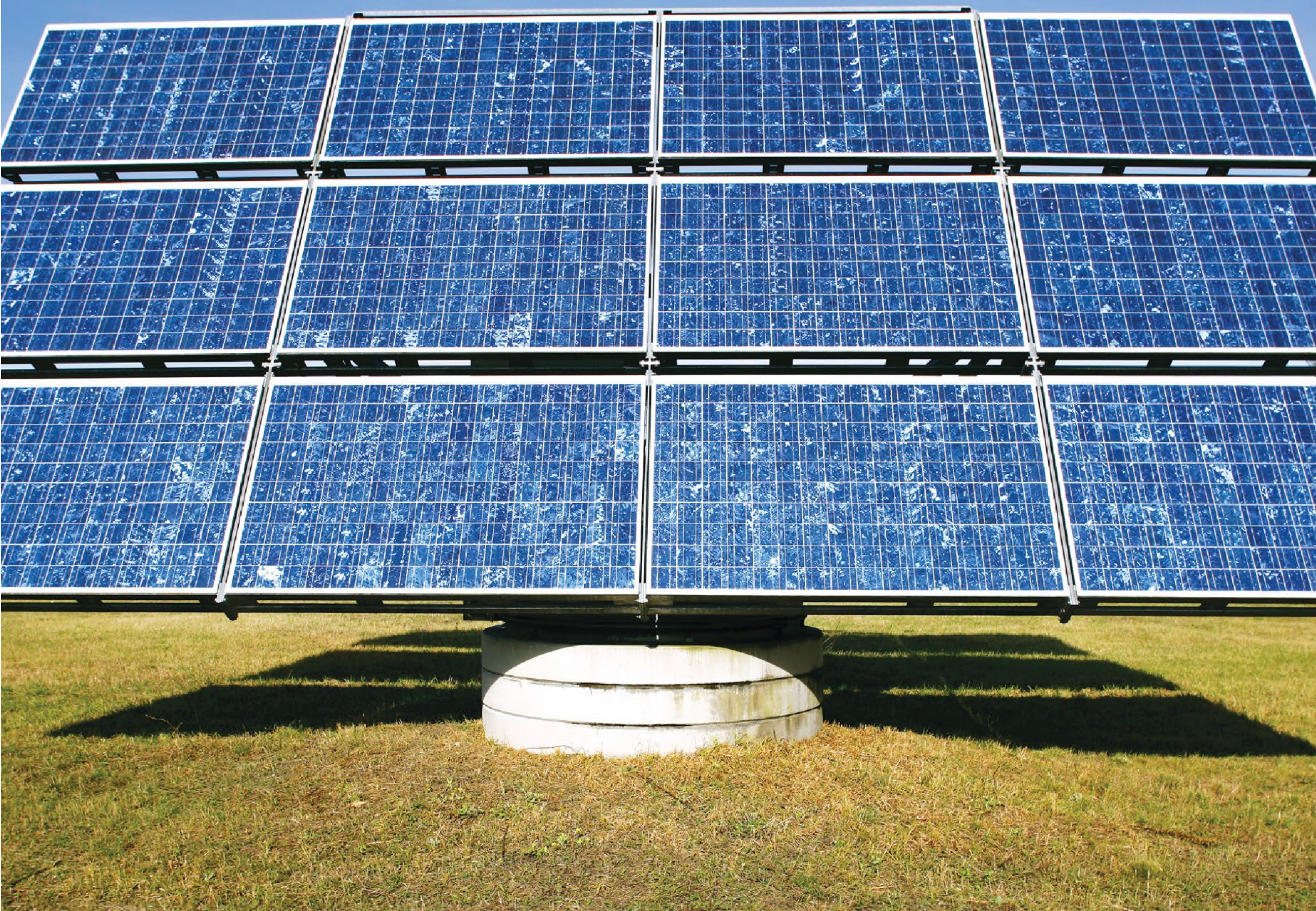
CENTER FOR STUDY OF SCIENCE, TECHNOLOGY & POLICY

Viewing India's Net-Zero Ambition Through the Lens of Polysilicon



Viewing India's Net-Zero Ambition Through the Lens of Polysilicon

Center for Study of Science, Technology and Policy
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Disclaimer

Contributors: Sweta Bhushan, Vidisha K, Kaveri Ashok, and Ramya Natarajan

(The author list provided assumes no particular order as every individual contributed to the successful execution of the project.)

