RP Current Trends In Agriculture And Environmental Sciences
Vol. 2, No. 4 (October – December 2023) pp. 38–51
e-ISSN: 2583-6293

Cite this article: A. Kumar, Current trends in solar energy production in India, *RP Cur. Tr. Agri. Env. Sci.* **2** (2023) 38–51.

Original Research Article

Current trends in solar energy production in India

Arun Kumar*
Department of Physics, Government College, Bahadurgarh – 124507 (Jhajjar), Haryana, India
*Corresponding author, E-mail: arun250981@gmail.com

ARTICLE HISTORY
Received: 24 Aug. 2023
Revised: 3 Nov. 2023
Accepted: 4 Nov. 2023
Published online: 6 Nov. 2023

KEYWORDS
Solar energy production; Solar manufacturing; Photovoltaic cells and modules; Policy incentives; Economics of solar manufacturing.

ABSTRACT
Having installed over 50 GW of solar PV throughout the past ten years, India has been among the leading users of this technology. In addition, there has been a lot of interest since 2021 in establishing the nation's solar production chain, from polysilicon and wafers to cells and modules. Many companies have declared and started solar manufacturing as a result of numerous government regulations and incentives. An estimated 40 GW of modules would be produced in India by 2025, some of which will have either full or partial upstream integration. As a result, India would rank among the top two or three solar producers worldwide. The incentives offered and the companies' reactions to them are discussed in this paper. It also assesses India's manufacturing cost competitiveness by comparing nations and technologies, and it outlines and suggests the technology options accessible for Indian manufacturing. In order to assist and facilitate the development of a fully integrated contemporary solar manufacturing ecosystem in India, the document goes on to identify the requirements for ancillary manufacturing units, as well as for coordinated R&D and training. While this article primarily focuses on India, the potential and difficulties it raises could equally apply to other members of the International Solar Alliance (ISA).

1. Introduction

Over the past ten years, photovoltaic (PV) deployments have increased significantly: from roughly 10 GW in 2010 to over 750 GW by the end of 2020 (REN21 [1]), and 900 GW by the end of 2021 [2]. This has been made possible primarily by advances in technology and economies of scale in the photovoltaic manufacturing industry. Solar power has already surpassed other accessible electricity sources in several nations. During the November 2021 COP-26 in Glasgow, several nations declared their intention to attain net-zero energy and to utilize renewable energy sources to meet their targets. These promises will guarantee that solar PV installations continue throughout the upcoming ten years and beyond, until 2050. The total worldwide deployment will reach 3.4 TW by 2030 and almost 20 TW by 2050 [2]. Production of solar PV modules will need to take place in multiple nations in order to meet this enormous demand. Countries, including the United States, Taiwan, India, and various European nations, used to contribute to the global solar manufacturing industry during the 1990s and 2000s. This image began to shift in the 2010s as China and a few other Southeast Asian nations started to take the lead in numerous areas of solar manufacture.

The manufacturing of solar modules from 2010 to 2020 is depicted in Figure 1 [3]. While the manufacture of relatively basic modules is still spread, the production of silicon wafers and polysilicon is becoming concentrated in few sites. About 8 GW of modules were produced in India in 2019. Several nations have rekindled their interest in solar PV production in the previous several years, especially in 2021 and early 2022, as a result of their net-zero promises at COP-26 and to prevent supply chain problems in the future, which were made especially evident during the COVID-19 epidemic. Countries can enter the relatively high-technology "green" manufacturing sector by manufacturing solar panels. Since PV modules have become more affordable, shipping and transportation have added more to the overall cost of PV installations.

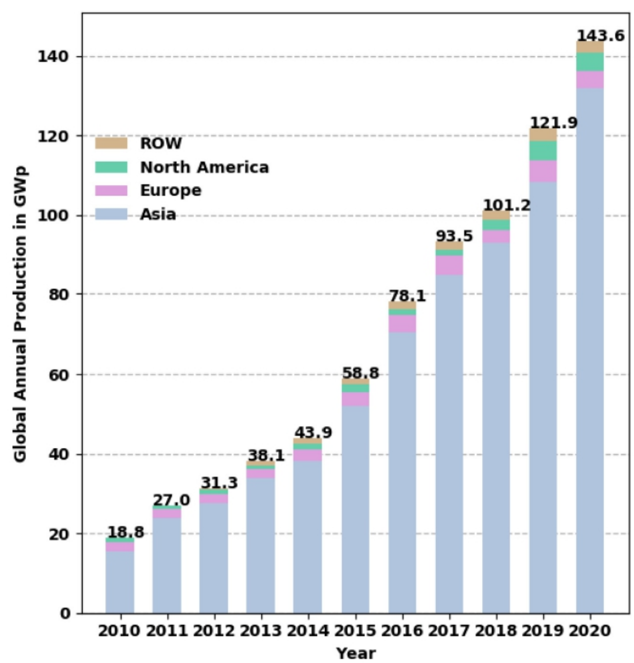

Figure 1: Annual production of PV modules worldwide from 2010 to 2020 [2].

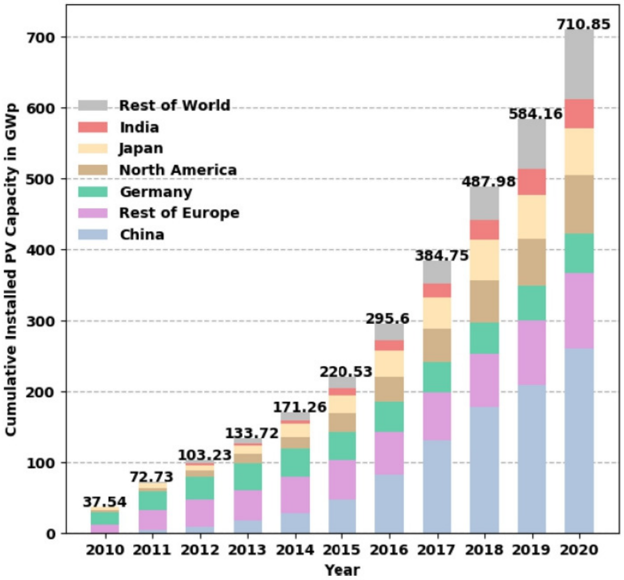

Figure 2: PV capacity installed globally cumulatively from 2010 to 2020 [2].

Another compelling reason for nations to support domestic solar manufacturing is energy security, which makes them less susceptible to changes and developments in the geopolitical sphere. This is so that a nation may avoid supply delays, disruptions, and reliance if the complete value chain is developed there. India is among the nations witnessing a significant surge in solar manufacturing. This essay explains the background, present state, and upcoming advancements that will significantly improve solar manufacturing in India in the near future. It outlines the government's policy decisions as well as the industry's reactions. Along with estimating the relative cost competitiveness of solar manufacturing in India in comparison to other nations, this article also evaluates which solar PV technologies are most appropriate for India and the relative costs of certain significant technology possibilities. It also discusses the necessity of maintaining R&D and creating an auxiliary ecosystem. This article focuses on India, but it also addresses opportunities and challenges that other members of the International Solar Alliance (ISA) may face.

