leader in Solar Manufacturing

Ways to Achieve Technology Leadership and Global Competitiveness

Shreyas Garg and Rishabh Jain

Report | May 2022

With only 2.5 GW cell and 11 GW module manufacturing capacity, India lacks sufficient domestic solar manufacturing capabilities.

Image: Waaree Energies Ltd.

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CEEW-CEF acts as a non-partisan market observer and driver that monitors, develops, tests, and deploys financial solutions to advance the energy transition. It aims to help deepen markets, increase transparency, and attract capital in clean energy sectors in emerging economies. It achieves this by comprehensively tracking, interpreting, and responding to developments in the energy markets while also bridging gaps between governments, industry, and financiers.

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The clean energy transition is gaining momentum across the world with cumulative renewable energy installation crossing 1000 GW in 2018. Several emerging markets see renewable energy markets of significant scale. However, these markets are young and prone to challenges that could inhibit or reverse recent advances. Emerging economies lack well-functioning markets. That makes investment in clean technologies risky and prevents capital from flowing from where it is in surplus to regions where it is most needed. CEEW-CEF addresses the urgent need for increasing the flow and affordability of private capital into clean energy markets in emerging economies.

CEEW-CEF's focus: analysis and solutions

CEEW-CEF has a twin focus on markets and solutions. CEEW-CEF's market analysis covers energy transition–related sectors on both the supply side (solar, wind, energy storage) and demand-side (electric vehicles, distributed renewable energy applications). It creates open-source data sets, salient and timely analysis, and market trend studies.

CEEW-CEF's solution-focused work will enable the flow of new and more affordable capital into clean energy sectors. These solutions will be designed to address specific market risks that block capital flows. These will include designing, implementation support, and evaluation of policy instruments, insurance products, and incubation funds. CEEW-CEF was launched in July 2019 in the presence of HE Mr Dharmendra Pradhan and H.E. Dr. Fatih Birol at Energy Horizons.

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"With the policy movements in 2021, Indian industry now has a strong footing to scale up solar manufacturing. However, incentives and duties can only provide short-term support. To build a sustainable manufacturing sector that can compete in the global market, India must also focus on technology and demand expansion. This report takes learnings from the global solar landscape and identifies measures to make Indian manufacturers technology-led global players."

"Better late than never. Solar manufacturing has not been India's strength. Despite the huge market, we continue to rely on imported products for manufacturing and deployment. However, proactive measures by the industry and the government can reduce our reliance on imported products. This report highlights the key strategic steps that need to be undertaken in the short and medium term to ensure the global competitiveness of the solar manufacturers."

Policy interventions, such as incentives, duties, and certification requirements, have created a favourable near-term landscape for domestic solar manufacturing.

Image: Goldi Solar

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Acronyms

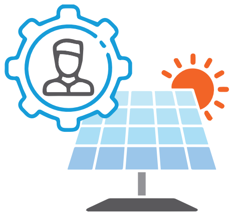
ALMM	Approved List of Models and Manufacturers
ARC	anti-reflective coating
ARPA-E	Advanced Research Projects Agency-Energy
BCD	basic customs duty
BOM	bill of materials
CVD	chemical vapour deposition
DCR	domestic content requirement
DST	Department of Science and Technology
EUR	euro
EVA	ethylene-vinyl acetate
GST	goods and services tax
GW	gigawatt
HJT	heterojunction
INR	Indian Rupee
IREDA	Indian Renewable Energy Development Agency
ISA	International Solar Alliance
MEA	Ministry of External Affairs
MG	metallurgical grade
MNRE	Ministry of New and Renewable Energy
MW	megawatt
PECVD	plasma-enhanced chemical vapour deposition
PERC	passivated emitter and rear contact
PLI	production-linked incentive
PV	photovoltaic
RE	renewable energy
TMA	trimethyl aluminium
TOPCon	tunnel oxide passivated contact
UK	United Kingdom
UNSW	University of New South Wales
US	United States of America
USD	United States Dollar

India's plans to set up new solar manufacturing factories can lead to investments of USD 7.2 billion in capital expenditure and create over 41,000 jobs.

Image: Goldi Solar

Executive summary

The process of manufacturing crystalline silicon solar modules involves four stages – (i) making polysilicon, a highly pure form of elemental silicon, (ii) converting polysilicon into silicon wafers, (iii) processing wafers into solar cells, and (iv) assembling solar cells into modules. Currently, India has no manufacturing capacity for the first two stages, an estimated 2.5 GW of cell manufacturing capacity, and an 11 GW of module manufacturing capacity (MNRE 2021a; Joshi 2021). India is, therefore, heavily reliant on solar imports – domestic modules made up only 35 per cent of utility-scale solar installations in India in financial year 2019-20 (Garg et al. 2021). While new policy measures will increase this share, the volume of imports are also expected to rise further up the supply chain.



10 GW of fully integrated solar manufacturing capacity can create over 10,000 jobs

The current situation of manufacturing presents multiple challenges. First, due to significant import reliance, India is highly exposed to supply chain shocks. These can become a bottleneck for India's solar deployment targets as the global demand for solar products scales up. For instance, the years 2020 and 2021 saw significant disruption across the solar supply chain, delaying deliveries and raising prices. Second, without a robust technology ecosystem, manufacturers must rely on technology developed in other nations. Indian solar manufacturing typically lags global technology shifts by 3–5 years, making Indian products outdated and unable to compete in the global market. Third, India is missing out on significant opportunities for job creation. It is estimated that 10 GW of fully integrated solar manufacturing capacity (polysilicon to modules) can create 10,500 jobs in plant operations alone[1]. Further jobs will be created in ancillary requirements and bill of materials manufacturing.

A. Solar manufacturing received strong policy support in 2021

In 2021, the government announced import duties, constituted a pre-approved list of modules for usage in projects, and announced a manufacturing-linked subsidy scheme. In March 2021, the Ministry of New and Renewable Energy (MNRE) announced a basic customs duty (BCD) of 25 per cent on imported solar cells and 40 per cent on imported solar modules from April 2022 (MNRE 2021b). MNRE released the first Approved List of Models and Manufacturers (ALMM) for solar modules in 2021. As per government orders, nearly all projects to be set up in India must use only the modules included in the ALMM list.[2] The December 2021 version of the list only includes domestic manufacturers, essentially restricting foreign manufacturers from selling in India (MNRE 2021a).

1. Based on data from industry experts and Woodhouse et al. (2019).
2. Only models and manufacturers included in the ALMM list are eligible for use in government projects, government-assisted projects, projects under government schemes and programmes, open access, net-metering projects installed in the country, including projects set up for sale of electricity to the government (MNRE 2022).

The government also announced USD 600 million (INR 4,500 crore) support through the *Production Linked Incentive* (PLI) scheme to scale integrated solar manufacturing.[3] The scheme received bids totalling 16 GW of polysilicon, 29 GW wafer, 52 GW cell, 52 GW module, and 3 GW integrated thin film manufacturing capacity. Three manufacturers planning to set up a total of 12 GW of fully integrated solar manufacturing capacity were shortlisted (IREDA 2021a). The government has allocated an additional USD 2.6 billion (INR 19,500 crore) to expand the list of PLI awardees (Ministry of Finance 2022a).

B. Focusing on technology and ecosystem-building is now essential

Submissions to the PLI scheme and other announcements by solar manufacturers suggest that India will rapidly scale up manufacturing capacity across the four solar manufacturing stages by 2025. While the BCD, ALMM, and PLI provide strong near-term protections in the domestic market, manufacturers must gradually become competitive in the global market to create a self-sustaining sector that can thrive in the absence of policy support. This will require:

- **A holistic approach to research and development (R&D)** – The solar technology landscape is dynamic and major shifts in production processes are typically seen in every five years. To stay competitive, India must both develop new manufacturing technologies and successfully take them to market. This will require a drastic increase in industry involvement in R&D programs.
- **Localising production of bill of materials (BOM) and manufacturing machinery** – Localising production of BOM is critical to ensure supply chain security and reducing import dependence. Further, making manufacturing equipment in India can help cut capital expenditure and improve manufacturers' access to servicing. Industry-led R&D is critical for both BOM and machinery, as Indian players must first develop high-quality, cost-competitive options before scaling up.
- **Unlocking new sources of demand** – Establishing multi-gigawatt scale manufacturing facilities and running them at high utilisation rates is essential to drive down production costs. As multiple players have announced plans to set up manufacturing facilities, they may face high competition in the domestic market. Therefore, manufacturers should simultaneously try to unlock demand from export markets.

Further, in the near term, India's push to indigenise solar manufacturing will require USD 7.2 billion (INR 53,773 crore) in capital expenditure and can create over 41,000 jobs.[4] These investments can unlock significant revenues for manufacturers. For example, suppose India achieves a 70 per cent share of domestic modules in Indian solar installations from 2022–2030 and meets its 2030 target of 280 GW installed solar capacity. In this scenario, manufacturers would clock revenues of USD 32 billion (INR 2.4 lakh crore) during 2022–2030, while the government would be able to earn USD 3.9 billion (INR 29,000 crore) in GST revenue in this period.[5]

3. USD-INR conversion at USD 1 = INR 75, based on average USD-INR exchange rate in 2021 (data from Financial Benchmarks India Limited).
4. Detailed in Section 4.1.
5. Considering a fixed module price of INR 15/W_{DC} and GST rate of 12 per cent. 24 GW of annual solar installations are required from 2022 to 2030 to meet the 2030 target (Ranjan 2022a).

C. Policy measures taken internationally can guide India's strategy

Table ES 1 summarises the various kinds of support provided to the solar manufacturing industry in China, India, South Korea, Southeast Asia (Malaysia, Thailand, and Vietnam), Taiwan, and the United States. China stands out for supporting its manufacturers by leveraging all the means listed; its comprehensive strategy is the key reason for its global solar supply chain dominance today. Our analysis of measures taken by various nations highlights the importance of providing access to capital and focusing not just on research and development but also on deploying new technologies.

Table ES 1 China stands out by providing the highest number of benefits and support measures to domestic solar manufacturers

S.No.	Support provided	China	India	South Korea	Southeast Asia	Taiwan	United States
1	Manufacturing subsidies and incentives	✓	✓		✓		
2	Dedicated access to debt capital	✓					
3	Other financial support from the government (equity, grants, loan guarantees)	✓				✓	✓
4	Manufacturing hubs and regional government support	✓			✓		
5	Technology transfer and R&D thrust	✓		✓			✓
6	Targeted demand creation and incentive structure for high-efficiency products	✓	✓	✓		✓	
7	Tariffs and other import barriers to support domestic products	✓	✓	✓		✓	✓

Source: CEEW-CEF analysis

D. Recommendations

India must implement a multi-year solar manufacturing technology roadmap, initiate measures to unlock export markets, and provide measures to support manufacturers set up and scale up upcoming factories

The MNRE has introduced critical near-term support measures such as the basic customs duty (BCD) and PLI scheme. A long-term strategic approach is now essential to bring sustainability to the sector and establish Indian manufacturers as technology leaders. India needs to establish a framework to ensure that new technologies are deployed in the market. To do so, it needs to bring together academia, industry, and international experts. Critically, industry must play a more significant role if laboratory concepts are to be successfully commercialised. India must also open up new sources of demand through innovative routes to help manufacturers compete globally.

Our recommendations, listed in Table ES 2 and detailed in Chapter 6, focus on three strategies to support solar manufacturing:

i. setting up a long-term solar manufacturing technology roadmap, backed by five elements (detailed below),

ii. strategically opening up avenues for export demand, and

iii. providing measures to help manufacturers set up and scale up upcoming manufacturing facilities.

India's solar targets and climate ambitions promise a deep, long-term market for Indian manufacturers. The PLI, BCD, and ALMM have set the stage for rapid manufacturing capacity expansion over the next three years. Policymakers must now take strategic measures to position the Indian solar manufacturing industry as a domestic force and a global leader in terms of technology and market presence.

Image: Goldi Solar

Table ES 2 A focus on technology, demand, and scale is essential to support the domestic solar manufacturing industry

S.No.	Recommendation	Timeline	Implementing authority	Nature of expense
	Set up a long-term solar manufacturing technology roadmap with enhanced funding, a dedicated R&D division in MNRE, and an advisory board.			
1	Identify thrust areas and timelines based on key research requirements and establish solar research funding grants.	2022–2028	MNRE	Grants
2	Incentivise industry-led R&D by (i) setting up a central R&D centre, (ii) providing capex subsidy for manufacturers setting up R&D facilities, and (iii) mandating a minimum spend of 3 per cent of revenue on R&D from 2025.			Capex outflow, subsidy
3	Target partnerships with reputed international solar research institutes and leverage these connections to apply for international research funding programmes.			Nil
4	Set up an independently managed investment fund with anchor investment from the Government of India.			Equity
5	Mandate that solar projects awarded under government tenders use products developed under the solar technology roadmap for a minimum of 5 per cent of their capacity.			Nil
	Strategically create export demand for Indian modules			
6	Create markets for low-carbon manufacturing by (i) providing approval and support for open-access renewable power consumption, (ii) trade deals with nations that have stated a preference for low-carbon products.	2022–2023	MNRE, Ministry of External Affairs (MEA), state regulators	Nil
7	Enhance financing for solar projects in developing countries that are members of the International Solar Alliance (ISA) through India Exim Bank, securing export demand for Indian modules.	Rolling	MNRE, MEA, India Exim Bank	Loan
8	Consider expanding the ALMM list and bilateral duty exemptions based on trade deal negotiation requirements.	Rolling	MNRE	Nil
	Support scale for upcoming manufacturing capacity			
9	Raise the share of loans to the RE manufacturing sector to 20% of Indian Renewable Energy Development Agency's (IREDA) loan book by 2026.	2022–2026	IREDA	Loan
10	Set up manufacturing hubs with attractive land rates, labour availability, deemed open-access approval, and thrust sector status for solar manufacturing.	2022–2023	State industrial development corporations	Revenue outflow
11	Apply BCD on polysilicon or wafer imports from 2027, start tapering BCD on cells and modules from 2025.	2025 onwards	MNRE	Nil

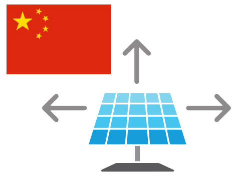
Source: CEEW-CEF analysis

With manufacturers around the world announcing large capacity expansions, Indian companies face a competitive global market.