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Center for Study of Science, Technology and Policy

Bengaluru

18, 10th Cross, Mayura Street
Papanna Layout, Nagashettyhalli, RMV II Stage,
Bengaluru-560094, Karnataka (India)

Noida
Smartworks Corporate Park
1st Floor, Tower-A, Sector 125,
Noida-201303, Uttar Pradesh (India)

Tel.: +91 (80) 6690 2500
Email: cpe@cstep.in

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Contents

1. Introduction

As India dons the role of a solar superpower, a crucial hurdle in the country's journey to self-reliance in this sector is the availability of the key raw material—polysilicon. It is a semiconductor that helps convert photons to electricity, thereby forming the brick of solar cells. The production of polysilicon—an energy-intensive material—requires copious amounts of high-quality silicon. While silicon is abundantly found in India and the rest of the world, competition for the mineral is extremely high (International Energy Agency [IEA], 2023). This is due to its wide range of applications, such as in electronics, semiconductor, and glass industries. The recent Ministry of Mines report on critical materials lists silicon as a highly critical mineral (Ministry of Mines, 2023). This sought-after mineral when coupled with high-purity requirements for polysilicon manufacturing makes polysilicon a very critical material for solar energy transition.

India is fourth largest solar power generator globally, with an installed capacity of 67 GW and a target of 280 GW by 2030 (Joshi, 2023; Press Information Bureau [PIB], 2023). India's solar capacity has witnessed a compounded annual growth rate of 41.39% between 2016 and 2022 (Desk, 2023). Furthermore, annual capacity additions are expected to increase to 75–100 GW/year in the coming decades to steer the country towards net-zero emissions (Das et al., 2023). However, although various schemes have been launched to foster domestic solar photovoltaic (PV) manufacturing, the current domestic PV manufacturing capacity stands at only 38 GW/year (Ministry of New and Renewable Energy [MNRE], 2023).

Because of this nascent stage of domestic PV manufacturing in India, the demand for polysilicon has been negligible. In addition, factors such as high capital and operational costs of polysilicon factories and low clarity on raw material access/quality act as barriers to domestic polysilicon manufacturing. Therefore, India is currently dependent on polysilicon (and solar cells/panels) imports, mainly from China. In 2022, China produced 89% of the world's polysilicon (Bellini, 2023). Furthermore, polysilicon manufacturers in China are increasing their production capacities, which may lead to an addition of 1.5 million tonnes of polysilicon in the next 2 years (Saurs News Bureau, 2023). Because the availability of polysilicon from China is plentiful and prices are cheaper, the financial and practical advantage of domestic polysilicon manufacturing remains challenging. However, as we equip ourselves to build a larger solar capacity over the coming decades, domestic manufacturing of modules and polysilicon will increasingly become a determining factor for the resilience and sustainability of power systems in India. Domestic polysilicon manufacturing will augment this journey by increasing self-reliance, bettering cell efficiency, localising supply chains, and lowering costs in the long term.

By centring on the causal loop diagram (Figure 1), this technical note discusses pertinent points regarding domestic polysilicon manufacturing and levers that promote and may derail it. The causal loop diagram in Figure 1 shows the variables affecting polysilicon demand and supply, both globally and within India.