2. Solar installations and manufacturing in India

Soon after the oil price surge in the late 1970s, solar manufacturing began in India. A public sector company called Central Electronics Limited started producing solar cells and modules in addition to installing solar systems. Early on in their existence, silicon solar cells were produced on circular wafers with diameters of two and three inches; in the middle of the 1980s, they switched to four inches [4]. Following this, a number of other businesses started producing solar cells in the 1990s. These included Tata BP Solar, a private joint venture that focused on the emerging terrestrial applications, and two public sector enterprises, BEL and BHEL, which also produced solar cells for space applications. In the 2000s, Websol, Moser Baer, and Indosolar were among the companies that joined Tata BP Solar in its expansion. Moser Baer possessed both (multi-)crystalline and amorphous silicon. India was one of the few nations in the world producing solar cells and modules at the time, first for off-grid uses in isolated locations and then for export to the USA, Europe, and the Middle East. Particularly in the 2000s, India's exports to Germany, Spain, and the USA enjoyed robust demand, and the country's goods were competitively priced for their quality. Additionally, research and development (R&D) in semiconductors and solar photovoltaics (PV) at Indian academic institutions was at a respectable level from the 1980s to the 2000s. The early generation of workers who would eventually operate India's solar enterprises in the 2010s was formed by professionals and students taught at these institutes. The National Solar Mission was started in 2010 by India with the goal of producing 20 GW by 2020; in 2015, this target was raised to 100 GW by 2022. As Figure 2 illustrates, the nation's solar installations grew significantly in the 2010s. However, India's solar manufacturing industry failed because of China's formidable cost and scale barriers. India had 49 GW of solar PV deployed by the end of 2021. As a result, India is now among the top five nations in the world for cumulative and yearly deployment [3]. Nonetheless, a large portion of this deployment was made possible by modules and cells that were brought into the nation. In spite of this, India kept producing cells and modules, albeit on a small scale and typically with outdated technologies. India set a lofty goal of 450 GW of renewable energy by 2030, of which 280–300 GW were predicted to come from solar power in 2020. The Indian Prime Minister recently declared at COP-26 that his country would achieve carbon neutrality by 2070 and 500 GW of "non-fossil fuel" power by 2030 [5]. Of course, the urgency to combat climate change was addressed in these statements, but the focus on solar energy was also based on the need to quickly install capacity in India. According to these targets, India will have to deploy 20–30 GW of solar PV annually over the next ten years. This amount is sufficient to guarantee continued domestic demand for many years to come. Economies of scale will restore manufacturing's competitiveness at these levels. Motivated in part by this mandate and the desire to lessen reliance on imports, the Indian government unveiled many initiatives to boost solar production domestically. In the section that follows, these are explained.

3. Policy announcements to promote solar manufacturing in India

Approximately 3–4 GW of cell and 10-15 GW of module production capacity were available in India by the end of 2020. Some of the technology was out of date, and not all of this capacity was used to its full potential. With a manufacturing capacity of 3500 MW for modules and 1500 MW for cells, Adani Solar was the largest manufacturer. Adani, Tata Power Solar, BHEL, Premier Solar, Jupiter Solar, Websol, and RenewSys were among the businesses involved in the cell manufacturing process. Adani, Waaree, Vikram Solar, Premier Solar, Websol, and RenewSys were among the leading module makers. Numerous small and medium-sized businesses were also producing modules, with capacities varying from several hundred megawatts to less than half a megawatt [6]. Policy measures were required to invigorate the solar manufacturing sector. Reports from a few years ago [7, 8] had detailed the state and potential of solar manufacturing in India; the most recent updates are provided in the Gulia et al. [6] article. The Ministry of New and Renewable Energy (MNRE) and the

Ministry of Electronics and Information Technology (MeitY) released three significant policy pronouncements in 2020–2021 that targeted solar manufacturing in India.

Production linked incentive (PLI)

The Production Linked Incentive (PLI) was implemented in 2021 [9] with the aim of providing incentives for the establishment of global-scale factories capable of producing the whole value chain of high-performance solar modules. This was comparable to China's 2017-launched Top Runner initiative. Businesses would be chosen based on their manufacturing capability and level of integration, as indicated in Table 1. In addition, as Table 2 illustrates, the amount of incentive would be determined by the module's efficiency and temperature co-efficient performance (Note: INR. 1 = USD 0.013). For the same deployment in Watts (rated at Standard Test Conditions), a higher energy yield would be obtained with better temperature coefficients. This is especially important for India, as the majority of the country experiences hot weather, and modules are meant to function at temperatures much higher than 25 °C. The "Base PLI" from the preceding Table is used to compute the real PLI; however, it is only applicable to 50% of the capacity. Additionally, the PLI is discounted according to the module's cost-wise percentage of imported components. The PLI is multiplied by a decreasing value from 1.4 to 0.6 from Year 1 to Year 5, rather than remaining constant throughout the course of the five years. A module would receive an average incentive of 0.7 to 2.0 US cents/Wp, according to our estimate. This is equivalent to about 5% of the module cost as of right now. The government was supposed to provide a maximum of INR 4500 crore (or USD 600 million) in total PLI; but, as will be explained later, that amount was eventually exceeded.

Table 1: Selection criteria for companies.

Selection criteria table parameter	Stages of manufacturing	Marks	Max. Marks
1. Extent of integration	**Stage-1:** Manufacturing of Polysilicon from outsourced (imported/domestic) M.G. Silica	50	50
	+ Stage-2: Manufacturing of Ingots-Wafers from Stage-1 Polysilicon		
	+ Stage-3: Manufacturing of solar cells from Stage-2 Wafers		
	+ Stage-4: Manufacturing of Modules from Stage-3 Solar Cells		
	Stage-2: Manufacturing of Ingots-Wafers from outsourced Polysilicon	35	
	+ Stage-3: Manufacturing of solar cells from Stage-2 Wafers		
	+ Stage-4: Manufacturing of Modules from Stage-3 Solar Cells		
	Stage-3: Manufacturing of solar cells from outsourced Wafers	20	
	+ Stage-4: Manufacturing of Modules from Stage-3 Solar Cells		
2. Manufacturing capacity in MW	4000 MW & above	50	50
	3500 MW and above but less than 4000 MW	45	
	3000 MW and above but less than 3500 MW	40	
	2500 MW and above but less than 3000 MW	35	
	2000 MW and above but less than 2500 MW	30	
	1500 MW and above but less than 2000 MW	25	
	1000 MW and above but less than 1500 MW		

Table 2: Calculation of PLI (INR/W_p and USD/W_p).

Performance matrix table						
		During five year period after commissioning				
		Base PLI rate in INR/W (or USD/W)				
	Module efficiency (%)	Less than 19.50%	19.5% and above but less than 20%	20% and above upto 21.5%	Above 21.5% and upto 23%	Above 23%
Module's temperature coefficient of P_{max}^{*} (in % / Celsius)	Position		W	X	Y	Z
Worse than -0.40		0	0	0	0	0
-0.40 to -0.30	A	0	0	2.50 (0.033)	3.00 (0.04)	3.50 (0.047)
Better than -0.30	B	0	2.25 (0.03)	2.75 (0.037)	3.25 (0.043)	3.75 (0.05)

Table 3: Charges for Site Inspection under ALMM.

Location of manufacturing site	Installed capacity (MW)	Inspection fees	
		(INR)	(USD)
For units situated in SAARC (South Asian Association for Regional Cooperation) countries	Upto 100 MW	5 Lakhs	6666
	More than 100 MW & upto 250 MW	10 Lakhs	13,333
	More than 250 MW	15 Lakhs	20,000
For units situated in non-SAARC countries	For all capacities	30 Lakhs	40,000

Basic customs duty (BCD)

Apart from the PLI, MNRE suggested in 2021 to implement a Basic Customs Duty (BCD) that would take effect on April 1, 2022 [10]. For the import of cells, 25% of BCD would be applicable, and for the import of modules, 40%. This is a big restriction that might make locally produced modules even more affordable or competitive with imported goods. Since the BCD has not yet taken effect, it is highly likely that both the LCOE and the price of solar power projects will rise. It remains to be seen if this will cause a delay in deployments in 2022 and 2023 because entirely domestically manufactured modules won't be accessible in large enough quantities just yet.