Image: Goldi Solar

1. Introduction

The process of manufacturing solar modules consists of four stages – (i) making polysilicon, a highly pure form of elemental silicon, (ii) converting polysilicon into silicon wafers, (iii) processing wafers into solar cells, and (iv) assembling solar cells into modules. Chinese solar manufacturers dominate each of these steps, holding a 67 per cent market share in polysilicon, 97 per cent in wafers, 79 per cent in cells, and 71 per cent in modules, as of 2019 (Garg et al. 2021). They were able to achieve this market concentration due to the strategic importance given to solar manufacturing by the Chinese central and provincial governments since the 2000s. State support enabled solar manufacturers to stay afloat during crises and construct large-scale, integrated gigafactories over 2015 to 2020. Chinese companies now dominate the solar manufacturing value chain, research and development, and equipment and ancillary materials manufacturing. Localising the supply chain has helped Chinese solar manufacturers cut costs and achieve scale. Leading Chinese players are doubling down on their market dominance and have announced large-scale manufacturing capacity expansions across the supply chain. Estimates suggest that Chinese manufacturers announced capacity expansion plans totalling 340 GW of wafer, 170 GW of cell, and 160 GW of module manufacturing in 2021 (Ranjan 2022b).



Leading Chinese manufacturers are doubling down on their dominance and have announced large-scale capacity expansions across the solar value chain

India's cell, wafer, and polysilicon manufacturing lags not just China's but also that of other Asian countries such as Malaysia and South Korea (PVPS 2021). Currently, India has 11 GW of module, a 2.5 GW of cell, and no polysilicon or wafer manufacturing capacity (MNRE 2021a; Joshi 2021). Further, India is heavily dependent on imports for bill of material (BOM) components in solar manufacturing. In contrast, by the end of 2021, the global manufacturing capacity of polysilicon is expected to reach 230–250 GW, wafer 310 GW, cell 325 GW, and module 400 GW (Duggal 2021a; Clean Energy Associates 2021; PV Magazine 2021).

While India's solar manufacturing sector has failed to significantly grow so far, domestic manufacturers have an opportunity to aggressively expand their presence and benefit from a favourable policy landscape. The years, 2020 and 2021, saw large-scale supply chain disruptions and global shortages in polysilicon and other raw materials, which have led to a 40 per cent increase in the price of imported solar modules.[6] These disruptions highlight the criticality of a robust and fully integrated domestic manufacturing industry. Simultaneously, global overcapacities of wafer, cell, and module production promise a competitive global market. This report outlines a broad set of recommendations for Indian policymakers to establish a robust and technology-led solar manufacturing sector.

6. Between October 2020 and October 2021, as per CEEW-CEF analysis of Cybex import data for HS Code 854140.

Methodology and objectives

Today, photovoltaic (PV) solar is predominantly based on two technologies – crystalline silicon and thin film. Crystalline silicon accounts for 95 per cent of global production (Fraunhofer ISE 2021). Therefore, this report only discusses crystalline silicon solar cell manufacturing, given its market dominance. Our recommendations focus on long-term strategic measures in addition to short-term actions. To build our recommendations, we collected inputs from Indian solar experts (list of experts provided in Acknowledgments) and analysed the literature on global solar technology and market trends.

We provide a brief overview of recent policy measures to support the industry and detail the key technologies currently operational in solar manufacturing. We also expand on projections regarding the global solar technology landscape and identify key considerations for Indian solar manufacturers as they set up new facilities and scale up. Acknowledging the benefits of learning from other nations, we discuss how China, South Korea, Taiwan, Malaysia, Thailand, Vietnam, and the United States have supported their solar sectors.

2. Will manufacturing policies finally deliver?

Image: iStock

India's first policy attempts to support domestic solar manufacturing included a 2012 scheme to provide capital expenditure subsidies and a 2011 policy establishing domestic content requirement (DCR) for projects set up in India. However, these measures failed to significantly develop solar manufacturing. Manufacturers faced delays in subsidy distribution, while the DCR policy allowed exemptions for thin film modules and was ultimately discontinued as it was not compliant with World Trade Organisation rules. Further, India's solar capacity development occurred through the reverse auction route, which encouraged aggressive tariff decline, instead of the feed-in tariff route. Developers preferred low-cost imports over relatively expensive domestic products (Jain, Dutt, and Chawla 2020). MNRE imposed a safeguard duty on imported products in 2018, however, the duty was applicable for only two years and did little to support domestic manufacturers.

Since March 2021, MNRE has taken steps to resolve uncertainties in the solar manufacturing sector regarding and bring in fiscal support and strong protections for domestic manufacturers. Three initiatives are discussed briefly below:

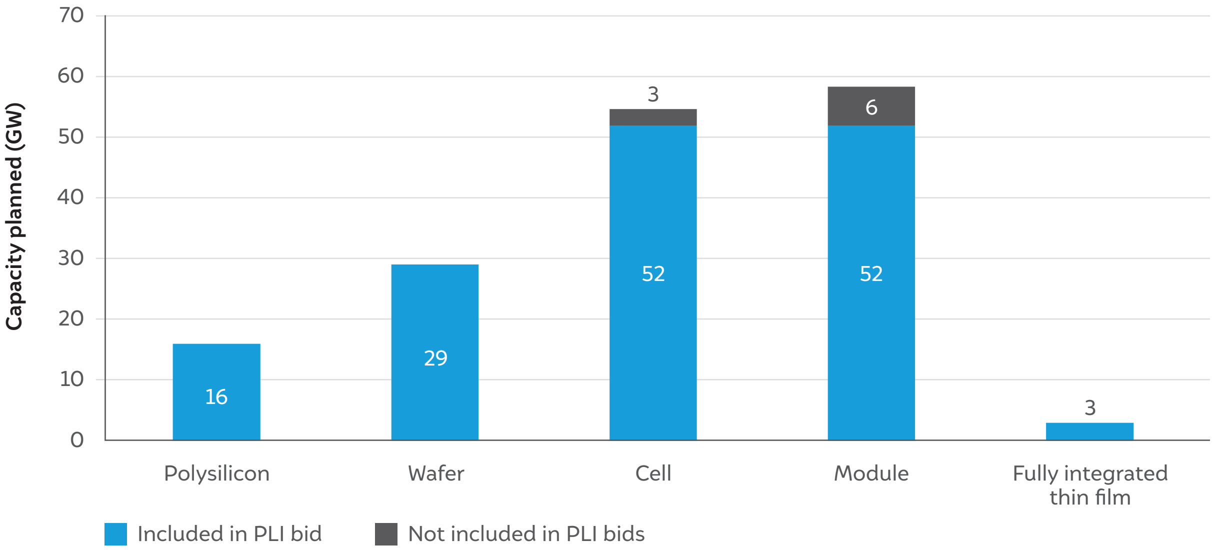
- **Basic customs duty**: In March 2021, the MNRE introduced a BCD of 40 per cent on solar module imports and 25 per cent on solar cell imports, effective from 1 April 2022 (MNRE 2021b). While the BCD will make domestic manufacturing cost-competitive, it is likely to lead to a 20–25 per cent increase in solar tariffs (CEEW-CEF 2021).
- **Production-linked incentives**: In June 2021, the MNRE initiated the auction process for the *Production-linked Incentive* (PLI) scheme with a layout of USD 600 million (INR 4,500 crore) over five years.[7] The PLI scheme provides revenue incentives of INR 2.25–3.75 per Wp for solar modules up to 50 per cent of the capacity set up under the scheme (MNRE 2021c). The incentive rate depends on the module's efficiency and degradation. The scheme saw an overwhelming response with 55 GW worth of bids, of which 16 GW was for polysilicon to module manufacturing, 13 GW for wafer to module manufacturing, 23 GW for cell to module manufacturing, and 3 GW for thin film manufacturing (Koundal 2021). In November 2021, the government awarded incentives to three manufacturers, totalling 12 GW of fully integrated solar manufacturing, from polysilicon to modules, under the PLI scheme (IREDA 2021a). In 2022, the government sanctioned an additional USD 2.6 billion (INR 19,500 crore) to expand the list of PLI awardees (Ministry of Finance 2022a). The existing award and additional sanction will ensure the rapid scaling-up of Indian solar manufacturing across all process stages.
- **Approved List of Models and Manufacturers (ALMM)**: In March 2021, the MNRE released List-I under the ALMM. Only solar modules included in List-I are eligible for use in government projects, government-assisted projects, projects under government schemes and programmes, open-access, and net-metering projects installed in the country. This includes projects that supply electricity to government bodies. The MNRE plans to follow this up with List-II, which will consist of approved solar cell manufacturers. List-I manufacturers will then have to mandatorily source cells from List-II to be included in the ALMM. Currently, List-I only includes domestic manufacturers, effectively acting as a non-tariff barrier against imported modules. The latest version (December 2021) of this list includes 41 players with a total capacity of 10.9 GW, of which factories over 500 MW in size make up 64 per cent (MNRE 2021a).

Indian solar manufacturers have announced a spate of capacity expansions in response to these policy measures. While most manufacturers announced expansion plans under the PLI scheme, others have announced new capacity plans outside the scheme as well. Figure 1 represents the sum of these announcements and submissions to the PLI scheme.

Bids for the PLI scheme totalled to 55 GW, marking a significant shift in India's solar manufacturing plans

7. USD-INR conversion at USD 1 = INR 75, based on average USD-INR exchange rate in 2021 (data from Financial Benchmarks India Limited).

Figure 1 **Recent announcements and PLI submissions total 161 GW of new manufacturing capacity split across different stages**



Source: CEEW-CEF compilation

Image: Om Shanti Retreat, Gurgaon

While passivated emitter and rear contact (PERC) dominates global solar manufacturing today, a transition to n-type technologies is underway.

Image: iStock

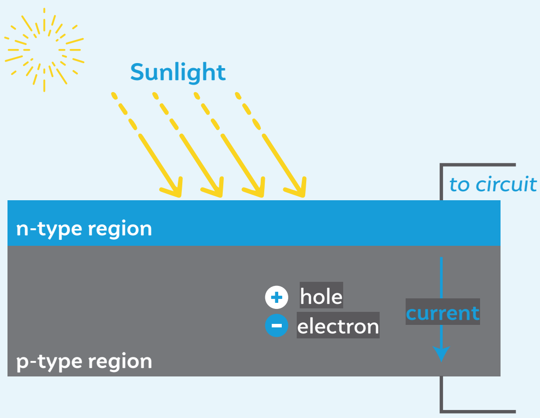
3. The solar technology landscape

With the Indian solar industry and policy pillars finally seeing some much-needed alignment, it is important to go a step further and assess the solar technology landscape. Over time, solar manufacturers have introduced drastic changes in manufacturing processes. These improvements have led to a rapid increase in solar efficiency, bringing down the levelised cost of electricity. In this section, we discuss the basics of solar power generation (Box 1) and how manufacturers have optimised cell manufacturing to improve the efficiency of their products. We also detail the current and future technology landscapes.

BOX 1 How do solar cells generate power?

A solar cell is essentially made of silicon, a semiconductor. It generates electricity from sunlight through the photovoltaic (PV) effect. When sunlight falls on silicon, the photons present in sunlight energise the silicon atoms. When an atom is energised, a valence electron is knocked out of its bond with the silicon atom, creating a free electron and a hole. Electrons from adjacent covalent bonds move into the hole, in turn creating a new hole, effectively resulting in the movement of holes. The movement of these electrons and holes facilitates the flow of electricity, generating power. The PV effect may be intensified by adding small impurities that greatly increase concentration of electrons or holes. These impurities are called dopants. If the dopant contains fewer valence electrons than silicon (less than four), it is called a p-type dopant (e.g., boron and gallium, which contain three valence electrons). If it contains more valence electrons than silicon, it is called an n-type dopant (e.g., phosphorous, which contains five valence electrons). P-type (positive) dopants increase hole concentration, while n-type (negative) dopants increase electron concentration. In the p-type region of the cell shown in Figure 2, holes will be the majority carriers of current, while electrons will be the minority carriers. The opposite will occur in the n-type region.

Figure 2 A solar cell generates power through the photovoltaic effect



Source: CEEW-CEF compilation

Additionally, electrical systems require current to flow in a single direction in a circuit. As shown in Figure 2, This is facilitated by creating a p-n junction in solar cells. The bulk body of the solar cell is doped with one of the two dopant types, while a small layer at the front is doped with the opposite charge. This ensures that electrons flow in a single direction through the solar cell. A single solar cell typically consists of a single p-n junction that generates a very low voltage (typically 600–700 mV). Typically, 60–72 solar cells are connected in series to generate enough voltage for practical applications. A solar cell's performance is typically measured by its efficiency, which is defined as the share of incident solar power that can be converted to usable power. It is an important measure of performance as a more efficient module can provide higher power output than a less efficient module of the same size. Efficiency improvements are a major driver in reducing solar costs.

When solar cells are assembled into modules, additional efficiency losses are incurred due to optical and electrical losses resulting from the addition of encapsulating layers and other parts of the solar module. Mismatches in cell alignment can increase losses. Solar cells based on the dominant solar technology in the market are up to 23.6 per cent efficient, while modules with these cells are typically up to 21.5 per cent efficient.

3.1 Understanding solar manufacturing

Before discussing the key differentiators across solar technologies, it is important to understand the efficiency losses that these differentiators solve. Figure 3 details the major losses that impact solar cell efficiency.

Figure 3 Power generation from solar cells is subject to three high-level losses – optical, electrical, and degradation

Solar cell losses

Optical

Losses due to incomplete absorption of incident light by the cell

- **Reflection** instead of absorption
- Light does not reach the surface due to **shading** by metal contacts that cover a part of the surface
- Each material absorbs only specific light wavelengths; therefore a part of incident solar **radiation is not absorbed**

Electrical

Losses due to hindrances in the flow of current through the cell

- **Resistive** losses due to the inherent electrical resistance of all materials
- Loss of energy as heat or light due to **recombination** of electron-hole pairs; recombination is higher at cell surfaces as surface atoms do not possess sufficient neighbours to bond with, creating vacant bonds that are highly active sites for electron-hole recombination

Degradation

Losses experienced when the cell is exposed to field conditions

- **Light induced** degradation of the cell within the first few hours of exposure to sunlight; significant for p-type silicon wafers doped with boron compounds
- Degradation due to other external factors such as **high temperature, and high humidity**

Source: CEEW-CEF adaptation from UNSW (2017) and Axelevitch and Golan (2010)

Over time, the solar manufacturing process has evolved to improve performance by reducing these losses. Figure 4 depicts the solar manufacturing process for the dominant solar technology (cells with monocrystalline p-type wafers and a passivated emitter and rear contact). The processes shown in Figure 4 are for the technology that dominates the market today. Technological alternatives do exist; e.g., aluminium oxide can be deposited by atomic layer deposition instead of by plasma-enhanced chemical vapour deposition; polysilicon can be made by the fluidised bed reactor method instead of the Siemens chemical vapour deposition process. Further, the process and inputs will differ for different cell and module technologies. For example, glass–glass modules use solar glass on the rear instead of a backsheet.