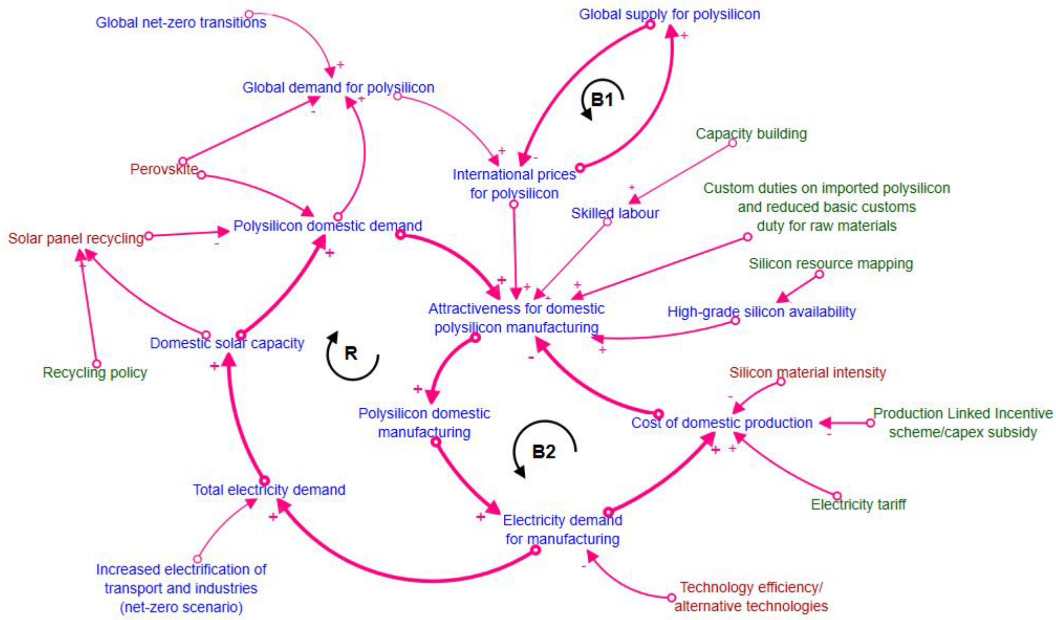

Figure 1: Causal loop diagram showing enablers and disrupters for domestic polysilicon manufacturing ('+' = positive correlation between the connected variables; '–' = inverse correlation between the connected variables; variables in green = policy interventions; variables in red = technological interventions; 'B1' = balancing loop 1; 'B2' = balancing loop 2; and 'R' = reinforcing loop)

The dynamics of domestic polysilicon manufacturing are driven by two key balancing loops (B1 and B2) and one reinforcing loop (R), as detailed below.

- **R:** An increase in domestic solar capacity (solar GW)—driven by an increase in overall electricity demand (in pursuit of electrification), particularly in a net-zero scenario—will drive upward the demand for polysilicon, thereby making domestic polysilicon manufacturing attractive. Domestic polysilicon manufacturing, in turn, would increase the demand for electricity, further driving up the total electricity demand. This reinforcing loop, in silos, resembles an unstable system—an infinite loop of increased demand for polysilicon, electricity, and solar capacity. However, each of these variables is also influenced by other factors, policies, and balancing loops.
- **B1:** Increased international polysilicon prices (driven by higher demand than supply) will lead to an increase in global polysilicon supply to meet the demand and stabilise the prices. However, with the increase in the global polysilicon supply, international prices for polysilicon will eventually reduce. This balancing loop represents market dynamics for polysilicon.
- **B2:** Increased attractiveness for polysilicon manufacturing will increase domestic manufacturing of the material, thereby pushing the electricity demand. This would then directly impact the cost of domestic production, decreasing the attractiveness of domestic polysilicon manufacturing. This balancing loop signifies an ultimate deceleration in the attractiveness of domestic polysilicon manufacturing due to the high cost of domestic production.

2. Polysilicon Demands in a Net-Zero Scenario

Growth in solar power would be primarily driven by the demand for clean electricity in the coming decades. To understand the scale of growth needed, we used the Sustainable Alternative Futures for India (SAFARI) model to simulate a few net-zero scenarios with increased electrification across sectors and an increased uptake of solar power to meet the electricity demand. In these scenarios, the solar operating capacity reaches over 3,000 GW by 2070, requiring annual average capacity additions of around 50 GW/year in the 2030s and 2040s and 100 GW/year in the 2050s and 2060s. This would lead to an annual average polysilicon demand of 150–300 kilo tonnes. Between now and 2070, the cumulative polysilicon demand for a net-zero scenario could be over 10 million tonnes. Furthermore, domestic polysilicon manufacturing (including mining, refining, purification, and ingot casting and slicing) would translate to an annual average electricity demand of 30–85 GWh in the coming decades.

These demands across the value chain would be influenced by the policy landscape and other enablers and disrupters as described below.