Approved list of module manufacturers (ALMM)

"Lab Policy for Testing, Standardization and Certification for Renewable Energy Sector" was published by MNRE in 2017. This requested that the modules sold in India adhere to the "Solar Photovoltaics, Systems, Devices and Components Goods (Requirements for Compulsory Registration) Order, 2017" and register with the Bureau of Indian Standards (BIS). A "Approved List of Module Manufacturers" (ALMM) was mandated by MNRE in 2019 for all manufacturers who had registered their goods with BIS and wanted to take part in government-funded solar PV installation projects. The ability to track and confirm the cells' or modules' provenance to different manufacturing sites and guarantee adherence to specific quality requirements was one of ALMM's driving forces. Each model of the manufacturer's module (or cell) would need to be submitted for separately in order for it to be authorized; the first model would cost INR 5000/MW (USD 67/MW), while subsequent models would cost INR 50/MW (USD 0.67/MW). A module or cell with the same nominal power rating is referred to as a model in this context. The nominal power rating of each module datasheet normally varies slightly, and all of those models may be combined under a single ALMM model. It would also be necessary to conduct a production site examination, and the costs associated with such an inspection are stated in Table 3 [11]. The manufacturing entities would have to provide information regarding their purchases of raw materials, sales records, any history of breaking contracts with customers, detailed balance sheets, etc. as part of the ALMM registration procedure. It should be mentioned that the Indian government already receives part of this data from the businesses who operate there for income tax purposes. To access and validate the previously specified information, MNRE-designated officers and agencies would need to conduct an additional preliminary inspection for firms operating outside of India. Additionally, at the manufacturer's expense, ALMM would entail sporadic audits and inspections of the facilities and modules. While the stated purpose of the ALMM is to guarantee high-quality modules, it is evident from the site inspection fees that manufacturers outside of SAARC would have to pay a higher price than Indian manufacturers. According to our calculations, a factory in India with a 1 GW capacity producing six different kinds of modules would be charged INR 68 lakhs (USD 90,000), while a manufacturer outside of the SAARC region would be charged INR 83 lakhs (USD 111,000). The approval would be valid for two years. (In 2021, MNRE added another slab of less than 50 MW; the fee would be INR 2.5 lakhs, or USD 3333, in response to appeals from small- and medium-sized businesses.) Recently, MNRE announced that, in addition to the initial "government-backed" initiatives, only ALMM authorized modules will be eligible for all open-access and net-metering projects, effective April 1, 2022.

Semiconductor policy

The Ministry of Electronics and Information Technology (MeitY) launched an ambitious policy to reinvigorate the "Semiconductors and Display Fab" sector in India in December 2021. The ministry provided INR 76,000 crore (USD 10 billion) for this project, which was carried out independently [12]. This included the construction of packaging units, GaN, and silicon fabrication facilities, as well as the provision of upfront capital expenditure incentives ranging from 30 to 50%. Solar PV is not specifically mentioned in this policy, but it is clear that there will be good synergy to build up a sustainable silicon ecosystem, for example in terms of the need for clean rooms, high-purity chemicals and gases, wafer requirements, ancillary support for silicon-based fabrication (clean room supplies, etc.), and the development of trained manpower. These two projects are also expected to have a major positive impact on India's already thriving R&D efforts in the wide field of semiconductors.

4. Responses to policy announcements

Manufacturers reacted quite positively to the policy announcements; developers and owners of power plants, who would have to pay significantly more for imported cells and modules, were less enthusiastic. The manufacturers were greatly encouraged to begin solar production in India by the combination of PLI and BCD. In fact, some businesses that had previously developed and installed solar facilities concluded that in order to remain competitive, they would also need to begin manufacturing locally. As a result, up to 19 enterprises with bids totaling over 58 GW applied for the PLI scheme. This was in addition to the recognition by many traditional companies that green, sustainable energy was the way of the future. Only roughly three enterprises could be supported by the INR 4500 crore original sum that was sanctioned. It was announced in late 2021 that the total amount of PLI would be increased from INR 4500 crore (USD 600 million) to INR 24000 crore (USD 3200 billion) in response to the surprisingly large response to the PLI initiative. This was further confirmed in the Indian Budget that was presented to Parliament in February 2022 [13]. A total of fifteen businesses were listed for the PLI based on the initial bids. This comprises 14 silicon module companies and 1 thin-film (CdTe) module firm [14]. Out of the latter, the largest capacity (4 GW) and complete integration from polysilicon to modules have been bid on by three companies. Table 4 provides an order of priority for the list of qualifying companies. Only the top two businesses, plus a portion of the third, would be eligible because the initial PLI funding of INR 4500 crore (USD 600 million) would only be used to establish 8.73 GW of integrated silicon facilities. The announcement that the PLI would be raised to INR 24,000 crore (USD 3200 million) was made because the entire amount of bids was approximately INR 22000 crore (USD 2930 million). The ranking above, with the exception of the top 3, is likely to alter, though, as the Minister of MNRE said in mid-February 2022 that bids would be solicited again for the additional INR 19500 crore (USD 2600 million). However, the list is useful since it provides insight into the kind and quantity of businesses engaged in solar manufacturing. The list includes both established solar manufacturing companies looking to increase their production capacity (like Tata Power Solar and Emvee), companies looking to expand their manufacturing capacity but also backward integrate from modules to cells (like Waaree and Vikram), developers of power plants looking to begin production (like ReNew Power and L&T Power), and newcomers to the market (like Shirdi Sai, Reliance, Coal India, and First Solar). Below is a more thorough description of a couple of these businesses. As the largest company in India by market capitalization, Reliance Industries Limited is highly diversified, operating in industries including energy, natural gas, petrochemicals, telecommunication, retail, and textiles. It is ranked 155th on the Fortune Global 500 list. More than half of its revenue comes from petrochemicals and natural gas. In June 2021, it announced plans to invest at least USD 10 billion in renewable energy, a clear sign of its intention to transform its own business going forward and to alter the global and Indian energy landscape. On 5000 acres in the Gujarat state, it has started to build the Dhirubhai Ambani Green Energy Giga Complex. Following its announcement, Reliance established a subsidiary called Reliance New Energy Solar Ltd. and proceeded to move quickly, investing substantially in forward-thinking businesses like Ambri (USA) and NexWafe (Germany) and acquiring foreign companies like REC (Singapore) and Faradion (UK). Reliance's global reach and financial resources guarantee that it will play a significant role in the global energy transition and that it will be able to establish the necessary scale of operations in solar manufacturing in India. One of the biggest renewable energy firms in India, ReNew Power is responsible for the development and management of utility-scale wind and photovoltaic projects. It has been operating as a developer up until now, but it has made the decision to start producing modules, cells, and wafers. They want to establish production facilities for greenfield cells and modules in Gujarat.

Table 4: List of bidders for PLI (‘Bucket-List’).