Figure 4 The solar manufacturing process

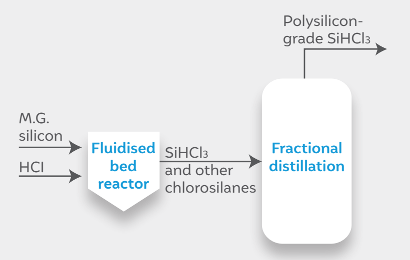
Raw materials for the process step | Raw material cost | Machinery cost | Utilities cost | Labour and maintenance cost

Harvey ball cost brackets (INR / Wp): 0.0–0.15 | 0.15–0.5 | 0.5–1.0 | 1.0–1.5 | 1.5–2.5

STAGE 1

Metallurgical grade silicon → Polysilicon

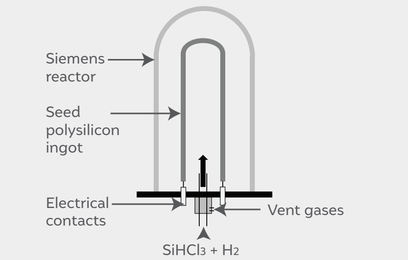
1 Trichlorosilane production from metallurgical grade silicon (MG silicon)



MG silicon, hydrochloric acid (HCl), catalyst

The process uses MG silicon, a 98 per cent pure form of elemental silicon which is refined from quartzite (silicon oxide). MG silicon is ground into powder and injected into a fluidized bed reactor with HCl, forming trichlorosilane ($SiHCl_3$) and other gases. $SiHCl_3$ is separated by fractional distillation.

2 Siemens chemical vapour deposition (CVD)



Seed polysilicon ingot, hydrogen gas

$SiHCl_3$ and hydrogen gas are fed into a Siemens reactor where graphite electrodes pass current through a U-shaped seed polysilicon ingot. $SiHCl_3$ is reduced, and solid polysilicon gets deposited onto the seed ingot, which grows in size.

3 Harvesting and packaging

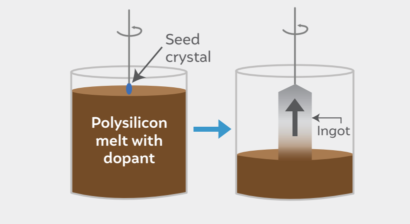
-

The resultant ingot contains 99.9999999 per cent or 9N (9 nines) pure polysilicon, called 'solar grade' silicon. 11N pure silicon is called 'electronic grade', and both can be used in PV manufacturing. The ingot is broken into chunks for wafer production.

STAGE 2

Polysilicon → Ingot → Wafer

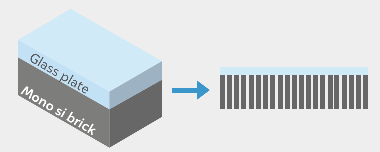
1 Ingot formation through the Czochralski process



Polysilicon, dopant (boron / gallium for p-type wafer)

Polysilicon chunks are melted and mixed with the dopant. A single seed crystal is placed on the melt surface, rotated, and slowly drawn upward in a furnace. Polysilicon solidifies around the seed crystal into a long, continuous single-crystal ingot. This forms a 150–200 kg cylindrical ingot of monocrystalline silicon (mono-Si). mono-Si has largely replaced a previous technology that produced multi-crystalline silicon (multi-Si) by directionally solidifying the polysilicon melt. Multi-Si wafers contain multiple silicon crystals in different orientations are less efficient that mono-Si wafers.

2 Diamond wire wafer slicing



Polysilicon (as waste during wire slicing)

The cylindrical ingot's head and tail are cropped off, following which it is ground and cut into a square brick with rounded edges. One side of the brick is glued to a glass plate, and it is then sliced into individual wafers using diamond wires. The glue is then dissolved using a chemical bath, and the wafers are removed from the glass plate.

3 Cleaning and metrology

Industrial cleaning agents

The wafers are cleaned and inspected for defects. The pseudo-square shape is preferred to circular wafers as they can be more efficiently packed in the module.

STAGE 3

Wafer → Cell

1 Wafer unloading, inspection

-

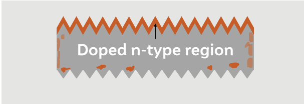
Wafers are inspected for defects before processing.

2 Saw damage removal and surface texturisation

Industrial cleaning agents, etchants

Saw damage and contaminants left over from wafer cutting are cleaned. The wafer surfaces are textured with etchants to form pyramidal edges that reduce surface reflection and consequently cut optical losses.

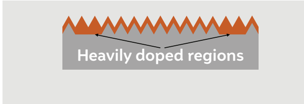
3 Dopant diffusion in tube furnace



Phosphorous oxychloride ($POCl_3$)

The front side of the wafer (called the emitter) is doped with an n-type dopant. A tray loaded with wafers is moved laterally through a diffusion tube that also contains the dopant gas. Phosphorous diffuses into the wafer's front side and small quantities of phosphorous are also deposited on other edges.

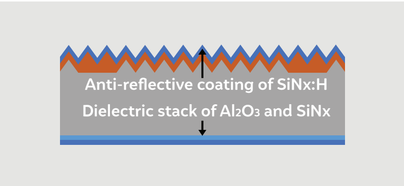
4 Selective doping, edge isolation, and cleaning



Industrial cleaning agents

A laser tool melts through the regions where metal contacts will be placed on the emitter to create heavily doped regions. This improves electron flow and reduces recombination and resistive losses. Dopant contaminants on the sides and rear are cleaned with cleaning agents, and the rear edge is planarised.

5 Plasma-enhanced chemical vapour deposition (PECVD) of anti-reflective coating (ARC) on the front side, and a dielectric stack on the rear side

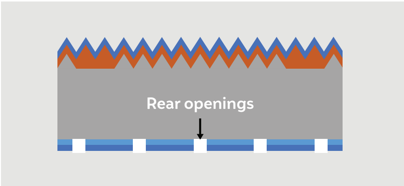


Trimethyl aluminium (TMA - $Al(CH_3)_3$), silane (SiH_4), ammonia (NH_3), and inert gases

An anti-reflective coating is deposited on the front side to reduce surface reflection and optical losses. This is done through PECVD, wherein a feed gas (SiH_4 and NH_3) is converted to plasma via a plasma generator. The feed gases ionise and deposit a solid film of silicon nitride (SiNx) and hydrogen on the emitter surface. PECVD is carried out at the rear side to deposit a stack of aluminium oxide (Al_2O_3) using TMA as a feed gas, SiNx, and hydrogen.

The front ARC and rear dielectric stack reduce surface recombination through two methods – (i) both films contain hydrogen, which bonds with surface silicon atoms during the co-firing step to close vacant bonds and reduce recombination sites, and (ii) reducing the concentration of minority carriers at the surfaces by introducing a layer with the same charge as the minority carrier. This is called surface passivation, and cells with this feature are called passivated emitter and rear contact (PERC) cells.

6 Laser contact opening of a dielectric layer on the rear side



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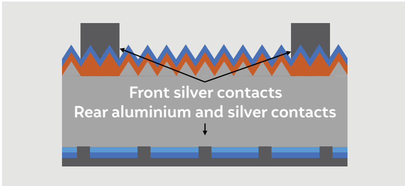
A laser tool is used to open spaces in the dielectric stack on the rear side to allow contact between the silicon wafer and metal contacts on the rear side.

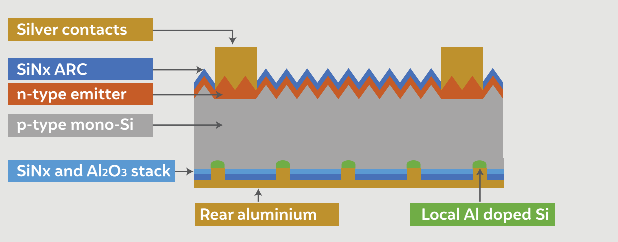
7 Screen printing silver and aluminium pastes



Silver paste, aluminium paste

Metal contacts are required on both surfaces to carry current. On the front side, silver paste is printed through a screen to create a grid of busbars and contacts. On the rear side, the aluminium paste is printed on the entire surface, while silver tabs are added for interconnection to other cells.

8 Co-firing



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The cell is fired in a furnace, reaching a peak temperature of 750–870°C. This does three things: (i) allows the metal contacts to melt through the passivation layers and establish contact with the silicon wafer, (ii) activates passivation by closing the dangling silicon bonds with hydrogen released from the films deposited during PECVD, and (iii) creates locally doped regions of aluminium in the rear silicon side, which reduces recombination and aids in electron flow.

9 Inspection, I-V testing, sorting, and packaging

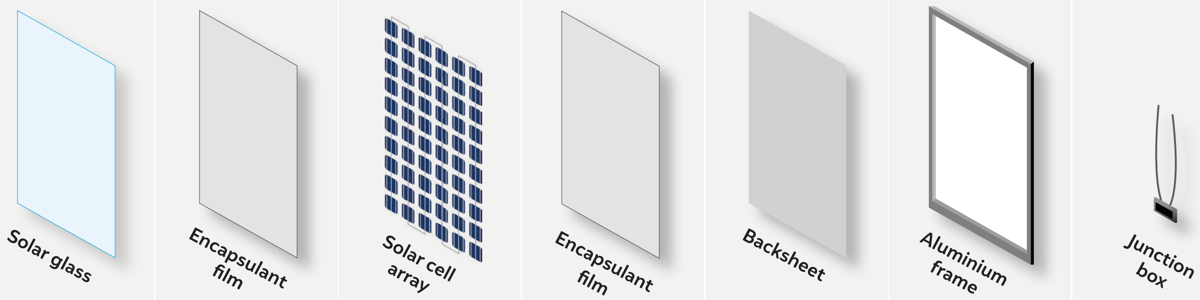
-

Cells are inspected, tested for output, and packaged for module assembly.

STAGE 4

Cell → Module

1	2	3	4	5	6	7
Glass loading and laydown of the first EVA sheet	Cell loading, tabbing, stringing, and soldering to front and back silver contacts	Placement of cell strings, soldering connector ribbons, laydown of the second EVA and backsheet	Visual inspection and electro-luminescence testing, lamination	Edge trimming, aluminium frame, and silicone sealant	Solder string connector leads in junction box and final assembly	I-V test, inspection, packaging



1	2	3	4	5	6	7
Glass, encapsulant (typically EVA – ethylene vinyl acetate)	Tabbing and stringing ribbons	Backsheet, encapsulant, ribbons	-	Aluminium frame, seal	Junction box, potting agent	-

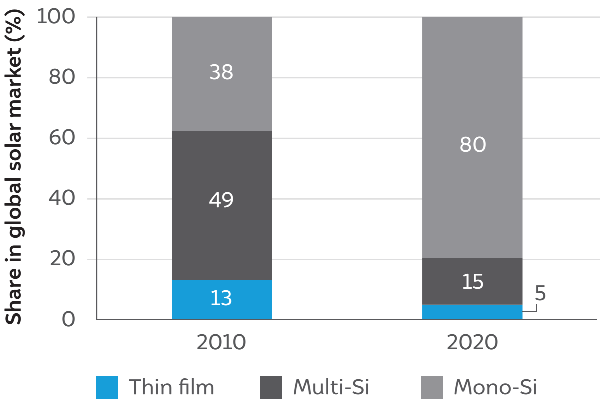
The module creation stage is an assembly process. The encapsulant layer is first laid over the glass sheet. Cells are connected into strings with metallic ribbons and mounted on the encapsulant. The second encapsulant sheet is then laid on top of the cell array. The backsheet is laid over the encapsulant film. The assembly is first put through tests and then fit into an aluminium frame with a silicone sealant. Finally, the junction box is added with connector leads and filled with a potting agent. The ready solar module is inspected and put through current-voltage tests. Modules are then packed and readied for shipping.

Source: CEEW-CEF adaptation from UNSW (2017); Woodhouse et al. (2019); Kafle et al. (2021); Louwen et al. (2016); Bernreuter Research (2020a).

3.2 The current market for solar technologies

Figure 5 shows that solar cells with mono-Si wafers dominate the global solar market, with an 80 per cent market share in 2020. The technology has more than doubled its market share since 2010, rapidly surpassing the previously dominant technology, multi-Si. Manufacturers drove this change by reducing the cost of mono-Si wafers by adopting new techniques such as multiple ingot pulls in a single run and diamond wire slicing.

Figure 5 **Mono-Si dominates global solar production with an 80 per cent market share**



Source: CEEW-CEF adaptation from the National Renewable Energy Laboratory (2011) and Fraunhofer ISE (2021).

Passivated emitter and rear contact (PERC) cells with p-type mono-Si wafers make up 65–70 per cent of the global production capacity (ITRPV 2021). Older technologies (such as multi-Si and mono-Si without rear-side passivation) and advanced technologies based on n-type wafers make up the balance.

