Figure 4 The solar manufacturing process

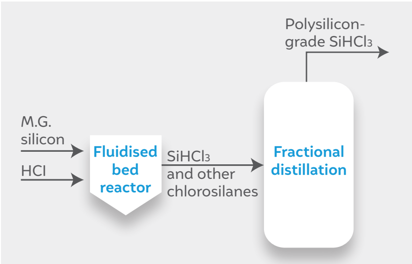
Raw materials for the process step | Raw material cost | Machinery cost | Utilities cost | Labour and maintenance cost

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

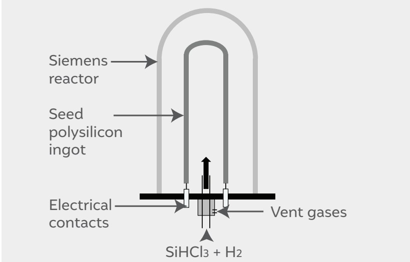
1 Trichlorosilane production from metallurgical grade silicon (MG silicon)



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

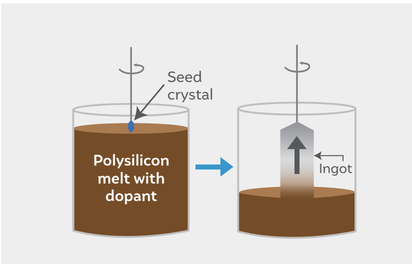
-

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

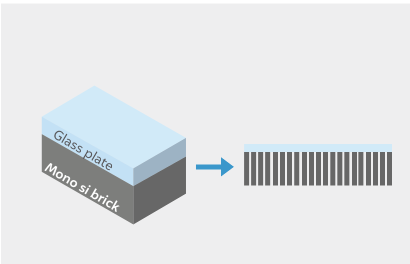
1 Ingot formation through the Czochralski process



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.

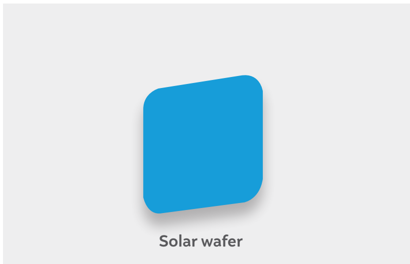
2 Diamond wire wafer slicing



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

-

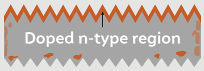
Wafers are inspected for defects before processing.

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 ($POCl_3$)

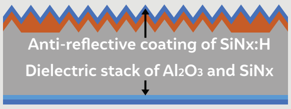
The front side of the wafer (called the emitter) is doped with an n-type dopant. A tray loaded with wafers is moved laterally through a diffusion tube that also contains the dopant gas. Phosphorous diffuses into the wafer's front side and small quantities of phosphorous are also deposited on other edges.

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

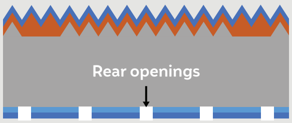


Trimethyl aluminium (TMA - $Al(CH_3)_3$), silane (SiH_4), ammonia (NH_3), and inert gases

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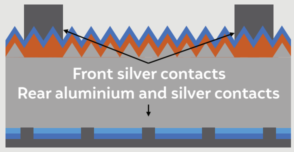
A laser tool is used to open spaces in the dielectric stack on the rear side to allow contact between the silicon wafer and metal contacts on the rear side.

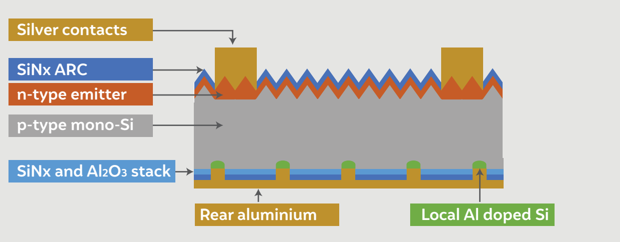
7 Screen printing silver and aluminium pastes



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

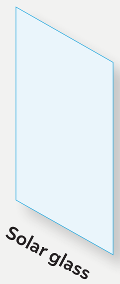
-

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

STAGE 4

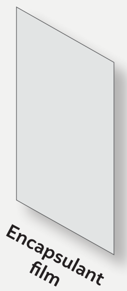
Cell → Module

1 Glass loading and laydown of the first EVA sheet



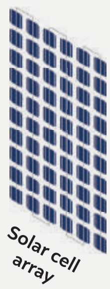
Glass, encapsulant (typically EVA – ethylene vinyl acetate)