Sr. No.	Bidder’s name	Bidder’s manufacturing capacity (in MW)	Eligible capacity (in MW)	Total PLI for 5 years (INR Crore)	(USD million)
1	Shirdi Sai Electricals Ltd.	4000	2000	1875	250.0
2	Reliance New Energy Solar Ltd.	4000	2000	1917	255.6
3	Adani Infrastructure Pvt. Ltd.	4000	2000	3600	480.0
4	FS Solar Ventures Pvt. Ltd.	3009	1504	1752	233.7
5	Coal India Ltd.	3000	2000	1340	178.7
6	Larsen & Toubro Ltd.	4000	2000	1360	181.3
7	Renew Solar (Shakti Four) Pvt. Ltd.	4000	2000	1950	260.0
8	TATA Power solar Systems Ltd.	4000	2000	1500	200.0
9	Waaree Energies Ltd.	4000	2000	2340	312.0
10	Vikram Solar Ltd.	3600	1800	1285	171.3
11	Avaada Ventures Pvt. Ltd.	3000	1500	878	117.1
12	Megha Engineering and Infrastructure Ltd.	2000	1000	333	44.4
13	Premier Energies Ltd.	2000	1000	499	66.5
14	Acme Eco Clean Energy Pvt. Ltd.	2000	1000	625	83.3
15	Emmvee Photovoltaic Powwwer Pvt. Ltd.	1000	500	349	46.5

Situated in the public sector and owned by the state, Coal India Limited is the biggest coal firm globally. Its bid for PLI for ingot/wafer/cell/module manufacturing for the full 4 GW capacity highlights not only its own desire to move into clean energy, but may also be a sign of the Indian government's vision to transition from a coal-based economy to a sustainable green economy, thereby meeting both its long-term net-zero commitment of 2070 and its 2030 COP-26 commitment. It has no prior experience in renewable energy. Even though the PLI initiative has been extremely successful from the manufacturers' perspective, the Indian power plant developer community has generally viewed it negatively. They anticipate that module prices will rise, delivery schedules may be impacted, at least temporarily, as Indian manufacturing capacity increases, and that the introduction of BCD will add a degree of uncertainty. Since there would be fewer high-performance modules built in India in the near future, the BCD itself is expected to raise module costs considerably. This could have a detrimental effect on installations in 2022 and possibly 2023. We predict that even in 2023–2024, when there will be a sufficient supply of Indian modules, their average cost would still be five to ten percent more than that of imported modules (see our analysis in Section 6). Thankfully, the impact on LCOE might not be that great because the cost of the modules makes up a smaller portion of the total system cost than it did a few years ago. Regarding BCD, it's unclear how the WTO will affect the duty. It is believed that the government would back the BCD at the WTO to shield the country's industrial industry from a flood of lower-priced imports. For similar reasons, the government has frequently opposed rolling up its strict import policies in the past, particularly with regard to export subsidies in the agriculture sector. It should be mentioned, too, that India's 2015 WTO complaint on the solar module "domestic content mandate" was unsuccessful. If questioned initially, it's feasible that the government may support this attempt at the WTO in order to protect India's energy security and competitiveness. Although it is widely assumed that the BCD would eventually be phased away, the topic of how long it will remain in existence has not been addressed. The path and rate at which this will happen are uncertain, but our projections for the cost of manufacturing in 2022 suggest that it might be possible to taper down the BCD in the future as more experience and learning drive down prices. Domestically, the National Solar Energy Federation of India requested a six-month delay in the BCD for cells due to the fact that there won't be adequate cell manufacture in India in the upcoming year. It seems improbable that this request will be approved. There has been confusion over the ALMM, including when a comprehensive list will be available and which areas the ALMM will actually be applied to. As was previously indicated, minor manufacturers requested modifications to the ALMM technique so they could compete with the larger corporations. There was also dissatisfaction over the PLI scheme, as smaller businesses were not able to be chosen for PLI awards. However, this was probably built into the process to guarantee that funds are only awarded to businesses that operate on a worldwide scale, ideally with substantial back integration. Early in 2022, 22 Indian-based manufacturers with an aggregate enlistment capacity of 8082 MW and more than 530 different module variants were registered under ALMM. Notwithstanding the fact that a number of foreign manufacturers had registered and even paid the fees, no foreign manufacturer could be recruited because to the pandemic's difficulty making inspection trips abroad.

5. Technology options for solar manufacturing in India

Businesses in India will inevitably investigate several technologies when they begin or grow their manufacturing operations in order to determine which ones are most suitable for the markets they intend to serve. Before the manufacturing initiative began, in December 2020, the National Centre for Photovoltaic Research and Education (NCPRE) and CASE-Bharat [15] submitted a report to MNRE titled "Re-energizing Sustainable Solar Manufacturing in India: Technology Roadmap and Recommendations," which thoroughly examined the available technology options. A follow-up study [16] was presented at the IEEE Photovoltaic Specialists Conference, putting the Indian manufacturing activities in the context of a larger global picture. Naturally, the first concern is whether thin film or silicon technology should be used. Without a doubt, silicon holds 90% of the market today, making it the mainstream technology. However, this begs the question of whether it would be feasible to enter a well-established market later. It remains to be seen if thin films will reappear as a viable option through a disruptive perovskite or tandem method. Anyway, we start with silicon-based technologies because, out of the fifteen firms, fourteen have chosen to work with silicon, and this does appear to be a secure and tried-and-true approach.

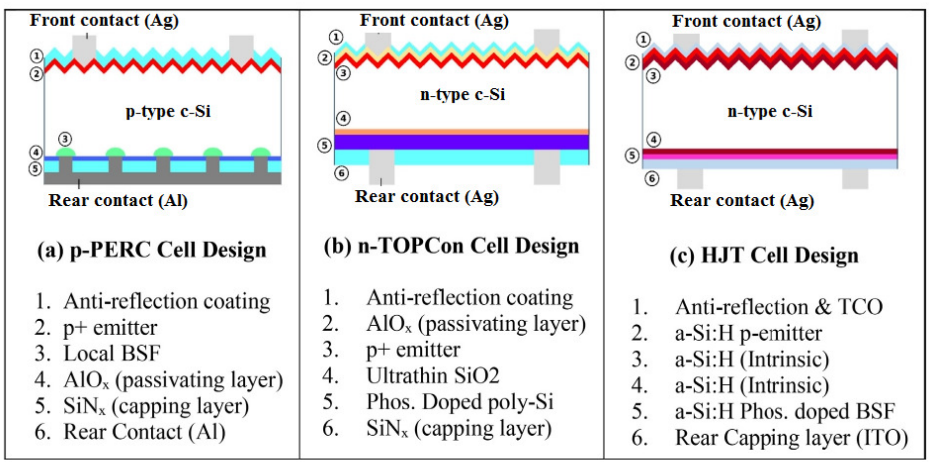

Figure 3: Schematics of different cells (a) p-PERC (b) n-TOPCon (c) HJT.