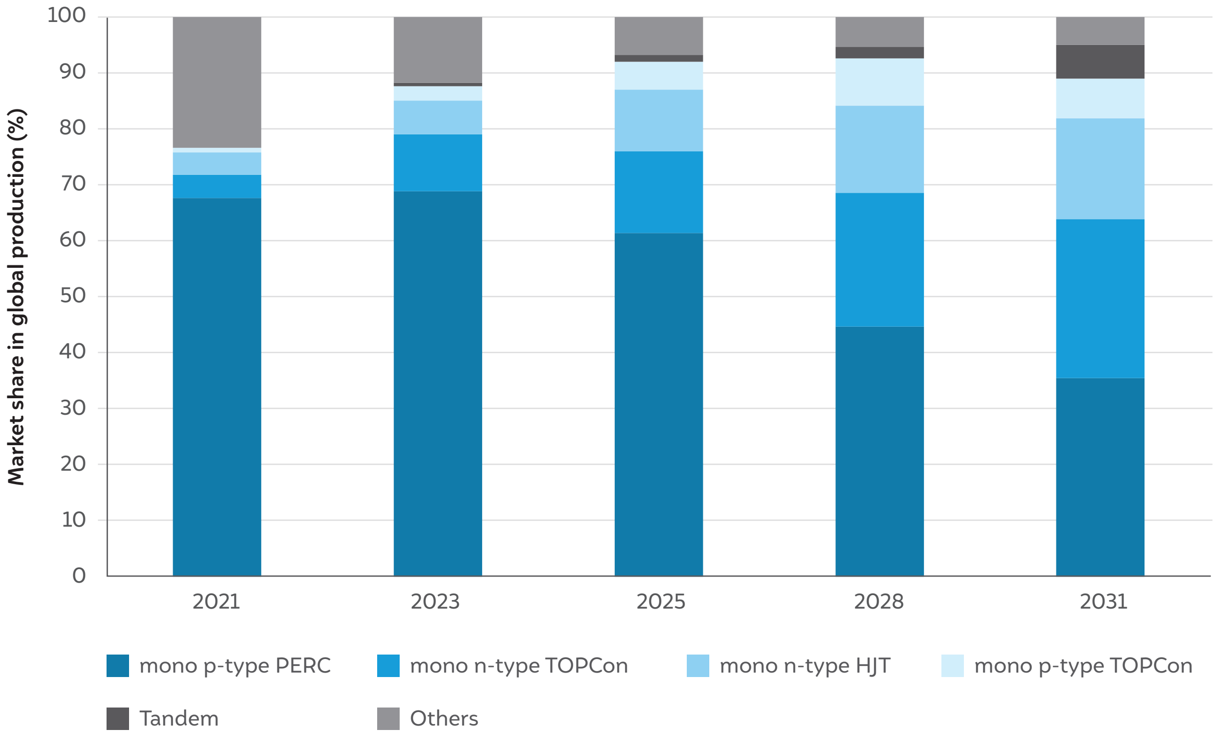
Indian solar manufacturing is dominated by multi-Si and has lagged in adopting mono-Si wafers. In 2019, 87 per cent of the modules produced by the top seven manufacturers in India were made of multi-Si wafers (Garg et al. 2021). Indian manufacturing lines are also aligned to smaller wafer sizes (156–158 mm) as compared to their Chinese counterparts (166–210 mm). Larger wafer sizes increase the power generation per module, reducing the unit cost. Failing to keep up with the latest technology trends has been a key driver for the low competitiveness of Indian manufacturing. However, new manufacturing facilities, such as those established by Tata Power and Premier Energies, utilise PERC technologies (Gupta 2021a; 2021b). With the PLI scheme prioritising high-efficiency modules, new facilities will likely use the PERC technology.

3.3 Shifting to n-type – the next big revolution in solar PV?

The solar PV landscape has seen dramatic shifts in technologies, from multi-Si to mono-Si and PERC. The next major shift in the industry is likely to be a move from p-type mono-Si wafers to n-type mono-Si wafers. Chinese industry leaders are debuting n-type modules. These have displayed record-breaking commercial efficiencies, with module efficiency above 22 per cent and cell efficiency above 25 per cent (Xiao 2021). While n-type wafers are more expensive than p-type wafers, technology breakthroughs in cell processing promise efficiency gains that outweigh additional costs. Globally, 15 GW of n-type cell capacity was estimated to be operational by the end of 2021 (Colville 2021).

Two n-type technologies are expected to dominate solar manufacturing in the coming years – tunnel oxidation passivated contacts (TOPCon) and heterojunction (HJT). Most new Chinese n-type modules use TOPCon technology. However, a ramp-up in HJT module offerings is also expected. Leading manufacturers outside of China have already launched or are planning to launch HJT modules. Analysts estimate that Chinese companies own over 50 per cent of the existing TOPCon and HJT production capacity as of 2020 (Shaw 2021).

Figure 6 **Market analysts expect TOPCon and HJT to make over 50% of global crystalline silicon production capacity by 2031**[8]



Source: ITRPV (2021)

Given its market dominance and further expansion plans, PERC is likely to be the most common solar cell technology for the next 4–5 years. 6 shows that market analysts expect TOPCon and HJT to capture over 50 per cent of the crystalline silicon market by 2031 (ITRPV 2021). A small share of TOPCon capacity is expected to be based on p-type wafers. Analysts also predict that solar modules based on tandem cells (discussed in Box 2) will start entering the market towards the end of this decade.

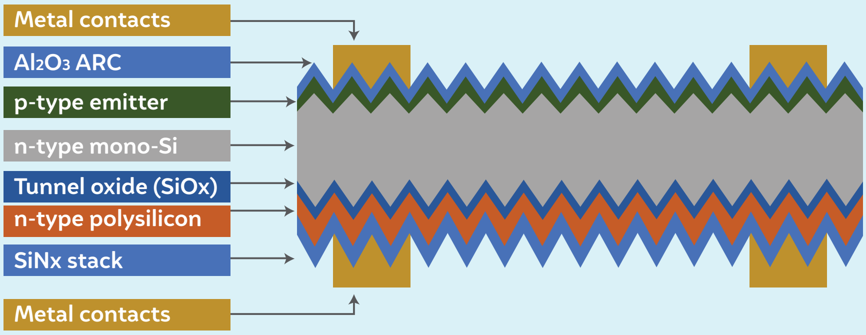
8. Others includes mono-Si n-type PERC, cells based on multi-Si wafers, cells without rear side passivation, and interdigitated back contact cells (cells with both metal contacts on the rear side).

BOX 2 The challengers – TOPCon, HJT, and tandem cells

Tunnel oxide passivated contacts (TOPCon)

The TOPCon manufacturing process is based on the PERC process. Figure 7 shows the TOPCon cell structure. As the technology is based on an n-type wafer, the p-n junction is formed by doping the wafer's front side with boron compounds to make a p-type emitter region. The front anti-reflection coating is made of aluminium oxide (Al_2O_3). The other main difference from PERC lies at the rear end. The rear side of the wafer is first covered with a silicon oxide layer (SiOx) that is called a 'tunnel oxide' as electrons can pass or 'tunnel' through it. The SiOx layer is followed by a doped polysilicon layer and a silicon nitride stack to complete the passivation.

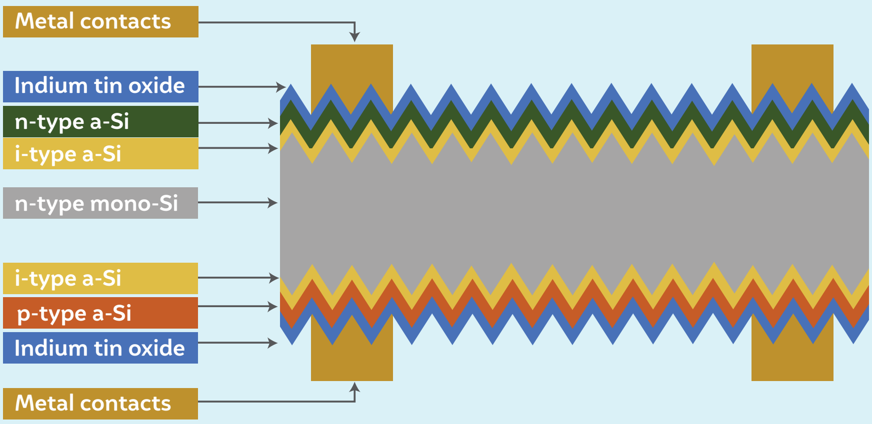
Figure 7 TOPCon solar cell structure



Source: CEEW-CEF adaptation from Wilson et al. (2020) and Kafle et al. (2021)

In addition to efficiency gains from the n-type wafer, the inclusion of a tunnel oxide and doped polysilicon layer cut recombination losses even further. The silicon oxide (SiOx) layer may either be grown directly on the wafer or deposited separately. The polysilicon layer is formed by depositing n-type amorphous silicon (a-Si), which gets converted to polysilicon during the high-temperature annealing step. Currently, multiple industrial options exist for both these processes. As the TOPCon technology matures, manufacturers are likely to standardise these differences. Manufacturers have debuted modules with a claimed efficiency of 22.3 per cent, a significant gain from existing PERC modules (LONGi Solar 2021).

Figure 8 HJT solar cell structure



Source: Louwen et al. (2016)

Silicon heterojunction (HJT)

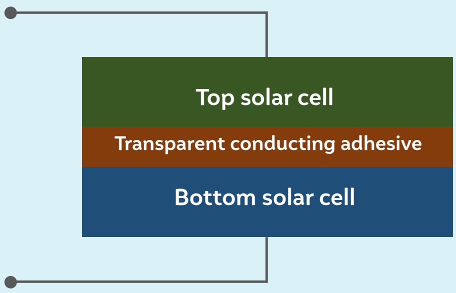
While HJT technology has existed since the 1990s, it has not yet gained significant market share. Recent advances in commercialising production have made HJT a high-efficiency alternative to PERC. Leading Chinese and European manufacturers have announced that they are setting up HJT production lines, while Singapore-based REC Solar already sells HJT modules targeting the residential market.

BOX 2 The challengers – TOPCon, HJT, and tandem cells

Current silicon-based cells involve a single p-n junction. This is between the bulk body of the wafer and the doped region at the front. HJT cells consist of two junctions, one at either end of an n-type silicon wafer. Figure 8 shows the HJT cell structure.

The n-type wafer is covered on both sides with thin layers of undoped amorphous silicon, also called intrinsic amorphous silicon (i-type a-Si). The front side is then covered with a layer of n-type amorphous silicon, while the rear side is covered with a layer of p-type amorphous silicon. This forms the heterojunction n-n-p structure. Further, each side is covered with a layer of indium tin oxide, which acts as a transparent anti-reflection coating. The amorphous silicon layers offer strong passivation, which can cut recombination losses better than PERC cells. The HJT process involves significantly fewer steps than PERC or TOPCon and produces high-efficiency cells. Early commercial HJT modules announced by Chinese players have efficiencies above 22 per cent (Xiao 2021). As the technology matures, module efficiency is expected to rise.

Figure 9 **A sample tandem solar cell structure**



Source: Wilson et al. (2020)

Perovskites and tandem – the future of solar PV?

While TOPCon and HJT cells have room to become more efficient, they are constrained by the theoretical limits of crystalline silicon solar efficiency and may reach an efficiency ceiling in the next 4–5 years. The solar industry continuously researches alternate photovoltaic materials to achieve cost reductions and efficiency improvements. In recent years, the material perovskite has emerged as a promising candidate due to its low manufacturing cost. Perovskites are compounds that have the same crystal structure as the mineral calcium titanate ($CaTiO_3$). While perovskite can be used in single-junction solar cells, it has delivered its most impressive results in perovskite-silicon tandem cells. A tandem cell combines two solar cells of different materials (Figure 9). Each material absorbs a certain portion of the solar spectrum. Most existing tandem models use a perovskite top cell and an HJT crystalline silicon bottom cell. The top cell absorbs high-energy photons, while the bottom cell absorbs low-energy photons. Therefore, a tandem cell absorbs a greater portion of the solar spectrum than any of the individual cells, delivering higher efficiency.

While perovskite-silicon tandem cells have shown impressive laboratory performance, much remains to be learnt about their suitability for mass production and their performance in real-world conditions. Stability is a key issue for perovskites as they degrade within 1–2 years while silicon modules last for 25–30 years (Extance 2019). Further, research on alternate materials and recycling is critical as perovskites used for solar cells contain lead, a toxic material.

The laboratory efficiency record for perovskite-silicon tandem cells stands at 29.5 per cent, a significant increase over similar records for HJT and TOPCon cells, which reached a maximum of 25.8 per cent, as of November 2021 (Shukla 2021; Scully 2021). The tandem cell record is held by Oxford PV, which was set up by the University of Oxford's physics department with investments from UK government bodies, RE manufacturers (Meyer Burger and Goldwind), and RE developer Equinor (Hutchins 2019). The company set up its first tandem cell manufacturing site in 2021, a development that will significantly improve the understanding of the technology's practical performance (Gifford 2021a).

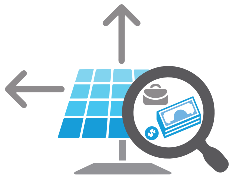
Source: CEEW-CEF compilation

Going forward, India must focus on capital expenditure, localisation across the value chain, and technology development.

Image: iStock

4. What next for Indian solar manufacturing?

India has taken a concrete step towards establishing vertically integrated solar manufacturing capacity through the PLI scheme and may soon have the largest solar manufacturing capacity outside of China. Based on the extent of integration, manufacturing facilities must be established within 1.5–3 years from sanctioning (IREDA 2021b). Accordingly, cell and module manufacturing facilities will likely come up by 2023, wafer factories by 2024, and polysilicon factories by 2025.



The capacity expansion plans of Indian solar manufacturers will require over USD 7 billion in capex and can create over 41,000 jobs

The policy support measures detailed in Section 2 create both incentives and safeguards for Indian manufacturers. Policymakers must now shift their attention to achieving self-sufficiency and global competitiveness. In this section, we discuss three critical steps that can help establish India as a prominent solar manufacturer – (i) scaling up the core business from polysilicon to module manufacturing, (ii) securing supply chains by localising production of BOM components and manufacturing equipment, and (iii) developing technology leadership through a focus on R&D.

4.1 Scaling will require significant sums of capital

If domestic manufacturers are to realise the ambitious plans set in their announcements and PLI submissions, they must mobilise significant capital and operating expenditure flows. Table 1 shows the capex requirement for each manufacturing stage. Based on these estimates, setting up the crystalline silicon manufacturing capacity shown in Figure 1 would require USD 7.2 billion (INR 53,773 crore) in capital expenditure by 2025.[9] These plans can also create over 41,000 jobs in plant operation.

Further, process consumables such as MG silicon, metal pastes, and module BOM account for 50–60 per cent of the production cost of solar modules (for a fully integrated polysilicon to module manufacturing facility) while capital expenditure accounts for 15–20 per cent (Woodhouse et al. 2019). Therefore, access to short-term working capital will be critical for manufacturers, particularly if the supply chain challenges seen in 2021 persist.