2.1. Domestic Solar Capacity

The Indian government has initiated several schemes to encourage domestic production of PV cells and modules. For example, a basic customs duty (BCD) of 25% and 40% on imported PV cells and panels, respectively, was operationalised in 2022, and the Production Linked Incentive (PLI) scheme was implemented in 2021 to incentivise the setting up of large-capacity plants focusing on full-value chain of efficient solar modules (PIB, 2022a). Furthermore, in 2019, the Ministry of New and Renewable Energy (MNRE) mandated the enlistment of PV module manufacturers complying with the Bureau of Indian Standards in the Approved List of Module Manufacturers—a move to identify the source material and encourage quality control. This list has grown from a mere 23 manufacturers with 8,200-MW capacity to 91 manufacturers with 22,000-MW capacity in 2023 (Solarclap, 2022). However, the list has been put on hold in the financial year (FY) 23 until FY 24.

These policies aim to decrease the reliance on imports and address the challenges posed by global supply chain disruptions, thereby making India self-sufficient in solar PV manufacturing. While these policies may reduce a part of the capital expenditures of polysilicon factories, a significant part (around 42%) of plant costs are dominated by energy and maintenance (Verma et al., 2016). When coupled with high industrial energy tariffs, this may lead to very high operational costs. Therefore, policies must adapt to the challenges of the upstream solar value chain to make it feasible for domestic polysilicon manufacturers.

2.2. Domestic Polysilicon Demand

As described earlier, over 10 million tonnes of polysilicon could be needed for India's transition to net-zero emissions. Considering such high requirements, the volatility in international polysilicon prices, and India's goal of self-reliance, it is desirable to take the route of domestic manufacturing particularly because India has ample amounts of quartz and quartzite—ores required to process high-grade silicon (the quality of these ores are yet to be explored). It could be helpful in strategically positioning India as an exporter of polysilicon or solar modules. However, two factors that determine the demand are the shift to non-silicon-based solar cells, such as perovskite, and efficient solar panel recycling.

2.2.1. Major shift in cell technology

Innovations in cell construction, such as perovskite cells, may or may not reduce dependency on domestic polysilicon demand, based on how they are designed when commercially viable. Traditionally, perovskite cells are not made of silicon, and if dissipated in the market, will reduce domestic polysilicon demand. This will lead to a scenario of controlled demand, which will probably be beneficial for the polysilicon industry because rampant increases in production capacities will not be required. However, current research indicates that using them in conjunction with silicon wafers can provide cell efficiency of up to 30%, which is more than what can be achieved through traditional silicon or perovskite cells (Roy, 2023). Research on perovskite cells continue to unfold new combinations. However, in the possibility of using perovskite cells in tandem with silicon wafers, the need for polysilicon would be sustained, demanding factories to increase their capacities. This implies that the shift in cell technology will nevertheless be an enabler for domestic polysilicon manufacturing, wherein, the differentiation factor for either of the cases is the scale of production, which will dictate the extent of material use and subsequent emissions.

2.2.2. Solar PV waste recycling

Solar PV waste recycling will reduce the demand for domestic polysilicon manufacturing. However, because of the time required for recycling the existing stock, recycling solar waste does not omit the need for domestic manufacturing. In fact, it indirectly enables domestic manufacturing by reducing demand pressures on factories. According to a recent paper, India's PV waste in the business-as-usual scenario could amount to 6.64 and 5.48 million tonnes due to early and regular loss, respectively, by 2040; in the ambitious scenario of scaling PV, the estimated waste is much higher (Sharma et al., 2023). According to SAFARI, cumulative PV waste in 2050 is projected to be 12 million tonnes[1], assuming the lifecycle of solar panels to be 18–25 years. Avoiding the use of new raw materials and instead using recycled materials in solar PV production could reduce the environmental impact by up to 70% (Sharma et al., 2023). Recovering and reusing silicon wafers can reduce energy consumption by approximately 25% at the module level alone (Alsema & Scholten, 2006).

The waste generated from solar modules is still considered as general industrial scrap or e-waste. Currently, PV waste handling is within the scope of E-Waste Management Rules, 2022, which enforces module manufacturers and producers to store the PV waste until 2034–2035. However, mandating solar PV waste recycling remains pending. Advanced recycling methods can help India significantly reduce pressure on polysilicon manufacturing and energy demands, as recycling can help retain 95% of the material value chain (Solarcycle, n.d.). However, this is subject to the availability of ample panel stock in the system and innovation and development in recycling

[1] Assuming 3.125 million panels are needed to generate 1 GW of solar power (Greenwatch, n.d.)
Assuming the weight of each solar panel to be 18 kg (Allen, 2023)

technology. According to the National Research Energy Laboratory, recycling a solar panel can cost USD 20–30, whereas dumping it in a landfill will cost a mere USD 1–2 (Bhatti & Sharma, 2022).