Silicon technology

The silicon PV value chain revolves around the solar cell. Now that PERC solar cells are the norm, the 2021 ITRPV [17] predicts that the earlier Al-BSF technology will completely vanish and that PERC and PERC-like cells would dominate the market in the years to come (exceeding 80% by 2025). In Figure 3(a), a schematic of the PERC cell is displayed. There will also be a shift from multi-crystalline to mono-crystalline silicon due to the continually declining cost differential between these wafers and the cheaper cost/W of mono-based cells due to their higher conversion efficiency. Although p-type PERC solar cells exhibit the issue of light-induced deterioration (LID), they are now less expensive than n-type solar cells. Silicon flaws associated to boron are the origin of LID; however, the issue is mitigated when gallium-doped Si is substituted for boron-doped Si. According to ITRPV 2021 [17], p-type and n-type will coexist until 2030, but by then, Ga will take the position of B as a dopant in p-type silicon. The TOPCon (Tunneling Oxide Passivated Contact) solar cell, depicted in Figure 3(b), is a significant PERC variant. Since TOPCon has been in the works for a while, ITRPV has projected that the percentage of cells that are either p- or n-TOPCon will rise from roughly 15% in 2022 to 50% in 2030. Nonetheless, a number of significant businesses have begun shipping TOPCon cells and modules as a result of extremely aggressive advances, and it's possible that their market share will rise faster than anticipated. In the upcoming years, it is also anticipated that solar cells utilizing silicon heterojunction technology (HJT, sometimes referred to as HIT or SHJ) will proliferate (ITRPV 2021 projects that by 2028, it will hold a

15% market share). There are several reasons for this: it is more suited for tandem and bifacial technologies, has a possibly simpler production line, and has the highest efficiency of all silicon-based research solar cells (as of December 2021) at 26.7% [18]. But in addition to the greater initial expenditure, there is also a higher final cost/W. Meyer Burger aims to cater to the high-performance sector, which is less price-sensitive, by starting to manufacture HJT cells and modules in Germany and intends to continue doing so in the USA [19]. Since HJT is not as widely used as PERC, it could work to the benefit of Indian producers looking to make a splash with a unique offering. Its superior temperature coefficient adds to its appeal for the Indian market as well as for other tropical nations that are anticipated to see significant increases in solar energy deployments in the ensuing decades. Another high-performance cell and module technology is the IBC; however, we did not advise [15] using this technology since its great efficiency comes at the expense of a more complex system, which raises the cost/W and makes it appropriate only for installations with limited space. The size of the wafer and whether to use monofacial or bifacial cells are two more cell-related choices that manufacturers must make. Wafer size has been rising, with some modules now coming with 210 mm wafers after remaining steady at 156 mm square for more than ten years. Even if they are utilized in monofacial modules, bifacial cells are expected to have a 50% market share by 2023, making them an appealing alternative. The technology, size, and kind will need to be determined by the Indian manufacturers. One of its advantages is that since the majority will be building up green-field cell fabs, they won't need to retool and can instead incorporate flexibility. Based on current data, the majority of silicon cell producers in India are using mono PERC (n- or p-type) wafers up to 210 mm in size, while they may start with smaller wafers, like 182 mm. The capital expenditure for lines for PERC (about USD 22 million/GW), TOPCon (approximately USD 30 million/GW), and HJT (approximately USD 55 million/GW) remains significantly different [20]. Given the high cost of capital in India, this can be a crucial consideration for Indian producers when selecting a technology. A significant number of the projected fab sizes are 4 GW, which is significant since ITRPV 2021 projects that by 2025, cell fabs larger than 5 GW would predominate, and Indian companies will need to be working at that scale to remain competitive. The switch from PERC to TOPCon has already begun, and it's probable that Indian producers will incorporate the necessary processing power. In greenfield facilities, when plant planning and equipment purchasing may be prearranged, the switch from n-type PERC to n-type TOPCon should go rather well. However, in order to deposit the a-Si layer using LPCVD, which is necessary for TOPCon, additional equipment is needed. It has been demonstrated that TOPCon can increase efficiency by up to 1% (absolute). According to a thorough cost analysis by Kafle et al. [21], TOPCon cells have the potential to offer reduced LCOE since their better efficiency more than makes up for their higher fabrication costs. Thus, greenfield plants in India (and elsewhere) find it appealing to switch to TOPCon in the near future. More recently, Indian manufacturing enterprises may want to consider investigating TOPCon using p-type wafers, which are more widely available and less expensive [22]. A few Indian businesses might also be considering HJT carefully; one such business is REC, which Reliance recently purchased and is a well-known HJT manufacturer. The benefits of HJT were previously mentioned, but they must be weighed against the line's higher cost and reputation as a more demanding technology. As can be seen from our cost estimates in Section 6, HJT modules cost a little bit more per watt than PERC.

For a number of years, Indian companies have been involved in the production of modules, with a minimum of a handful of them functioning at a capacity above 1 GW annually. But going forward, more improvements in automation, production capacity, yield, and throughput would be needed. The efficiency of modules has increased because to a significant decrease in cell-to-module (CTM) losses brought about by technological advancements in module materials and structures. The modules now have more than five busbars and mesh-type interconnects; they also use cut cells; they are bifacial; they use variable solar cell sizes ranging from M2 to M12; they have transparent backsheets; they have junction boxes that house a single bypass diode for improved heat dissipation; and they have thinner tempered front glass. The assembly facilities for the modules should be adaptable enough to handle these variations as well as any future adjustments brought about by advancements in module design. Greenfield plants ought to be able to incorporate all of this. Large operational scales (> 3 GW) in module manufacturing will also enable units to compete globally; however, unlike in cell manufacturing, smaller units may also be able to survive if they produce modules for specialized products like solar pumps and street lighting, which are crucial for India and other developing nations. This seems to be the justification for tiny units' reduced ALMM payments. Module producers in India may also want to concentrate on producing and certifying modules that are appropriate for India and require high temperatures for operation. It could be necessary for these modules to adhere to the recently published IEC 63126 standard [23]. According to ITRPV, by 2030, the need for these modules may only reach 20% worldwide; however, requirements in India and other tropical nations are expected to be significantly greater. It is evident from the works of Dubey et al. [24] and Golive et al. [25] that modules in India's hotter regions degrade more quickly than those in its colder regions, and therefore modules that are certified to function at higher temperatures are necessary. In addition to increasing the temperature, Indian module producers might alter the designs of their products to account for unique Indian circumstances, such as extensive soiling. They might consider focusing their marketing efforts on tropical nations across the world. The silicon solar value chain includes more than just the production of cells and modules. Polysilicon and ingots/wafers come before them. Manufacturers were incentivized to incorporate these upstream features via the PLI system. Two more businesses bid to convert ingots and wafers into modules, while three companies bid for the entire value chain. This was a positive result because it was long thought that making polysilicon in India would be difficult due to the high cost of power and the requirement for large capacities. Once more, the question is: What technology is best for India? For a number of years, the established technologies in business have been the Siemens or Modified Siemens processes (for producing hyperpure polysilicon). We advise India to investigate the Fluidized Bed Reactor (FBR) option as well. This is due to FBR's guarantee of a manufacturing energy reduction of more than 50%. When compared to Siemens methods, the capex and opex could also be lowered by 20–30%. These significant benefits can lessen the two major obstacles to establishing polysilicon production plants in India, which are the high energy and capital costs. It is true that our cost calculations in Section 6 indicate a cost advantage for FBR. This option does have some danger because, up until recently, it was thought to be a relatively new technology. Which technology the three Indian companies that submitted bids for the production of polysilicon would use is still unknown. The monocrystalline ingots and wafers from the polysilicon might be obtained using the batch type Czochralski (Cz), rechargeable Cz (RCz), or continuous Cz (CCz). Greenfield Indian manufacturing facilities may find CCz to be a better long-term option because of its reputation for producing wafers of higher quality. Indian firms might also want to investigate new wafer technologies that bypass the intermediate steps of polysilicon and/or ingots and move straight from gas or molten silicon to wafer. Although there is a risk associated with these technologies as they are not currently in production, it would be worthwhile to take them into consideration because they may offer a cost benefit that might make Indian manufacturing more competitive. Reliance's recent decision to become a significant investor in the German start-up NexWafe [26] suggests that at least one of the businesses is thinking about taking this route.