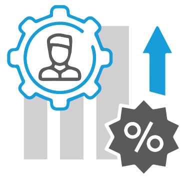
9. USD-INR conversion at USD 1 = INR 75, based on average USD-INR exchange rate in 2021 (data from Financial Benchmarks India Limited).

Table 1 Installing the planned solar manufacturing capacity will require USD 7.2 billion (INR 53,773 crore) in capex

Manufacturing stage for PERC	Planned capacity (GW)	Capex – USD million (INR crore)		Jobs created for plant operation		Source for capex and jobs
		Per GW	Total	Per GW	Total	
Polysilicon	16	53 (400)	853 (6,400)	200	3,200	Bernreuter Research 2018; Tsafos 2021; Woodhouse et al. 2019
Ingot and wafer	29	65 (485)	1,875 (14,065)	375	10,875	Inputs from market stakeholders
Cell	55	60 (450)	3,276 (24,570)	125	6,825	
Module	58	20 (150)	1,165 (8,738)	350	20,300	
Total		**198 (1,485)**	**7,170 (53,773)**	**1,050**	**41,200**	

Source: CEEW-CEF analysis

Domestic solar manufacturers face challenges in raising debt capital at competitive rates and pay out three to four times more interest than their Chinese counterparts (Jain, Dutt, and Chawla 2020). Manufacturers also face higher interest rates than renewable energy developers. For example, IREDA's interest rates for solar manufacturing are up to 105 basis points higher than interest rates for solar and wind deployment (IREDA 2022). Improving access to long-term debt and working capital is critical for sustained capacity growth.



Domestic solar manufacturers face high interest rates, paying three to four times in financing costs compared to their Chinese counterparts

4.2 Localising bill of materials production can secure supply chains

While the BCD, PLI, and ALMM offer incentives and protections for module manufacturers, further focus is needed on manufacturing BOM. As they account for 50–60 per cent of production costs, supplies of process consumables must be secured for a stable domestic supply chain. The PLI scheme includes a local value addition clause, wherein manufacturers receive higher incentives based on local BOM sourcing. Along with export markets, these developments guarantee a large market for domestic BOM manufacturers. While this report does not detail specific recommendations to scale-up domestic BOM manufacturing, we briefly discuss the key BOM elements in solar module and cell manufacturing that present significant opportunities.

Solar module BOM – glass, encapsulant and backsheet, aluminium frame, junction box

Apart from solar cells, the key BOM elements for a solar module are a solar glass sheet, encapsulant films, a backsheet, an aluminium frame, and a junction box. Other requirements include ribbons and materials for wiring, sealing, potting, etc. While some domestic manufacturing exists for all components, India is largely reliant on imports to meet the demand from module manufacturers. Module manufacturers have reported that in addition to the low domestic supply of these components, the available options cannot compete with imported products in cost and quality.

Localising production of process consumables is essential as these make up 50-60% of the production cost

The shift towards larger wafer sizes will result in heavier modules. Glass, aluminium frames, encapsulants, and backsheets make up 96 per cent of the module weight, with glass alone comprising 75 per cent (Tyagi and Kuldeep 2021). Global BOM manufacturers are accordingly researching alternate materials and technologies to reduce module weight. Therefore, as domestic players set up BOM manufacturing facilities, they must focus on cost, quality, and R&D to provide effective technology options for the future.

Solar cell BOM – silver paste

Silver paste makes up 50 per cent of the non-wafer BOM cost for PERC solar cells and 5 per cent of the total module cost.[10] TOPCon and HJT cells require 1.5–2 times more silver than PERC (Zhang et al. 2021). In 2020, the solar PV industry accounted for 10 per cent of the global silver consumption. Industry analysts expect the share to increase to 15 per cent by 2025 (Bellini 2021). Accelerated deployment of TOPCon and HJT will only increase the silver requirement.

The significance of silver in current and future solar technologies could be an opportunity for India. Currently, manufacturers largely import silver paste. As per our estimates, Indian manufacturers will purchase at least USD 96 million (INR 720 crore) worth of silver paste for every 10 GW of annual PERC production.[11] In addition to silver paste, there is an opportunity to enter silver powder (precursor to silver paste) manufacturing.

However, significant technological challenges exist. Silver paste production is a highly specialised process with strong intellectual property protections. Indian industry must first focus on developing quality and cost-competitive offerings through R&D before scaling up. Silver paste typically consists of silver particles, glass frit, and additives such as lead. Given the toxic nature of lead, manufacturers are likely to move to lead-free paste over the next 10 years (ITRPV 2021). Simultaneously, manufacturers are exploring alternatives such as copper and nickel alloys to reduce exposure to commodity price movements. In September 2021, an Australian start-up broke the commercial efficiency record for silicon solar cells by producing a silver-free cell (Carroll 2021). While it remains to be seen how the cell performs in real-world modules, the result could lead to a significant change in silver consumption globally.

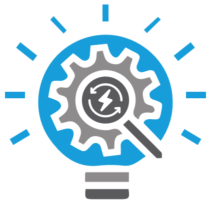
All these factors point to the importance of setting up strong R&D facilities that bring together solar and BOM manufacturers. Upcoming manufacturing facilities must recognise the global push to identify alternate materials and technologies to reduce weight and costs and ensure that R&D is aligned with this goal.

10. Based on CEEW-CEF analysis of data received from Indian solar manufacturers and Woodhouse et al. 2019.

11. Assuming silver consumption at 15 mg / WDC and silver cost at INR 46,800 per kg (Kafle et al. 2021).

4.3 Relying on imports for manufacturing equipment can be a roadblock

Currently, manufacturers largely import their machinery from China or Europe. Localising the production of manufacturing equipment has been a key lever to cut capex costs in China. Given the anticipated scale-up in manufacturing capacity and the 7–10-year lifetime of machinery, India will soon be a large market for manufacturing equipment. Acquiring manufacturing equipment locally can significantly reduce capex for Indian solar manufacturers. Since the Covid-19 pandemic, manufacturers with equipment made in China have faced challenges in accessing maintenance and services due to travel restrictions. Sourcing equipment locally would give domestic manufacturers constant access to equipment suppliers to service repair and retooling requirements. India should prioritise local manufacturing of Siemens CVD reactors, Czochralski ingot-pulling furnaces, and PECVD reactors. Together, these components make up 40 per cent of the equipment costs for a fully integrated PERC manufacturing facility (Woodhouse et al. 2019).



India allocated only USD 5 million for clean energy R&D (2022), while the US allocated USD 132 million for solar PV alone (2020)

There is also a significant market opportunity to reduce capex costs for newer technologies through localisation. While equipment costs for TOPCon are similar to PERC, machinery for HJT is 2–3 times more expensive (Gifford 2021b; Gifford 2019). HJT equipment costs are expected to reduce once Chinese equipment manufacturers scale up the supply of critical machinery such as PECVD reactors (a-Si deposition) and sputtering tools (indium tin oxide deposition). As the HJT landscape is not yet optimised, India can gain an advantage by moving quickly on R&D and piloting HJT manufacturing equipment.

4.4 Research and development critical for growth

So far, India's solar research grant programmes have been distributed between various ministries, with both the MNRE and Department of Science and Technology (DST) funding multiple programmes. In comparison, energy ministries lead the management of solar R&D funding in other technology-leading nations, such as the United States, South Korea, and Singapore.

R&D in the solar sector is severely underfunded in India. India's 2022–23 Union Budget allocated only USD 5 million (INR 35 crore) for R&D spending across all renewable energy technologies, and not limited to manufacturing (Ministry of Finance 2022b). Between 2015 and 2020, the DST funded solar R&D projects worth USD 28 million (INR 208 crore) (DST 2020). In comparison, South Korea allocated USD 60 million (INR 450 crore) for solar manufacturing research in 2020, of which 45 per cent went to crystalline silicon and 28 per cent to perovskite (PVPS 2021). The US allocated USD 132 million (INR 990 crore) to solar PV R&D and innovations in manufacturing in 2020 (PVPS 2021).

Our analysis of the projects funded by the DST and MNRE reveals that only academic institutions and research laboratories have availed of grants for solar research, with close to no participation from the solar manufacturing industry (DST 2021a; MNRE 2021d). In 2021, the DST called for new R&D grant applications under the Challenge Awards 2021 for Solar Energy (DST 2021b). The scheme covered many essential themes such as technology-specific focus areas, low carbon manufacturing, and a holistic approach to research. However, like previous funding initiatives, there is no concerted national strategy to deliver long-term results from this scheme.

As Indian solar manufacturers integrate backwards, industry must be a central pillar for solar R&D. Simultaneously, India will need to increase its spending on solar R&D through both public and private sources. In the next chapter, we discuss various nations' R&D approaches to solar manufacturing.

BOX 3 Direct and epitaxial wafers – a potential gamechanger

The Czochralski ingot-pulling process followed by diamond wire cutting enjoys complete dominance of the ingot wafer production stage. However, these processes have two major drawbacks – ingot-pulling is the most energy-intensive step in the entire solar manufacturing process, and diamond wire cutting wastes up to 30 per cent of the polysilicon in the ingot (Woodhouse et al. 2019; ITRPV 2021). To reduce these losses, manufacturing start-ups have patented new wafering technologies. Two attempts are noteworthy – direct wafering by CubicPV (formerly 1366 Technologies) and epitaxial wafer growth by Nexwafe.

In the direct wafering method, a multi-Si wafer is lifted directly from a bath of molten silicon, drastically cutting energy consumption and material wastage. However, as the process was developed before mono-Si wafers became the market standard, it is likely to face low adoption unless it can switch to mono-Si wafers. CubicPV is currently focusing on combining perovskites and tandem cells with its direct wafering technology (CubicPV 2022).

Nexwafe employs epitaxial growth, wherein a polysilicon layer is chemically deposited over a seed wafer and is then detached to form an independent wafer. Nexwafe claims that the process can cut wafer thickness by 17–20 per cent, costs by 50 per cent, and CO_2 emissions by 75 per cent (Nexwafe 2022). While the process is not ready for mass deployment, it is a promising contender for the future. In October 2021, Reliance Industries led Nexwafe's series C financing round with a USD 29 million (INR 218 crore) investment (Gupta 2021c).

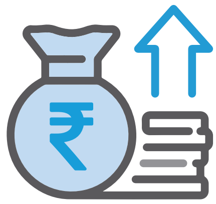
Source: CEEW-CEF compilation

Nations have provided multiple support measures for manufacturing from subsidies and capital to targeted R&D programs.

Image: Alamy

5. How have other countries supported their solar manufacturing sector?

Globally, many countries are working toward scaling up their domestic solar manufacturing. India must take into consideration the lessons drawn from their successes and failures when drafting new legislations to scale up solar manufacturing. In the next section, we look at the policies and approaches adopted by the United States and countries in Asia – China, South Korea, Taiwan, Malaysia, Vietnam, and Thailand.



Continuous access to credit and subsidy support from all levels of government helped Chinese manufacturers overcome financial challenges

CHINA

China's current dominance of the PV supply chain is the result of long-term strategic planning. The Chinese government significantly ramped up its manufacturing strategy in its 2011 five-year plan. While Chinese policymakers and manufacturers have leveraged a variety of methods to achieve their current dominance, we detail some of the key policy steps below:

- **Subsidy support from all levels of government** – Chinese central and local governments have provided solar manufacturers tax incentives, input subsidies, R&D grants, equity infusions, technology upgradation grants, subsidised land, and even pre-built factories. Further, the central and local governments provided relief to companies facing financial difficulties. For example, the Wuxi government provided a USD 150 million (INR 1,125 crore) cash injection to a solar manufacturer in 2013 after it defaulted on its public debt along with a five-year exemption from revenue taxes (Ball, Reicher et al. 2017).[12] The Chinese central government is now tightening previous subsidy regimes and focusing on the financial sustainability of these manufacturers (TERI 2019).

- **Access to financing** – Chinese central and local state banks have provided continuous access to debt funding for Chinese manufacturers, critically when manufacturers faced significant financial distress. For example, the China Development Bank made USD 43 billion (INR 3.2 lakh crore) available through Renminbi-denominated loans to 15 solar manufacturers in 2010 after the global financial crisis (Wiedenbach 2021). State lending programmes allowed manufacturers to rapidly expand their factories, while shielding them economic and financial challenges.

- **Manufacturing clusters** – Local governments built industrial parks to support the solar panel ecosystem and attracted manufacturers through subsidy support. The support from local governments allowed Chinese players to concentrate manufacturing in clusters. Many such parks offer manufacturers low electricity prices. PV manufacturers and

12. USD-INR conversion at USD 1 = INR 75, based on average USD-INR exchange rate in 2021 (data from Financial Benchmarks India Limited).

upstream raw materials and equipment suppliers have also constructed production centres in the same area, enabling the ecosystem to cut costs and achieve co-development between manufacturers and their vendors (Wiedenbach 2021; Ball et al. 2017).

- **Technology transfer and domestic R&D** – The Chinese government invited foreign players to set up joint ventures with Chinese companies and thereby gained access to new solar technologies. In turn, foreign investors obtained cheap labour and government subsidies. Domestically, the Chinese government set efficiency targets through its five-year plans and accordingly allocated R&D funding to academia and corporate R&D efforts. For example, in 2012–13, the central government provided R&D grants ranging from USD 170,000 (INR 1.3 crore) to USD 4.4 million (INR 33 crore) to different players (Ball et al. 2017). Further, Chinese manufacturers provided grants to foreign universities pursuing solar research and partnered on projects (Hopkins and Li 2015). In 2020, the government mandated solar manufacturers to spend at least 3 per cent of their revenues or USD 1.4 million (INR 10.5 crore) annually on R&D (Ranjan 2020). Expenditure on R&D varies significantly across big manufacturers. For instance, LONGi spent upwards of 5.5 per cent of its revenue on R&D in 2018, while JinkoSolar spent around 1.5 per cent in 2018 (Osborne 2019).

- **Top Runner programme** – The Top Runner programme creates demand for next-generation technologies through efficiency-linked deployment programmes. For example, the third phase of the programme was launched in 2017 with a reverse auction for 6.5 GW of PV capacity at dedicated sites. Bidders had to be meet minimum efficiency requirements to qualify (Wang 2020). PERC products accounted for 67 per cent of winning projects in the phase, while bifacial products won 50 per cent (Beetz 2018). Both these technologies were in the early stages of growth at the time. Projects based on n-type modules were also set up under the programme (Clover 2018).