To address these issues, the National Resource Efficiency Policy (NREP) has identified interventions, such as upscaling possibilities, easy financial options, and cost-effective solar panel recycling infrastructure (Ministry of Environment, Forest and Climate Change [MoEFCC], 2019). It emphasises the importance of setting up solar PV waste recycling facilities and has proposed targets of establishing four and eight major authorised dismantling facilities by 2025 and 2030, respectively—aiming for an 85% recovery rate of materials from discarded PV modules (MoEFCC, 2019).

India, thus, needs to not only implement policies and regulatory frameworks to promote and enforce PV recycling but should also look into making it financially viable to maximise the impact.

2.3. Attractiveness for Domestic Polysilicon Manufacturing

The increase in domestic polysilicon demand will most likely improve the attractiveness of domestic manufacturing. In addition, there are four factors that are likely to influence the attractiveness of domestic polysilicon manufacturing—international prices, availability of high-grade silicon, customs duty on imports, and the cost of domestic manufacturing.

2.3.1. International polysilicon prices

In 2021 and 2022, the average polysilicon price was USD 25.5/kg and USD 35.1/kg, respectively, with the price plummeting to USD 8.54/kg in 2023 (OPIS, 2023). According to the PV Price Watch, the price is expected to stabilise at USD 10–15/kg in 2023 (Jacobo, 2023). This drop in prices has been attributed to material oversupply and stock withholding by several Chinese manufacturers due to the lowering of prices (OPIS, 2023). This situation makes it evident that the polysilicon market is sensitive to price volatility due to supply–demand issues, implying that China's increased polysilicon production may be counterproductive for them, leading to losses. Because this situation is unfavourable in the long term for Chinese manufacturers, it is unlikely to last long with prices expected to rise again in a few quarters. As polysilicon from China is currently available in abundant quantities and at low prices, it poses a barrier for Indian players to venture into polysilicon manufacturing. On the flipside, the increased polysilicon prices from the United States and European manufacturers of USD 25.45/kg and USD 18/kg (as of September 2023), respectively, imply ground for fair competition for Indian counterparts (Mike, 2021).

2.3.2. Availability of high-grade silicon

Quartz and quartzite are predominantly present in the states of Andhra Pradesh, Rajasthan, and Gujarat. However, a major concern is the purity of the material, which affects processing, refining, electricity demands, and polysilicon quality. Because there has been no information on silicon minerals in the Indian Bureau of Mines (IBM) since 2015, it is even harder to understand the quality of ores present in India. Moreover, the desired purity of the mineral is unknown due to the lack of polysilicon manufacturing units in India. Policies to advance the resource mapping of silicon and silicon ores would be beneficial for locating the mineral and assessing its quality. However, in the situation wherein the desired quality of quartz or quartzite is unavailable in India, there is an opportunity to import the mineral and nurture polysilicon processing capabilities in India.

Silicon mineral status: Silicon is an extremely abundant mineral, which is used for a variety of specialised (electronics, solar PV, etc.) and generic (construction) applications. It was classified as a minor mineral in 2015 by IBM, which means that silicon resources are managed by the state governments. This also implies that information on reserves and trade regarding silicon is unavailable with the IBM central database after 2015. However, given its footprint in such a crucial transition technology, reclassifying silicon as a major mineral can help in more effective resource mapping, purity grading, and inventorying. Moreover, this will enable domestic manufacturers to consolidate the solar supply chain.

2.3.3. Custom duty on imported polysilicon

Waiving off the BCD on raw materials, such as high-quality quartz and metallurgical grade silicon, needed to manufacture polysilicon, as well as imposing a BCD on polysilicon, solar modules, and cells, can have a coupling effect and encourage domestic polysilicon manufacturing.