Thin film technology and tandems

Although silicon technology is expected to remain the primary technology, some businesses may benefit from having a thin film portfolio as well because there won't be as much competition worldwide and thin film processes are typically simpler and less expensive both in terms of capital expenditure and ongoing costs. There are only two choices for conventional thin-film solar modules: CIGS/CIS and CdTe. Due in part to its superior temperature coefficient and greater durability observed in Indian fields, the aforementioned report [15] suggested that CdTe be taken into consideration as one of the technologies to be used for manufacture in India [24]. With the exception of a flexible CIGS solution, CIGS was not advised. Both of these suggestions have proven to be accurate; First Solar is in fact one of the highly ranked shortlisted businesses for PLI, and in late 2021, Solar Frontier, the leading CIS company, made the transition to silicon modules. A recent NREL investigation [27] also revealed that, although the cost difference may narrow with time, CIGS modules are now much more expensive (USD/W) than silicon and CdTe. First Solar revealed plans to invest USD 684 million to build a 3.3 GW CdTe plant in the southern state of Tamil Nadu [28]. Niche markets continue to benefit from flexible CIGS, as Flisom has manufactured cells with an efficiency of 21.4% [29]. Roll-to-roll devices can create flexible CIGS with high throughput at relatively modest capital costs. India already has a respectable foundation for producing silicon, particularly modules, but because thin film alternatives have lower entry barriers, other developing solar nations might want to look more closely at them. Lately, perovskites and perovskite-on-silicon tandems have become attractive thin-film candidates. Even on small surfaces, perovskite solar cells have achieved efficiency of 25.7%. There are doubts about these as well as their long-term stability. The creation of perovskite cells is an active endeavor for several research groups in India. This could benefit from India's long history of exceptional R&D in chemistry and materials research. R&D in perovskite technology is also being supported by the Indian government.

Perovskite-on-silicon tandem cells have attracted a lot of interest lately, and in 2021 Helmholtz Centre Berlin (HZB) [30] announced the development of a 1 cm 2 29.8% tandem cell. The bulk cell in the majority of perovskite-on-silicon tandems is silicon HJT, however a recent simulation research has demonstrated that a PERC/TOPCon bottom cell can also be employed [31]. This paper investigated the full-area TOPCon and locally contacted and full-area TCO-based PERC, and found that both ideas can produce tandem efficiencies of roughly 30%. A 21.3% perovskite-on-PERC cell with a route to 29.5% was recently created by HZB [32]. After PERC/TOPCon (although in a few years), some Indian manufacturers would likely consider perovskite-on-silicon. They will likely investigate these and related possibilities, which offer a transition from PERC/TOPCon to perovskite-silicon tandems. There will soon be two more revolutionary tandem technologies [33]. The III-V cell and the bottom Si HJT cell are coupled in these tandems via a "smart stack" technique. While the procedure is intricate and the cells might be costly, they offer a path to cells with greater than 30% efficiency and none of the long-term stability risks associated with perovskites. Although research on this is still in its very early stages, the CdTe/Si tandem is the other tandem structure being investigated.

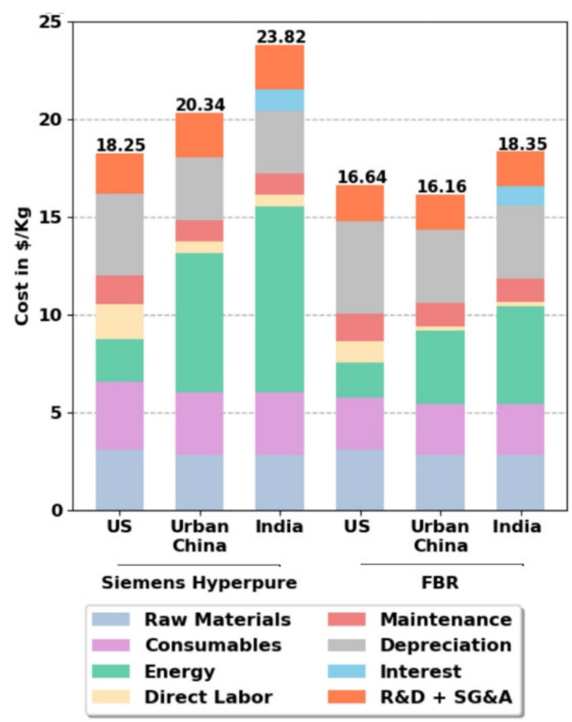

Figure 4: 2018 production costs for polysilicon using Siemens Hyperpure and FBR processes in the USA, Urban China, and India. Data from Woodhouse et al. [34] were used for the USA and urban China.

6. Comparative costs of solar manufacturing

The cost of manufacturing different goods varies throughout nations. As a result, it makes sense to concentrate on the relative prices of producing the different silicon solar value chain components and observe how Indian manufacturers stack up. India was not included in the 2019 NREL report by Woodhouse et al. [34], which provided comparative costs for the production of polysilicon, ingots, cells, and modules for different nations using 2018 costs. Other technologies were not examined in the report; only PERC solar cells were. This research was expanded upon in our previous paper [16], which contrasted the cost of producing cells and modules in India with those of six other nations. Smith et al.'s later 2021 NREL paper [27] compares the 2020 costs of emerging technologies like as perovskite-on silicon tandems, PERC, CdTe, and CIGS, but does not perform a country-by-country comparison. Since some Indian businesses are predicted to have complete or partial upstream integration, we have used the structure of these papers [34, 27] and some of their data to estimate manufacturing costs in India for all the steps in the silicon value chain, including poly and wafers. Although PERC remains the main emphasis, we also estimate the cost of producing HJT modules in India. We started by duplicating the data [34] for 2018 for the United States and Urban China, plus we added India. We used realistic assumptions about the expenses of labor, electricity, depreciation, etc. for India. For instance, it is commonly known that industrial electricity costs are higher in India than in the United States and China. We additionally tacked on a 5% interest load (since it costs more to access funds in India than it does in the USA or China). Figures 4–7 display the findings. The cost of producing polysilicon in 2018 (USD/kg) for the USA, Urban China, and India is depicted in Figure 4, which compares the hyperpure Siemens method and the FBR approach. It is evident that the increased cost of electricity and added debt burden make producing polysilicon in India more expensive. It has long been known that producing high-grade polysilicon in India would not be competitive, so this is not shocking. However, as was already said, the FBR method has a smaller differential than Siemens because of reduced energy and capital expenses. For this reason, it might be a better fit for India. The cost (USD/wafer) of producing mono wafers in the three nations is displayed in Figure 5. We have calculated the expenses for three possibilities for India: importing poly from China (IP), having Siemens make the poly locally (DSHP), or having FBR make the poly locally (DFP). As can be observed, the prices associated with these three approaches lead to wafers that are less expensive than those produced in the USA but more expensive than those produced in China.

The costs (USD/W) of producing mono PERC cells in the three nations are displayed in Figure 6. We have calculated the costs for four options for India: the cells are made using imported wafers imported into the country (IW), the cells are made using domestic wafers made in the country using imported poly (DWIP), the cells are made using Indian wafers using poly made in India by Siemens (DWPS), or the cells are made using poly made in India by FBR (DWPF). It is evident that the costs associated with all four of these approaches lead to cells that are less expensive than those in the USA but more expensive than those in China. Lastly, Figure 7 displays the 2018 USD/W costs associated with producing mono PERC modules in each of the three nations. The costs for the following five options are estimated for India: the modules are made domestically in India using imported cells (IC); the modules are made with domestic (Indian) cells made respectively with imported wafers (DCIW); the domestic wafers use imported poly (DCWIP); the domestic wafers use poly made in India by Siemens (DCWPS); and the domestic wafers use poly made in India by FBR (DCWPF). It is evident that the expenses of all five of these solutions lead to modules that are less expensive in the USA but more expensive than in China. These are all expected outcomes. It is evident that there are two factors contributing to India's high manufacturing costs: the country's higher industrial electricity costs and the increased interest required to get financing. Indian manufacturing would be fairly competitive without the need for such customs duties if the government were to enforce a lowering of these for the solar industries. We have recalculated the aforementioned figures, eliminating the 5% interest load and use China's electricity cost.