- **Import tariffs** – Chinese tariffs on American imports helped the country develop a strong domestic polysilicon supply. In 2012, the US imposed high tariffs on solar cell and module imports from China. In retaliation, China imposed anti-dumping and countervailing duties on polysilicon imports from the US (55–60 per cent) and South Korea (4.5–9 per cent) in 2013 (Bellini 2020a; Bernreuter Research 2020b). These duties led to a massive spurt in Chinese polysilicon manufacturing, which now makes up 77 per cent of the global capacity (Garg et al. 2021).

China's Top Runner program provided demand security for new technologies, such as bifacial and n-type

While China dominates global solar manufacturing, it is important to note that recent developments have raised questions over the use of forced labour in the Chinese solar supply chain, particularly for polysilicon (Murtaugh, Murphy et al. 2021). In June 2021, the US effectively prohibited imports containing products made by Hoshine Silicon Industry, a prominent manufacturer of MG silicon (Stoker 2021a). The order caused module shipments to be detained at US ports (Stoker 2021b). A wider bill to restrict all imports linked to the Xinjiang region in China, a hub for polysilicon manufacturing, is currently being considered in the United States Congress (Rai-Roche 2021a). Such a ban will have major consequences on the solar industry and may encourage similar actions by other countries.

SOUTH KOREA

South Korea's solar cell and module manufacturing capacity is highly concentrated among three large players – Hanwha, LG, and Hyundai. Each of these companies is an established solar manufacturer and a unit of a larger South Korean family-owned conglomerate. South Korea's solar deployment plans have provided these players with a strong domestic market. Domestic companies provide over 75 per cent of South Korea's solar modules as of 2019 (Bellini 2020b). The South Korean government has focused efforts on advancing the domestic industry through R&D funding to achieve end-of-decade cell efficiency targets. The government is also planning to invest USD 23 million (INR 173 crore) to set up a common PV research centre for testing crystalline silicon technologies (Bellini 2020c). In 2020, the government allocated over USD 60 million (INR 450 crore) to different solar technologies (PVPS 2021). In 2020, South Korea introduced carbon footprint rules that prioritise modules with low life-cycle carbon footprints for deployment. These regulations can support domestic manufacturers against Chinese competition (Bellini 2020b).

Tax incentives helped foreign manufacturers, particularly Chinese, set up factories in Southeast Asia and avoid US tariffs

TAIWAN

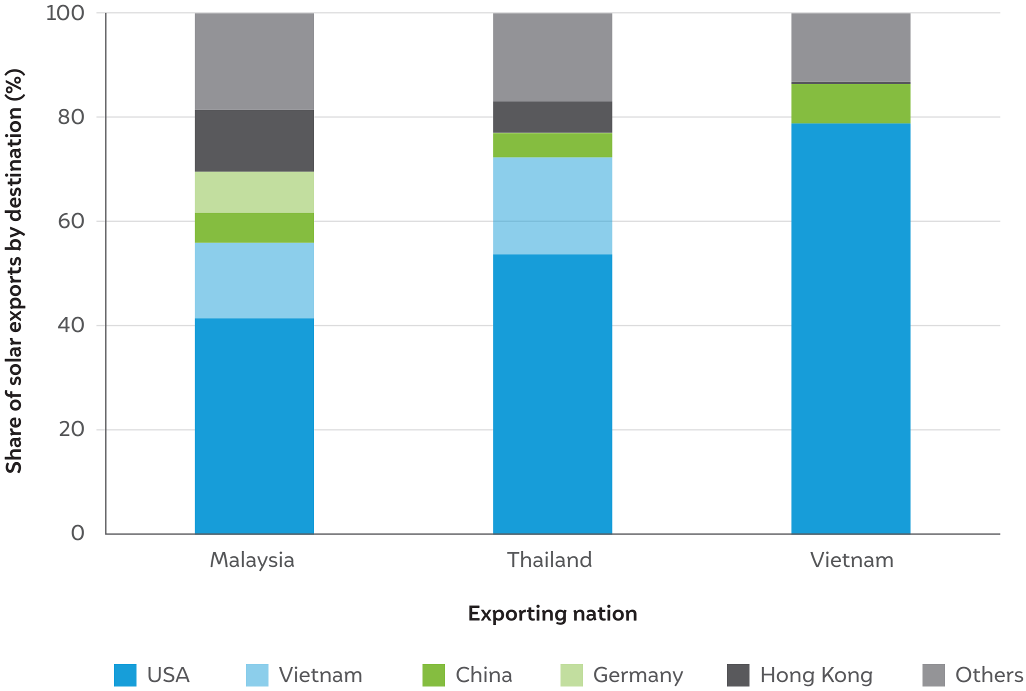
Taiwanese companies have established a significant cell manufacturing presence in conjunction with their strong semiconductor manufacturing presence. To ramp up its solar deployment programme, Taiwan has introduced domestic content requirements and fiscal support to promote local industry. Taiwanese regulations restrict the purchase of Chinese modules and provide a 6 per cent bonus on tariffs for power procured from energy generators that use certified, high-efficiency domestic modules (GlobalData Energy 2020). Further, Taiwanese cell manufacturers have restructured their businesses to expand into module manufacturing (TERI 2019). In a strategic move, three leading players consolidated their businesses into a single entity to leverage each company's individual expertise in wafers, cells, and modules, respectively (Clover 2017). The merged entity also received an investment from the Taiwanese government (Osborne 2018).

SOUTHEAST ASIA

To avoid duties imposed by the US and European countries on solar imports from China, large Chinese manufacturers have set up cell and module production units in Southeast Asian countries such as Malaysia, Thailand, and Vietnam. Local governments have welcomed such collaborations and provide tax incentives to new entrants setting up large-scale manufacturing facilities. For example, a 3 GW cell and module factory is being planned in Malaysia with administrative support in the form of a government incentive scheme that provides five-year tax exemptions to companies relocating to Malaysia. The government expects to generate over 3,000 employment opportunities through the planned factory (Duggal 2021b; MIDA 2020). Similar investments exist across Vietnam and Thailand (Shumkov 2021; Roney 2021).

Figure 10 shows that exports to the US account for the majority of Vietnam's and Thailand's solar exports and over 40 per cent of Malaysia's exports. In August 2021, an American solar manufacturers group filed a petition with the US Department of Commerce, highlighting how Chinese manufacturers are using factories in these nations to circumvent tariffs. The petition proposed extending duties to Chinese factories in Malaysia, Thailand, and Vietnam (Murtaugh, Eckhouse, and Saul 2021). However, the Department of Commerce rejected the petition in November 2021 (Reuters 2021).

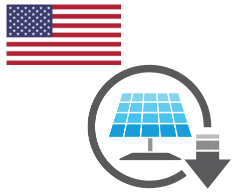
Figure 10 Exports to the US constitute the largest share of 2020 solar exports for Malaysia, Thailand, and Vietnam



Source: Export statistics for commodity code 854140 from United Nations (2021).

UNITED STATES

Silicon-based solar technology was first developed in the US. The US has been a leader in allocating R&D funding across energy technologies. In 2010, the Department of Energy launched the SunShot initiative, which targeted a 90 per cent reduction in solar power costs by 2030. Through this initiative, the US government poured R&D funding into early-stage solar technologies. Further, the Advanced Research Projects Agency – Energy (ARPA-E) funds potentially beneficial technologies across energy sources. Estimates suggest that ARPA-E channelled USD 2.8 billion (INR 21,000 crore) of government funding into clean energy technology between 2009 and 2021, which attracted USD 5.4 billion (INR 40,500 crore) in follow-on funding from the private sector (St. John 2021). However, while ARPA-E companies produced patents at double the rate of peer companies outside the programme, they did not attract significantly higher follow-on funding / acquisitions than peers not included in the program (Goldstein et al. 2020). Wafer maker CubicPV (formerly 1366 Technologies) is one of the success stories of this programme with its first-of-its-kind direct wafering technique (Sekaric 2015). CubicPV is now looking to set up manufacturing facilities, with India being one of the planned investment locations (Rai-Roche 2021b). It is important to note that while the US has invested significantly in R&D, its solar industry is almost entirely import-reliant, with imports contributing to over 90 per cent of solar deployment in 2021 (Feldman et al. 2022). The failure to ensure market deployment of technologies which received investment is a key reason.



Despite investing heavily in R&D, the US failed to establish a significant domestic manufacturing base for solar PV

Today, the only major American manufacturer of solar cells and modules is the thin film manufacturer – First Solar. In 2012, the US imposed anti-dumping duties on solar PV imports from China and Taiwan. However, these measures only succeeded in diversifying the manufacturing base of leading Chinese players. Further, the Chinese government imposed retaliatory tariffs on polysilicon that spurred the rapid growth of polysilicon production in the country. More recently, in 2018, the US imposed a safeguard duty on solar cell and module imports, initially at 30 per cent and which was then reduced to 18 per cent by 2022. The first 2.5 GW of cells and modules imported into the US were exempted from the duty (Prabhu 2018). Exports from India were exempted from the duty; however, the exemption was removed in 2019 (CEEW-CEF 2019). The US also supported its solar players with bailouts and grants, particularly in the wake of the 2008 recession. Despite interventions, the incentives failed to secure a robust manufacturing base in the US. In 2011, prominent thin film module maker Solyndra defaulted on a USD 535 million (INR 4,013 crores) federal loan guarantee, one of the most high-profile setbacks of the American solar industry (Wingfield 2012; Dlouhy 2021).

In 2021, American policymakers proposed a production-based tax credit for domestically manufactured solar PV components. The details of the incentive are provided in Table 2. The bill proposes that the incentives be phased out from 2029. The proposal also provides incentives for solar trackers and inverters, while the wider legislation includes incentives for different forms of low-carbon hydrogen production. The proposal is a part of the US's climate and social spending legislation, the Build Back Better Act, which is yet to receive congressional approval as of January 2022 (Diaz 2021).

Table 2 **The proposed incentive structure under the US Build Back Better Act**

S. No.	Component	Tax credit amount
1	Solar grade polysilicon	USD 3 / kg
2	Solar wafer	USD 12 / sq m
3	Solar cell	USD 0.04 / WDC
4	Integrated solar module (wafer to module produced in the US)	USD 0.11 / WDC
5	Non-integrated solar module	USD 0.07 / WDC

Source: US Congress (2021)

Long-term technology development, export demand creation, and ecosystem-building initiatives must be the next steps for solar manufacturing in India.

Image: Goldi Solar

6. Recommendations

As discussed earlier, the MNRE has made significant progress in setting up a clear policy landscape for domestic solar manufacturing in 2021. India now needs to consider long-term strategic measures to make domestic solar manufacturing a pillar of industrial growth. Our recommendations are geared towards the long-term actions required to make solar manufacturing advanced, competitive, and global. This will be particularly critical as the government tapers and withdraws subsidies and duties in the future. In the absence of a coherent ecosystem, the upcoming facilities may not be able to keep abreast of the latest innovations and may become redundant by the end of the decade. We present our recommendations in three parts – establishing a long-term solar manufacturing technology roadmap, strategically approaching export demand creation, and supporting manufacturers in setting up and scaling up upcoming manufacturing facilities.

Table 3 A focus on technology, demand, and scale is essential to support domestic solar manufacturing

S.No.	Recommendation	Timeline	Implementing authority	Nature of expense
	Set up a long-term solar manufacturing technology roadmap with enhanced funding, a dedicated R&D division in the MNRE, and an advisory board.			
1	Identify thrust areas and timelines based on key research requirements and establish solar research funding grants.	2022–2028	MNRE	Grants
2	Incentivise industry-led R&D by (i) setting up a central R&D centre, (ii) providing capex subsidy for manufacturers setting up R&D facilities, and (iii) mandating a minimum spend of 3 per cent of revenue on R&D from 2025.			Capex outflow, subsidy
3	Target partnerships with reputed international solar research institutes and leverage these connections to apply for international research funding programmes.			Nil
4	Set up an independently managed investment fund with anchor investment from the Government of India.			Equity
5	Mandate that solar projects awarded under government tenders use products developed under the solar technology roadmap for a minimum of 5 per cent of their capacity.			Nil

S.No.	Recommendation	Timeline	Implementing authority	Nature of expense
	Strategically create export demand for Indian modules			
6	Create markets for low-carbon manufacturing by (i) providing approval and support for open-access renewable power consumption, (ii) trade deals with nations that have stated a preference for low-carbon products.	2022–2023	MNRE, Ministry of External Affairs (MEA), state regulators	Nil
7	Enhance financing for solar projects in developing countries that are members of the International Solar Alliance (ISA) through India Exim Bank, securing export demand for Indian modules.	Rolling	MNRE, MEA, India Exim Bank	Loan
8	Consider expanding the ALMM list and bilateral duty exemptions based on trade deal negotiation requirements.	Rolling	MNRE	Nil
	Support scale for upcoming manufacturing capacity			
9	Raise the share of loans to the RE manufacturing sector to 20% of Indian Renewable Energy Development Agency's (IREDA) loan book by 2026.	2022–2026	IREDA	Loan
10	Set up manufacturing hubs with attractive land rates, labour availability, deemed open-access approval, and thrust sector status for solar manufacturing.	2022–2023	State industrial development corporations	Revenue outflow
11	Apply BCD on polysilicon or wafer imports from 2027, start tapering BCD on cells and modules from 2025.	2025 onwards	MNRE	Nil

Source: CEEW-CEF analysis

6.1 Long-term solar manufacturing technology roadmap

If India is to establish a self-sustaining and globally competitive solar manufacturing sector, it must approach research and development strategically. So far, research on solar is fragmented and disconnected from the industry. We recommend concretising the structure and direction of solar research and bringing R&D under a long-term national strategy. To this end, we recommend creating a **solar manufacturing technology roadmap** with five elements – (i) identifying thrust areas and timelines for research funding, (ii) providing support for industry-led R&D, (iii) leveraging international support, (iv) commercialising laboratory concepts, and (v) providing demand security for novel technologies. The first three elements focus on developing new technologies. The fourth measure provides a means to help new technologies survive the transition from the lab to early market deployment. The fifth measure creates a demand-pull to scale up mass deployment.

We recommend that the MNRE acts as the implementation authority for this roadmap. Implementing the roadmap will require a multi-year funding allocation with significantly increased annual spending from current levels. To manage the technology roadmap, the

MNRE should set up a dedicated R&D division with an advisory board comprising Indian and foreign domain experts. The R&D division must engage with both academia and industry and prioritise increasing the role of industry in defining the research questions. Our indicative roadmap runs from 2022 to 2028. However, timelines and targets should be subject to the inputs of the advisory board.