2.3.4. Cost of domestic production

The current cost of domestic polysilicon production stands at USD 10–20/kg ((Verma et al., 2016; Verma & Praveen, 2018). However, the market prices for polysilicon have been volatile with a steep downfall since February 2023; the prices dropped from a little above USD 30 to a hovering range around USD 10 since June 2023 (Bernreuter Research, 2023). Considering the current rates of polysilicon and assuming Indian factories will incur the lowest cost of production, domestic polysilicon manufacturing is just about viable, ensuring no profit or loss situation. However, considering that manufacturing set-up does not exist in India currently, a higher cost of production is likely. At the same time, owing to the wavering historical price trends of polysilicon, the prices may increase. This is to coincide with the time when domestic production is supposed to commence, making it profitable for the yet-to-emerge Indian polysilicon industry. Efforts to reduce domestic production costs through tariff reductions and subsidies for capital and operating expenditures would motivate local manufacturers while aiding business profitability. The three levers influencing the cost of domestic production are as follows:

- *Reduction in mineral intensity*: The mineral intensity of silicon for solar cells has gone down from 16 g/w in 2010 to 4 g/w in 2020 (Bernreuter Research, Polysilicon Market Reports, n.d.). Thus, driving down polysilicon demand for each solar panel (to a theoretical minimum) through innovation in cell technology can help in reaching production targets early on.
- *PLI scheme*: The primary objective of the PLI scheme is to push domestic manufacturing of high-efficiency solar PV modules and cells. The scheme accounts for stage-wise integration of manufacturing processes across the life cycle of PV modules, assigning maximum points for manufacturing polysilicon. Such policies can provide relief in the capital costs of the manufacturing plants. However, operational costs remain a concern, especially due to the high cost of electricity demand. Furthermore, similar schemes should enable access to efficient machinery and equipment of competitive standards that offer quality and allow scalability of products.
- *Electricity tariff*: The polysilicon manufacturing process is highly energy intensive, with only the Siemens[2] process being commercially viable. Therefore, factories would need to pay heavy electricity costs, making a polysilicon factory affordable to only top players with

[2] Polysilicon can be manufactured through two processes—the widely used Siemens process and the fluidised bed reactor (FBR) process. The energy consumption in the Siemens process is around 45–80 kWh/kg, whereas the FBR process consumes 4–16 kWh/kg (Alsema & Scholten, 2006). This implies that emissions from the FBR process are far lesser than the Siemens process, making it more cost-effective. While ample research has been conducted on the FBR process, several operational challenges limit its commercial use.

captive power plants. This limits access to newer or smaller players, who otherwise can help scale and meet the country's solar demands. However, technology shifts, incentives, and resource mapping (the purer the material, the lesser the energy spent on converting it to polysilicon and vice versa) can address this disadvantage. Reducing electricity costs through subsidies or support for captive power plants can help reduce energy demands. The development of less energy-intensive processes for scaling polysilicon manufacturing can smoothen India's solar journey by reducing electricity demand for manufacturing. Furthermore, automated machinery has aided China's high-capacity polysilicon factories. In India, improved and efficient machinery, if not automatic, can be an enabler for scaling and delivering quality output. A Norway-based polysilicon manufacturing company—REC Silicon—has been constantly updating its FBR technology to make it a commercial success, but the technology otherwise remains nascent. Incidentally, Reliance has acquired the REC group, which could imply that Reliance might go through the FBR route for manufacturing polysilicon in India.

2.3.5. Skilled labour

The availability of skilled labour in the solar industry remains a challenge for India. While this challenge is currently with respect to module manufacturing, domestic production of polysilicon, and subsequently cells, will demand very high-quality skills, widening the skilled labour gap of the solar industry. Until now, there has been no need for polysilicon; therefore, there is a negligible on-ground workforce with specific required skills. This will reduce the attractiveness of domestic manufacturing, not only from the viewpoint of manufacturers but also investors. On the flipside, large-scale capacity building will foster green jobs, increase attractiveness for domestic manufacturing, and aid in scaling production, ultimately expanding the solar industry.

Despite the challenges on the domestic front, such as high-energy manufacturing processes, purity of source material, high input energy tariffs, and high capital investment, some big companies, such as Adani Group and Reliance Industries Limited, are expected to begin polysilicon production in the upcoming years. However, the proposed plant capacities may not meet the annual demands, particularly for a net-zero scenario, underlining the importance of a mission and policies to enable ramping up production capacities while meeting the gap of skilled workforce for the industry.