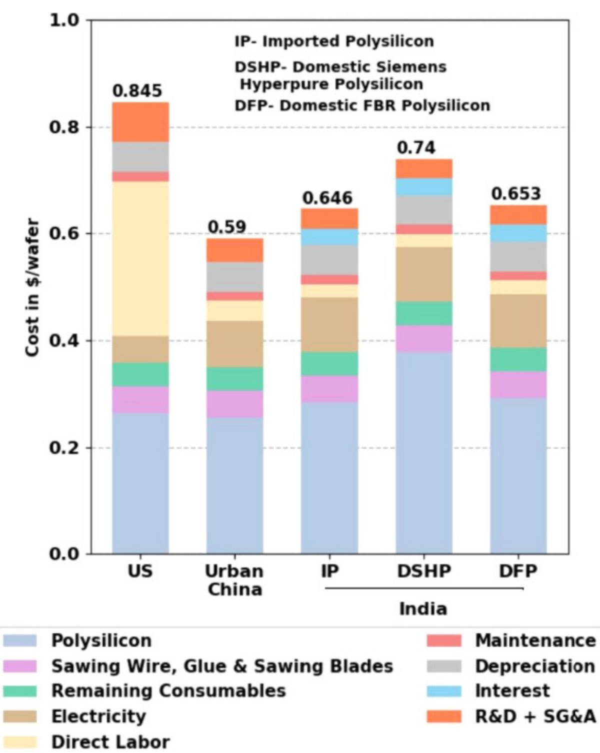

Figure 5: 2018 wafer manufacturing costs in India, China's cities, and the United States. In India, polymers can be imported (IP) or produced domestically using Siemens Hyperpure (DSHP) or FBR (DFP) processes. Data from Woodhouse et al. [34] were used for the USA and urban China.

This makes sense considering that, according to our data, the cost of industrial electricity in India is substantially greater than that of the USA. But since China likewise has higher electricity costs than the USA, our analysis's removal of the China-India differential in electricity costs did not significantly alter the costs associated with manufacturing modules. It should be mentioned, nevertheless, that India's "energy costs" in the production of polysilicon were assumed to be marginally higher than China's since they account for expenses associated with commodities other than electricity. It is also known that in India today, 24-hour solar electricity is less expensive than industrial power. A financially successful solar manufacturing company that wants to go completely green could save a lot of money on running electricity expenses if it builds its own solar PV generating facility. This would therefore lead to a discernible variation in the cost of manufacturing modules in India. We observe a 4% to 8% decrease in the cost of manufacturing modules in India for different types of modules when compared to the scenario with interest burden when the cost of energy in India is taken to be the same as that of China and the 5% interest burden is also removed. Additionally, this would bring the price of Indian modules practically on level with those of China. This demonstrates how the cost of producing modules would be significantly impacted by lowering the cost of capital. Since the 5% interest load in the following computation is indicative of the higher costs of capital that are now experienced in India, we have chosen to retain it. Using the 2019 and 2021 NREL papers [34, 27], we now project the final module costs of 2020 by predicting the approximate reduction in PERC module costs between 2018 and 2020. In urban China, the cost decreased by around 30% between 2018 (USD $ 0.34/W) and 2020 (USD $ 0.24/W). This allows us to calculate the estimated expenses for each of the five possibilities shown in Figure 7 in both China and India. We can now observe the results of applying PLI and BCD, assuming that the costs in 2022 are comparable to the costs in 2020 (because there has been a decrease in expenses followed by an increase). Although it depends on the module's performance and the percentage of imported components that are expensive, the PLI effect is not very significant. Figure 8 displays the 2020/2022 module costs in the USA, China, and India (with PLI for all) using USD 0.01/W (1 cent/W) as the PLI for modules. This figure also displays the cost (marked with O) of the modules from China and the USA that would attract a BCD of 40% if imported into India, as well as the modules from India that use imported cells and have a BCD of 25%. It is evident that, mostly as a result of the BCD, the cost of producing both cells and modules in India is now competitive. While the PLI impact naturally offers an incentive and can increase the profit margin, it is insufficient to make it competitive. Although the figures we have provided are highly imprecise, they do provide a general idea of the impacts of PLI and BCD. We also want to take into account how much it costs to produce HJT and PERC modules in India in comparison. We examine the 2020 data from Smith et al. [27] for this. This indicates that the bifacial HJT cost (USD/W) is 8% more than the monofacial PERC cost. By applying this figure to India as well, we find that the country's 2022 HJT costs will be approximately USD 0.257/W, as opposed to USD 0.238/W for PERC. HJT has the benefits stated in Section 5 previously, while being more expensive. We stress once more that the expenses shown in Figures 4–8 are only rough approximations intended to gauge the relative contributions of the various policy initiatives. Production, yield, and local learning are a few unpredictable but equally significant factors that need to be taken into account for a more thorough and accurate study. This kind of analysis can offer a means to adjust PLI values and gradually reduce BCD in the future.

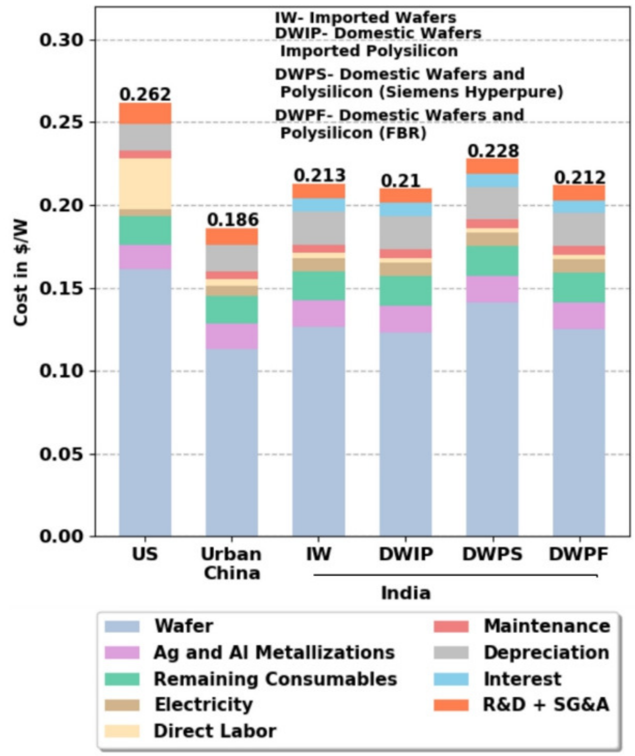

Figure 6: The cost of producing PERC cells in India, China's cities, and the USA in 2018. In India, wafers can be produced domestically (DWIP, DWPS, DWPF) or imported (IW). Data from Woodhouse et al. [34] were used for the USA and urban China.