2 Cell loading, tabbing, stringing, and soldering to front and back silver contacts



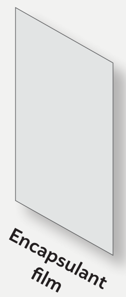
Tabbing and stringing ribbons

3 Placement of cell strings, soldering connector ribbons, laydown of the second EVA and backsheet



Backsheet, encapsulant, ribbons

4 Visual inspection and electro-luminescence testing, lamination



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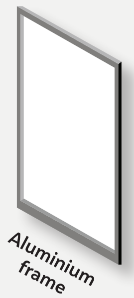
5 Edge trimming, aluminium frame, and silicone sealant

Aluminium frame, seal

6 Solder string connector leads in junction box and final assembly



Junction box, potting agent

7 I-V test, inspection, packaging

-

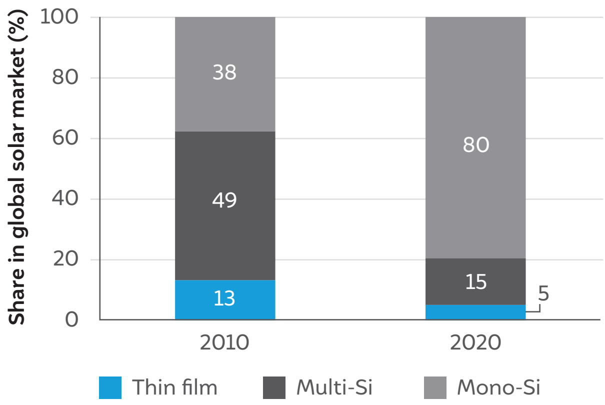
The module creation stage is an assembly process. The encapsulant layer is first laid over the glass sheet. Cells are connected into strings with metallic ribbons and mounted on the encapsulant. The second encapsulant sheet is then laid on top of the cell array. The backsheet is laid over the encapsulant 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.

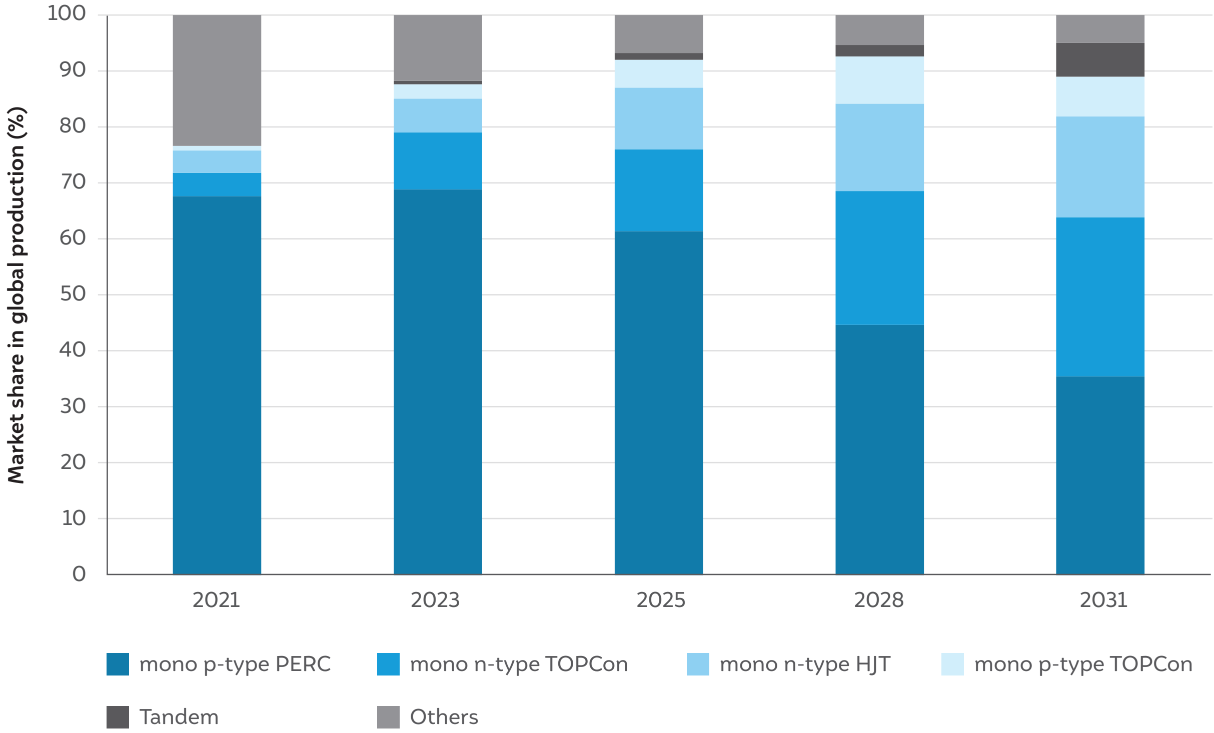
Indian solar manufacturing is dominated by multi-Si and has lagged in adopting mono-Si wafers. In 2019, 87 per cent of the modules produced by the top seven manufacturers in India were made of multi-Si wafers (Garg et al. 2021). Indian manufacturing lines are also aligned to smaller wafer sizes (156–158 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.