(i) Identify thrust areas and timelines based on key research requirements in solar technologies

India's solar manufacturing R&D funding must target technology-specific outcomes that address existing challenges and opportunities in commercialising new solar technology. Table 4 lists the recommended thrust areas and corresponding targets. The MNRE must ensure that the research grants awarded are in line with the thrust areas. Further, the MNRE must prioritise proposals with joint participation from academic institutions and the manufacturing industry. Industry participation is essential while defining the exact research problem and assessing the commercial suitability of research outcomes.

It is important to note that the research themes and targets listed in Table 4 are indicative. The MNRE must consult relevant stakeholders from industry, foreign R&D institutions, and academia to develop a final list of focus areas, targets, and timelines. The proposed R&D division and advisory board must be responsible for evaluating the roadmap's goals and progress and updating targets and timelines in line with global market developments.

Table 4 Indicative thrust areas for the solar manufacturing technology roadmap

	Research theme	Target outcomes (baseline 2021)
PERC, TOPCon, HJT (Outcome cells must have 25–26 per cent efficiency)	Reducing silver consumption	20–25 per cent by 2025, 50 per cent by 2028
	Reducing wafer thickness	10 per cent by 2025, 15 per cent by 2028
	Optimising processing costs and throughput for TOPCon and HJT	Production cost must be competitive with PERC by 2025 on a per watt basis
	Cutting the cost of low-temperature HJT silver paste	Cost-competitive with high-temperature silver paste by 2025
	Alternatives for critical materials	Cost-competitive modules with (i) silver-free cells (all technologies), (ii) indium-free HJT cells by 2027
	Cutting energy consumption and material wastage in polysilicon and wafer stages	15 per cent by 2025
Future / alternate technologies	Thin film	Copper indium gallium selenide and cadmium telluride cell efficiency of 19–20 per cent by 2025
	Perovskites-only modules	Cell efficiency of 25–26 per cent by 2025; mass-production ready, stable module by 2028
	Tandem cells and modules	Cell efficiency of 29–30 per cent by 2025; mass-production ready, stable module by 2028
	Direct wafering / epitaxial wafers	Cost-competitive, commercial-grade wafer production by 2027
	New application areas such as building-integrated PV, flexible cells	Cost-competitive, commercial-grade module products for specialised use cases by 2027
BOM and machinery	Designing low-cost solar PV manufacturing machinery	Commercial-grade machinery particularly, Siemens CVD, Czochralski ingot pulling, PECVD by 2027
	Reducing module weight	Cost-competitive solar module with 25 per cent weight reduction by 2025

Source: CEEW-CEF analysis.

(ii) Incentivise industry-led R&D and mandate R&D spending requirement

The MNRE must encourage and actively facilitate industry–academia collaboration under the solar technology roadmap. Solar manufacturers face hurdles in generating the initial investments for setting up R&D facilities. We recommend that the MNRE provide funding to R&D manufacturing facilities to bridge this gap. The MNRE has two pathways to provide this support:

- Establish a central solar PV R&D centre –
  - » The facility must have at least a 100 MW manufacturing capacity. Such a facility would cost USD 20–27 million (INR 150–200 crore)[13] (Bellini 2020c). The centre must at least have manufacturing capability across the wafer, cell, and module stages.
  - » It must have required machinery for different technologies, such as epitaxial wafers, TOPCon / HJT / thin film / perovskite / tandem cells, etc.

Image: Waaree Energies Ltd.

13. USD-INR conversion at USD 1 = INR 75, based on average USD-INR exchange rate in 2021 (data from Financial Benchmarks India Limited).

- Provide manufacturers with a 25 per cent subsidy on capital expenditure for setting up R&D laboratories. The MNRE must define minimum technical specifications that laboratories must meet to avail the subsidy. The MNRE can also explore the option of providing manufacturers concessional loans to meet their capex requirements. Manufacturers must fund projects with relevant research partners under the thrust areas identified in the technology roadmap to avail the subsidy.

Allocating a minimum 3 per cent of revenue to R&D will help set up the initial framework for industry-led research in solar manufacturing

While the industry may require R&D financing support in the initial years, the MNRE must mandate a minimum research expenditure for integrated solar manufacturers in the long term. We recommend mandating manufacturers with a total installed production capacity of over 2 GW to spend a minimum of 3 per cent of their revenue on R&D from 2025, which can be increased to 5 per cent by 2030. As the average size of manufacturers increases, the MNRE can change the minimum mandate from a percentage basis to an absolute INR amount basis.

(iii) Leverage international support through expertise and financing

Chinese companies have achieved multiple manufacturing innovations in collaboration with laboratories worldwide. Early Chinese solar manufacturers, Suntech and Yingli, developed technologies in collaboration with the University of New South Wales (UNSW) and the Dutch Energy Research Centre, respectively. Suntech also collaborated with a different university in a project funded by the Australian government (Hopkins and Li 2015).

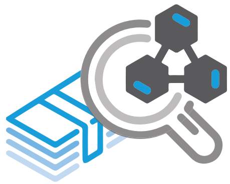
Both the MNRE and Indian companies must strike partnerships with research institutes in nations with strong expertise and funding for solar manufacturing research but limited domestic manufacturing capacity. Such institutes will benefit by gaining access to manufacturing facilities and a market to test their products. Examples include the National Renewable Energy Laboratory (US), Fraunhofer Institute (Germany), Solar Energy Research Institute of Singapore, and the UNSW-School for Photovoltaic and Energy Engineering (Australia).

Research funding opportunities are also available through this route. Many countries have allocated funding for renewable energy research under existing or planned initiatives such as the European Green Deal, the United States Bipartisan Infrastructure Deal, and the Australian Technology Investment Roadmap (DISER 2020; DOE 2021; European Commission 2020). To take this up, the MNRE must engage with energy ministries of other nations and leverage goodwill created through existing forums like the Indo-Germany Energy Forum, International Solar Alliance, the US-India Strategic Clean Energy Partnership, and the India-UK Energy for Growth Partnership.

(iv) Commercialise laboratory concepts through a government-anchored investment fund

While industry partners can directly commercialise many research outputs, a healthy research ecosystem will also lead to the growth of solar manufacturing start-ups. Companies such as Oxford PV (Oxford University) and Nexwafe (Fraunhofer Institute) are spin offs from research institutes. Apart from industrial investors, government-aligned investment entities have provided early-stage equity to these companies. Equity investments from government sources are crucial for renewable energy manufacturing start-ups as their products have significantly longer gestation periods than consumer or technology start-ups, making traditional investor capital difficult to access. This is particularly relevant for India.

We recommend that the MNRE create an independently managed investment fund that focuses on start-ups working with next-generation renewable energy manufacturing technologies. The Government of India should be the fund's anchor investor. The fund can tap into domestic and foreign investors' growing interest in climate technologies. The Bill Gates–backed Breakthrough Energy Ventures fund has raised USD 2 billion (INR 15,000 crore) from multiple global investors since 2016 and provides funds to start-ups working exclusively on breakthrough climate change mitigation technologies (Rathi 2021). The first Indian climate-tech focused fund, *NFC Ventures*, was launched in 2021 with a USD 100 million (INR 750 crore) target for its first fundraising round (Paul 2021). Both examples illustrate the rapid rise in investor flows towards climate tech. The fund should also seek investments from development finance entities, such as the World Bank, International Finance Corporation, the German Corporation for International Cooperation, the United States Development Finance Corporation, the UK's CDC Group, and the Dutch Rabobank. In addition to investments, the fund can also explore the option of loans or loan guarantees to start-ups to lower portfolio risk.



India's solar technology roadmap must connect laboratory research with investor funding and on-ground implementation to succeed

(v) Provide demand security through a mandate to use next-generation modules for at least five per cent of awarded capacity in government solar tenders

New technologies require assured demand to compete with existing low-cost products and to rapidly move laboratory concepts to the market. If India does not provide a market for new technologies developed under the technology roadmap, we may again find ourselves (in 3–5 years) lagging a global production shift in the solar industry.

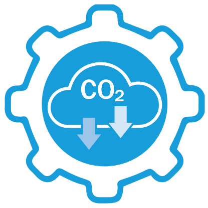
We recommend that solar tenders by all government entities mandate that at least five per cent of annual module installations come from high-efficiency modules developed under the technology roadmap. Tendering agencies must stipulate that all steps starting from wafer manufacturing must be performed in India for the module to qualify. As discussed earlier, authorities must also update the qualification criteria in line with the evolving targets in the technology roadmap.

Rather than conducting one-off exclusive tenders to meet the five per cent target, tendering agencies should mandate that manufacturers integrate a certain percentage of high-efficiency modules in multiple tenders over the year. This will allow better utilisation of manufacturing lines and improve demand visibility. Tendering agencies should leverage specialist tenders to create demand for novel use cases, such as building-integrated photovoltaics.

6.2 Strategically approach export demand creation

The BCD and ALMM provide strong protections to domestic manufacturers. However, manufacturers will enjoy no such protections in the global market where they must compete with high-efficiency, low-cost Chinese modules. In this section, we recommend strategic measures to help domestic manufacturers gain a foothold in foreign markets. These measures can also help Indian government further its foreign policy goals.

(i) Target the growing market for products with low manufacturing carbon footprints



Low-carbon manufacturing can become a positive differentiator for Indian modules if manufacturers receive renewable energy through open access

We recommend that the MNRE, MEA, and state electricity regulators implement this initiative from 2022–23.

France and South Korea have introduced regulations limiting carbon emissions produced through module manufacturing (Bellini 2019). The European Union has also discussed the possibility of regulating module carbon footprints (Hall 2021). Chinese solar modules can be a key target of such measures due to their reliance on coal-fired power for polysilicon and ingot production.

India can gain an advantage over Chinese competition in global markets if new manufacturing capacity uses renewable energy to minimise the manufacturing carbon footprints. India's state electricity regulators must ensure that upcoming manufacturing capacity has access to open-access renewable energy so that they can derive most of their power requirements from renewable energy. Open access power is cheaper than industrial power bought from utilities in many states (CEEW-CEF 2022). Therefore, states can benefit from providing approval for open access as manufacturers would set up facilities in the state to cut power costs.

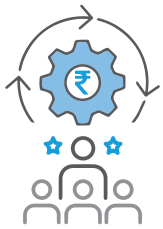
Simultaneously, the Indian government must aggressively secure trade deals with nations that prioritise low-carbon manufacturing. A trade deal built around low-carbon manufacturing would also be a strong indicator to the Indian industry to decarbonise. As countries have only recently started signing agreements and introducing regulations mandating low-carbon products, this is the right time for India to strike bilateral and multilateral trade details with potential partners. However, it is important to note that other nations, particularly China, have moved aggressively to close wide-ranging trade deals. India must act urgently to fully utilise this new opportunity.

(ii) Support projects in developing countries through the Export–Import Bank of India (Exim Bank)

We recommend that the MNRE, MEA, and the Exim Bank of India implement this initiative with a rolling timeline.

Through the International Solar Alliance (ISA), India has already taken a leadership position in promoting solar energy in developing countries. As a next step, India can secure an export market for its solar manufacturers by financing solar projects in ISA member countries through the Export Import Bank of India. In 2021, American thin film manufacturer, First Solar, signed an export contract in Guatemala secured by a financing guarantee from the US Exim Bank (Exim Bank US 2021). Chinese companies have used similar routes (Construction Review Online 2021).

Financing from the Exim Bank of India should align with existing initiatives under the ISA, such as improving African nations' access to finance for solar projects. In addition to furthering the goals of the ISA, Exim Bank financing can mandate the use of Indian manufactured modules for solar projects. Apart from low-cost loans, India can also provide exporter credit insurance to Indian manufacturers through the Export Credit Guarantee Corporation of India. Both routes would reduce risk for Indian manufacturers and foreign project developers, making domestic products cost-competitive with modules manufactured elsewhere. It is important to note that Chinese financing authorities have a significant presence in funding energy projects in developing countries and will compete with Indian banks. The Exim Bank has financed solar projects abroad and has the required expertise for this initiative (India Exim Bank 2021). India now needs to leverage these advantages aggressively and strategically partner with nations in the ISA to secure a rich pipeline of foreign projects for Indian manufacturers.



With the BCD, PLI, and ALMM in place, policymakers should provide financing and infrastructure support to help set up factories

(iii) Reassess the impact of protectionist measures

We recommend that the MNRE implement this initiative on a rolling timeline basis.

The BCD and ALMM provide domestic manufacturers with the required protection from low-cost imports. However, the MNRE must also consider whether these measures can impediment India's ambitious renewable energy deployment goals. The latest version of the ALMM contains 10.9 GW of module capacity and applies to government tenders, open-access projects, and net-metering projects. The current list effectively caps annual solar installations at 10.9 GW, which is significantly lower than the pace required to meet India's 2030 goal of 280–300 GW of solar capacity. We recommend that the MNRE actively engage with foreign module manufacturers, particularly those interested in setting up Indian factories, to include them in the list. This will augment supply for Indian solar developers while domestic manufacturers remain protected by the BCD.

India must also consider the impact of protectionist measures on its global trade ambitions. The net-zero targets of various nations ensure the availability of a large-scale export market. However, punitive tariffs and entry restrictions can limit India's ability to negotiate trade deals and promote Indian solar modules in the global market. Manufacturers in other nations may lobby against such deals. During such trade negotiations, India must consider expanding the ALMM list and introducing bilateral duty exemptions to further its export ambitions.

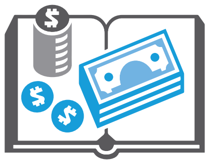
6.3 Support manufacturers in setting up and scaling up upcoming factories

The PLI, BCD, and ALMM have created a conducive policy landscape for Indian manufacturers to scale up their operations rapidly. In this section, we have listed three additional steps that regulators can take to support Indian manufacturers in setting and scaling up their factories – supporting fundraising, identifying manufacturing clusters, and providing long-term clarity on BCD to be imposed across all manufacturing stages.

(i) Raise share of manufacturing loans to 20 per cent of Indian Renewable Development Agency's (IREDA) loan book

We recommend that IREDA implement this initiative from 2022–26.