3. Conclusion

Fostering a domestic polysilicon industry is a strategic investment for the following reasons:

- Solar power is expected to play a key role in achieving India's net-zero goal, with annual capacity additions of up to 100 GW leading to annual polysilicon demands of 150–300 kilo tonnes. Furthermore, by 2027, the global solar capacity (a cumulative capacity of 1500 GW) is estimated to surpass coal, making solar power the largest power source (Solar, n.d.). Because polysilicon demand is about to skyrocket, prices may shoot up in the coming years. The market may not continue to be in oversupply, which indicates that we must consolidate our value chain by relying less on imports.
- Over 29,000 people were employed in the solar industry in 2021–2022. Moreover, with an estimated capacity of 940 GW by 2050, 3.26 million cumulative jobs can be created. MNRE estimated that the PLI scheme would directly and indirectly employ 1,95,000 and 7,80,000 people, respectively, during the tenure of the scheme (PIB, 2022b). Thus, when combined with India's growth in solar energy, green jobs can pave the way for a sustainable economy.
- The expanding and unpredictable nature of trade restrictions presents a risk to the import of PV modules and, in turn, to the net-zero goal. India's goal to achieve *atma nirbharta* will prepare the country to compete in this landscape while also ensuring much-needed long-term energy security (PIB, 2020). The pursuit of the global green transition has fast-tracked technological advancement, which continues to give rise to solutions demanding substantial resources and minerals, furthering intense competition in the global supply market. Domestic manufacturing can also shield against short-lived price volatility—a historical trend in polysilicon prices. Moreover, it will help prevent the influx of low-quality imports.

Table 1: Summary of hindrances and enablers for domestic polysilicon manufacturing

Domestic Polysilicon Manufacturing	
Hindrances	**Enablers**
Continued international price decline	Silicon mineral status
	Alternative/efficient manufacturing technologies
	Innovation in perovskite cells
	Government policies and initiatives
	Capacity building

In conclusion, polysilicon is as critical as its core material—silicon—to India's solar journey. The case for domestic manufacturing is justified through the high number of enablers in this ecosystem. Although being 100% independent of imports is unlikely, domestic polysilicon manufacturing can not only reduce the price and protect the industry from international market volatility but also ensure a high-quality product. This could ultimately make India an exporter of polysilicon, catering to the fast-growing solar industry globally. However, unplanned expansion of manufacturing (as in industrial precedents, such as cement and steel) must be avoided for the following reasons:

- It will help avoid an unsustainable increase in energy demand (via the infinite reinforcing loop R), even if most of the demand would be met with renewable sources.
- It will prevent a situation of oversupply, which would drive down costs rapidly and damage the nascent stages of domestic polysilicon production.
- Manufacturing planning should be in tandem with the solar energy requirement for net zero, with constant monitoring of capacities.

Self-reliance in polysilicon, the production of high-quality cells, and a push for a green economy will be the major factors enabling India to become a solar superpower. Incentives for acquiring raw materials, manufacturing equipment, and machinery; focus on capacity building; and research and development in the solar industry will enable an ecosystem for domestic manufacturing. While there might be some reliance on the import of raw materials or semi-processed materials, self-reliance can still be achieved in processing and manufacturing PV equipment.

Furthermore, logistical support by the government and ease of business for the inception of polysilicon industries are crucial. Policies impacting different stages of the PV value chain can also ease domestic polysilicon manufacturing and promote export, strengthening India's position in the national and global net-zero journey. The sub-systems associated with the birth of a new industry are complicated. Therefore, policies that are required to achieve the goal of developing a new and competitive industry have to be holistic in nature. The cumulative impact of policies across these sectors can enable the inception of the polysilicon industry in India, which will be a game changer for the country's solar future.

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Bengaluru
#18-19, 10th Cross, Mayura Street,
Papanna Layout, Nagashettyhalli (RMV II Stage),
Bengaluru - 560094, Karnataka, India

Noida
1st Floor, Tower-A, Smartworks Corporate Park, Sector-125,
Noida - 201303, Uttar Pradesh, India

www.cstep.in
+91-8066902500
cpe@cstep.in
@cstep_India