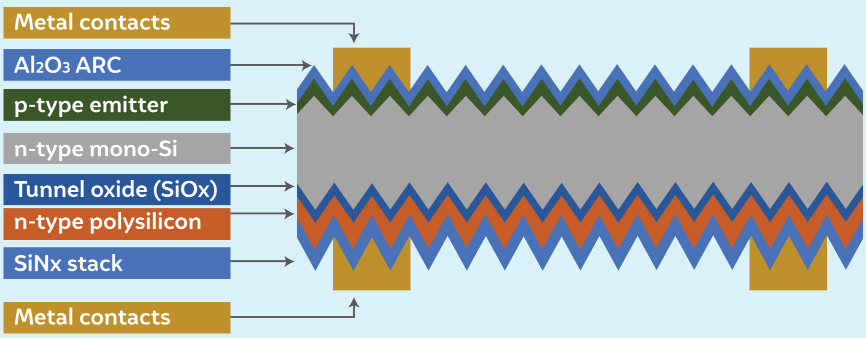
8. Others includes mono-Si n-type PERC, cells based on multi-Si wafers, cells without rear side passivation, and interdigitated back contact cells (cells with both metal contacts on the rear side).

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.

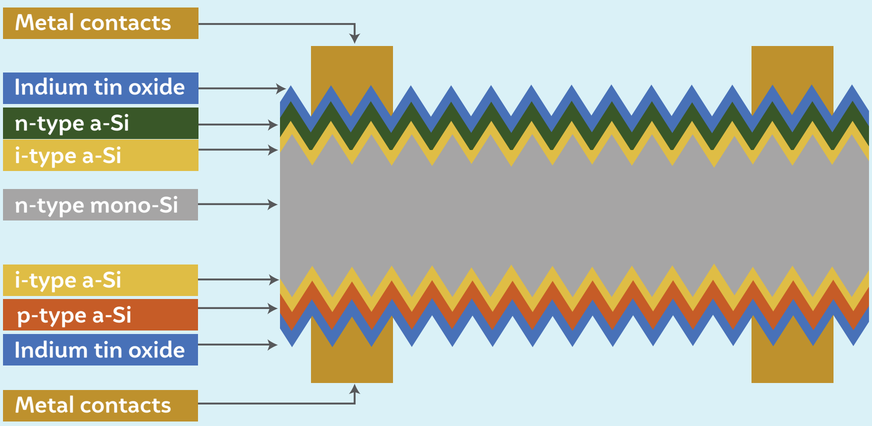
Figure 7 TOPCon solar cell structure



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)

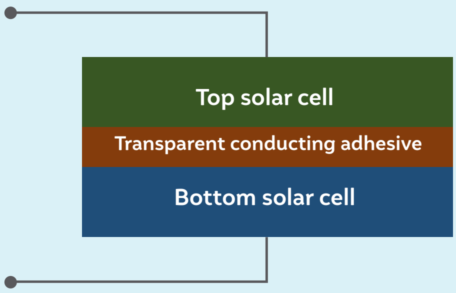
While HJT technology has existed since the 1990s, it has not yet gained significant market share. Recent advances in commercialising production have made HJT a high-efficiency alternative to PERC. Leading Chinese and European manufacturers have announced that they are setting up HJT production lines,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

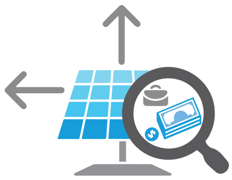
Source: CEEW-CEF compilation

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.

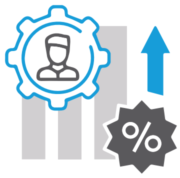
9. USD-INR conversion at USD 1 = INR 75, based on average USD-INR exchange rate in 2021 (data from Financial Benchmarks India Limited).

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.

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.

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

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