As discussed in Section 4.1, Indian solar manufacturers will require over USD 7.2 billion (INR 53,773 crore) by 2025 in capex funding to execute planned expansions of solar manufacturing capacity. This amount is likely to increase further when we consider machinery and BOM. As of March 2021, lending to the RE (solar and wind) manufacturing sector made up less than 4 per cent of IREDA's loan book. IREDA plans to raise its loan book from USD 3.7 billion (INR 28,000 crore) in March 2021 to USD 18 billion (INR 1.35 lakh crore) by March 2026 (IREDA 2021c). We recommend that IREDA raises the share of RE manufacturing in its loan book to at least 20 per cent in this period. This would translate to USD 3.5 billion (INR 25,900 crore) of debt funding for the RE manufacturing sector over the next five years.



Allocating 20% of IREDA's new loan book to solar manufacturing can unlock USD 3.5 billion in debt capital by FY 2026

IREDA has significant experience in raising funding from diverse sources at low interest rates, such as domestic and international bond markets and international development finance institutions. IREDA should leverage such sources to provide a portion of its capital allocation for manufacturing at concessional rates. Both IREDA and manufacturers must also explore new sources of climate-aligned capital. These includes avenues such as green bonds and capital from net-zero committed investors and lenders. Globally, corporate players have raised green bonds to support transitions, for e.g., Volkswagen and Daimler raised EUR 3 billion (INR 26,100 crore) in 2020 through green bonds to finance electric vehicle manufacturing, while Swedish solar manufacturer Midsummer issued green bonds in 2019 to finance its operations (Pronina 2020; Rocha and Cohen 2020; Midsummer 2019).[14]

(ii) State government support through low-cost manufacturing hubs

We recommend that state industrial development corporations and industry ministries implement this initiative over 2022–23.

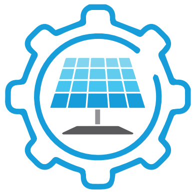
Manufacturing hubs concentrate manufacturers and suppliers in the same location, driving cost reduction and innovation. Infrastructure on these lines was set up in China (Pearl River Delta) and Malaysia (Kulim and Penang) for solar. In India, similar manufacturing hubs have provided significant benefits for the automobile manufacturing industry.

State governments can attract investments from solar manufacturers and their suppliers by developing manufacturing hubs. Given the scale of anticipated investment, multiple states have an opportunity to attract manufacturers and create multi-gigawatt scale hubs. We suggest that state governments develop manufacturing hubs through the following steps:

- Provide deemed approval of open-access renewable energy and remove net metering limits.
- Identify suitably sized land parcels with low leasing rates and road, port, and air connectivity.
- Provide a single-window clearance mechanism.
- Include solar manufacturing as a thrust/priority sector in their respective industrial policies.
- Support the labour requirements of manufacturers through skill-training initiatives and by building residential facilities in surrounding areas, particularly in underdeveloped regions.

14. EUR-INR conversion at EUR 1 = INR 87, based on average EUR-INR exchange rate in 2021 (data from Financial Benchmarks India Limited).

Further, as state-owned utilities account for the bulk of power procurement and distribution in the country, they can explore long-term tie-ups with developers and manufacturers located in the state to secure solar module supplies at potentially favourable costs. States can also anchor manufacturing hub development to large-scale upcoming solar parks.



Announcing a tapering BCD structure for cells and modules till 2030 will provide long-term visibility to manufacturers and encourage competitiveness

(iii) Impose BCD on polysilicon and wafer imports from 2027, start tapering BCD on cells and modules from 2025

We recommend that the MNRE implement this initiative (implementation timeline detailed below).

As per the submissions to the PLI scheme, India could add 16 GW of polysilicon and 29 GW of wafer manufacturing capacity by 2024–25. Until then, India is unlikely to have any significant polysilicon or wafer capacity, making domestic cell manufacturing reliant on imports. Further, these facilities will be the Indian industry's first experience with polysilicon and wafer manufacturing. The industry must gain experiential knowledge of how to optimise production processes before scaling up capacity and freezing costs. Therefore, we recommend that the MNRE impose a BCD or safeguard duty on polysilicon and wafer imports from 2026–27 onwards. Once India has set up and run its initial polysilicon and wafer factories, the MNRE must explore the option of a tapered BCD to scale-up manufacturing of these two stages rapidly.

Additionally, the MNRE has imposed a 25 per cent BCD on cells and a 40 per cent BCD on modules, effective from April 2022. We recommend that the MNRE detail the tapering plan for BCD to avoid the uncertainty that surrounds BCD imposition. This will allow both manufacturers and developers to plan their capacity development. We recommend a tapered plan (Table 5) to bring down the BCD on cells and modules to nil by 2030. The proposed structure allows for an overlap period from 2027 to 2030, wherein BCD will be applicable on all stages of solar manufacturing. This will help cell and module manufacturers remain competitive while domestic polysilicon and wafer manufacturing scale up to meet the required demand. Without a tapering plan, the case for investing in research and technology will be severely weakened.

Table 5 Recommended tapering plan for BCD on solar cells and modules

Timelines	BCD on cells	BCD on modules
April 2022 to March 2025	25%	40%
April 2025 to March 2028	20%	30%
April 2028 to March 2030	10%	20%
Beyond April 2030	Nil	Nil

Source: CEEW-CEF analysis

7. Conclusion

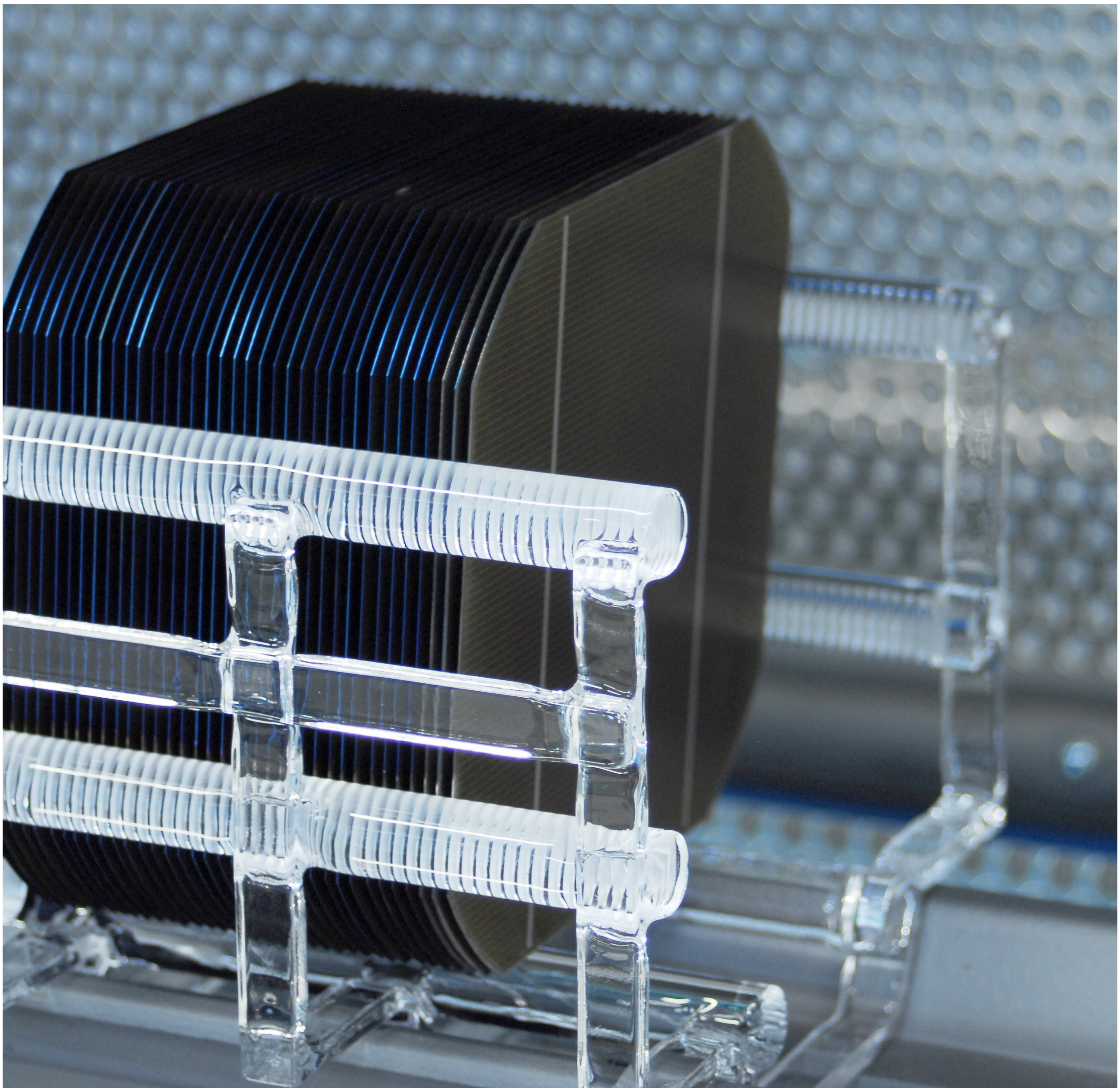


Image: iStock

While Indian cell manufacturing has lagged global leaders, there remains significant headroom to scale up and build a robust solar manufacturing ecosystem. The MNRE's recent efforts, such as the PLI scheme and BCD imposition, have brought much-needed clarity and momentum to the sector. Manufacturing capacity across all stages is likely to grow significantly in India over the next three years. However, it is important to note that leading Chinese solar manufacturers have also planned large-scale capacity expansions that dwarf India's potential growth. While the BCD and ALMM grant sufficient protection to Indian products, policymakers and manufacturers must focus on new technologies, novel demand creation, and realising scale to ensure competitiveness in the long term.

The government must work with manufacturers and academia to shift the industry towards outcome-oriented research and development. China's capacity to transform new innovations into market-ready products has driven the growth of Chinese solar manufacturing and the simultaneous decline of American manufacturing. India must learn from this experience and ensure that solar research and development covers all stages, from conceptualisation to mass deployment of new technologies. Ministries must shift their approach to R&D and ensure greater collaboration and involvement from key stakeholders. Further, India must leverage its foreign policy networks, such as the International Solar Alliance, to service solar demand in developing nations using Indian modules. Simultaneously, India should aggressively target the growing market for low-carbon products in developed nations. Both central and state governments can further support upcoming capacity through access to debt capital, manufacturing clusters, and long-term visibility on duties.

India's success in combining near-term policy measures with a long-term strategy focusing on technology leadership, novel demand creation, and scaling domestic factories will determine the trajectory of the solar manufacturing sector in the country.

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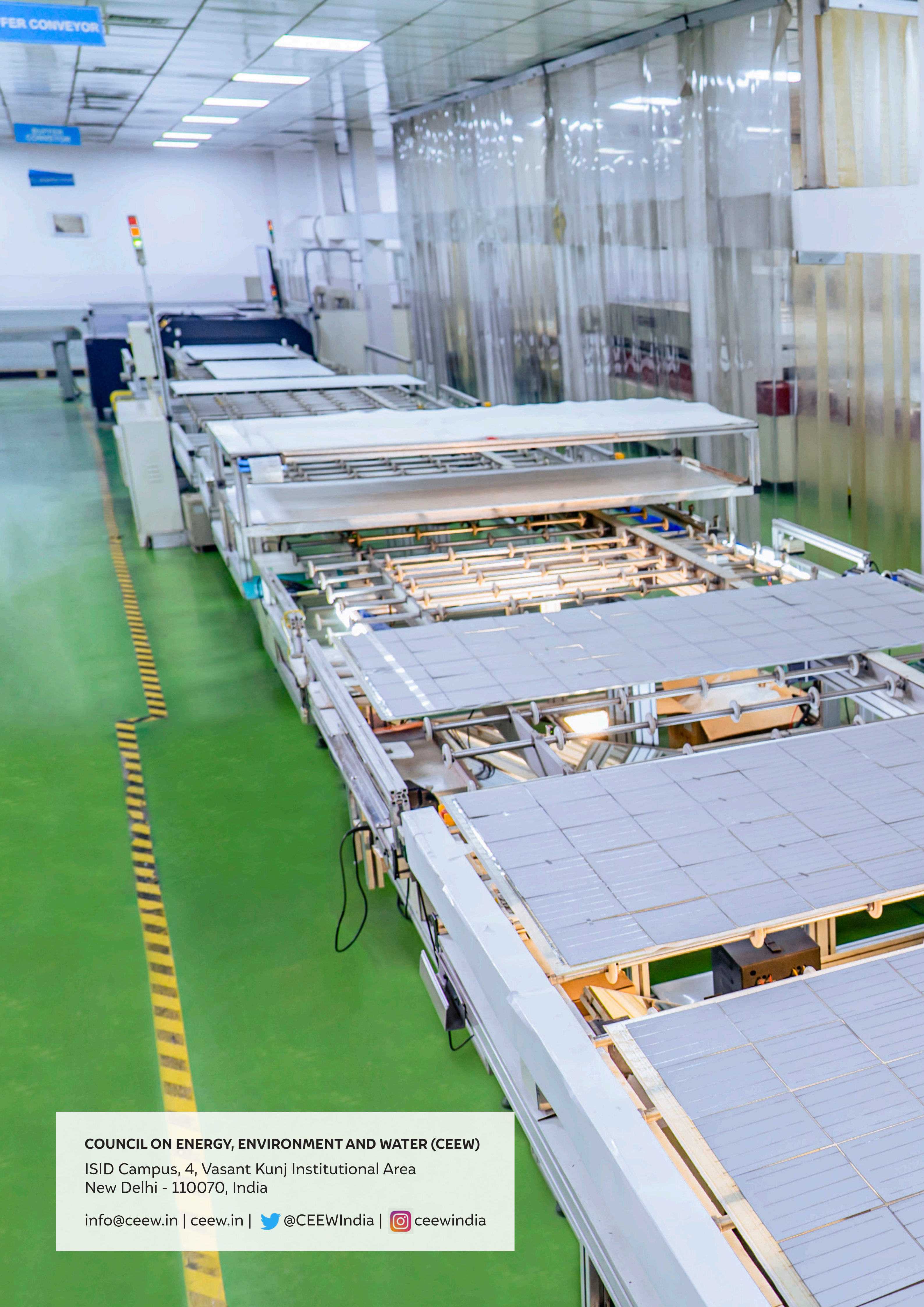
Firsteva

To develop a sustainable solar manufacturing sector, India must focus on technology development and implementation.

Image: Waaree Energies Ltd.



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