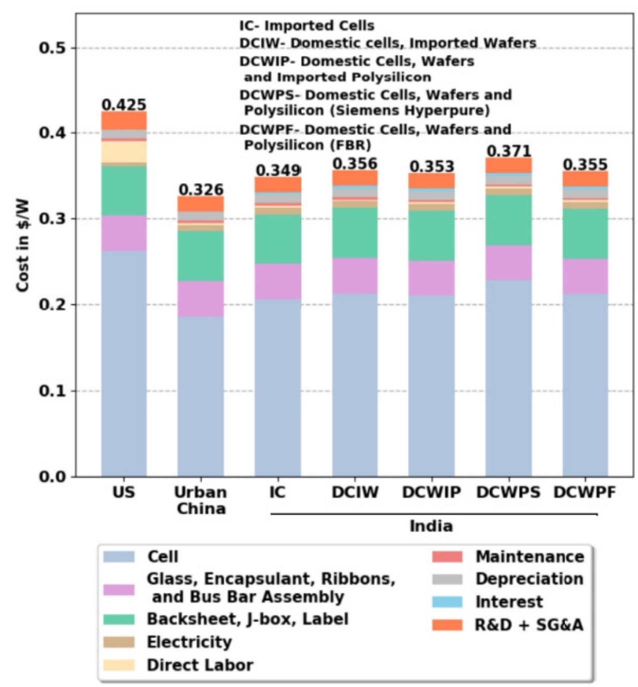

Figure 7: The cost of producing PERC modules in India, China's cities, and the USA in 2018. Cells for India can be produced domestically (DCIW, DCWIP, DCWPS, and DCWPF) or imported (IC). Data from Woodhouse et al. [34] were used for the USA and urban China.

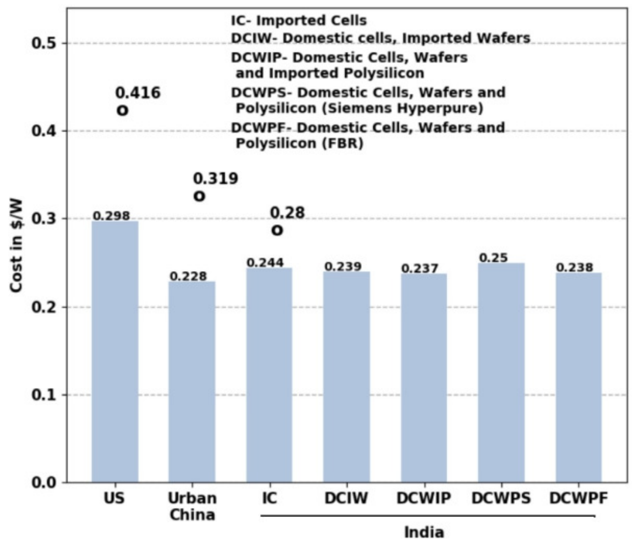

Figure 8: Cost of producing PERC modules in India, China's cities, and the USA in 2020–2022. Cells for India can be produced domestically (DCIW, DCWIP, DCWPS, and DCWPF) or imported (IC). The effect of adding BCD of 25% for imported cells and 40% for imported modules is depicted by the circles (O). Data from Woodhouse et al. [34] and Smith et al. [27] were used for the USA and urban China.

Table 5: R&D activities in India.

Area	Organizations
Silicon solar cells	IIT Bombay, IIEST, NISE, NPL, IIT Delhi, SSN University
Solar modules and module reliability	NISE, IIT Bombay, IISc, IIEST, NIT Hamirpur
Perovskites and Perovskite	IISc, IIT Bombay, NCL, NPL, IISER Pune, IACS, ARCI
Tandems	IIT Madras, IIT Delhi, IIT Kanpur, IIT Roorkee
Organic solar cells	IIT Kanpur, IIT Delhi, IIT Bombay, NPL, IACS
CIGS and CdTe	ARCI
Encapsulants	IISc, IIT Bombay, NISE
Soiling and mitigation	IISc, IIT Bombay, NISE, IIEST

7. Ancillary units and manufacturing hubs

The supply chain involves a number of additional materials and components in addition to the solar cell, which is the main component used in the manufacturing of modules. Glass, backsheet, encapsulant, ribbons, aluminum frame, and junction box are a few of these. All of these auxiliary units need to be available for India to have the capacity to manufacture the entire value chain. These units actually exist today, but they cannot accommodate the country's need due to their limited capacity. None of them are particularly targeted by the PLI effort, and no ongoing duties are applied to the import of these goods. Nonetheless, there is a "Local Value Addition" (LVA) clause in the PLI calculation for module producers, which provides benefits in the event that component imports are decreased. In the PLI scheme, this LVA is expressed as a value between 0 and 1, where 1 denotes that the manufacturing unit has not imported any materials to create the desired product (wafer, cell, or module). It won't appear as "imports" as long as the manufacturer taking part in the PLI scheme sources the auxiliary components from Indian vendors. This does not, however, imply that the supporting parts are genuinely created or produced in India. In addition, in the event that components are still imported, there may be logistical issues ensuring timely supply as well as a potential rise in shipping costs. These products can very well be manufactured in India because the technology required to make them is not as complex or expensive as that of cells. Borosil Renewables is one manufacturer that falls within this category. As the sole producer of solar glass in India, it has made numerous technological advancements, including the creation of completely tempered 2 mm thick solar glass, low-iron solar glass, and antimony-free solar glass. Additionally, solar glass with an anti-soiling coating is to be introduced. Borosil can currently produce 450 tons of solar modules per day, or 2.4 GW of solar modules annually. By 2023, Borosil may have doubled its capacity to 2000 tons per day [35]. The company is now expanding its capacity to 1000 tons per day. This would imply that it could support 10 GW annually. According to current projections by CRISIL, India's solar module manufacturing is expected to reach approximately 40 GW/year by 2025 [36]. Consequently, Borosil's production is expected to remain insufficient to fulfill the domestic demand. As a result, it's possible that more glass producers will open offices in India. For backsheets and encapsulants, another sample is provided. India is home to numerous manufacturers. Renewsys, which presently has 4 GW/year of backsheet capacity and 3 GW/year of encapsulant capacity, is one of the biggest. Its encapsulant is manufactured using polyolefin and EVA elastomer sheets. Motivated by the anticipated rise in solar module production in India, they intend to gradually raise the encapsulant capacity to 11 GW/year. It is anticipated that the primary drive for solar modules will also support other supporting elements of the Indian solar manufacturing ecosystem. The PLI program strongly encourages domestic PV manufacturing, although the topic of manufacturing equipment has not been brought up for discussion. There are very few indigenous equipment manufacturers in this market, and the majority of the equipment utilized for PV manufacturing and testing is now imported. Importing equipment can present challenges for domestic producers, as they must depend on foreign personnel and experience for tasks such as equipment repair, maintenance, calibration, and upgrade. The global health crisis has demonstrated that travel limitations may cause staff to move across international borders, which could seriously impair manufacturing operations in the event that major unit breakdowns occur. Long-term gains in the nation's capacity to manufacture equipment would result from utilizing the developments in the robotics and instrumentation sectors. Due to the substantial capital investment and technical know-how required, there are considerable barriers to entry in the design and manufacturing of PV manufacturing equipment. But in the near future, the PV production and testing companies will need a significant amount of characterisation and testing equipment. Making progress in the equipment manufacturing arena might be achieved by concentrating on the production of test and characterization equipment, in which India already possesses competence. Other BOS components, such as power electronics, inverters, storage, etc., will not be covered here. It should be noted, though, that some of the businesses have expanded into the more expansive field of renewable energy. For instance, Reliance's Dhirubhai Ambani Green Energy Giga Complex, in addition to its integrated solar energy complex, will manufacture green hydrogen, batteries, power electronics, and electrolysers. The company's acquisition of Faradion and significant investment in Ambri, for instance, demonstrate its interest in storage. For the latter, grid storage is undoubtedly the intended use for the liquid metal batteries. The existence of solar manufacturing hubs like to the Giga Complex has numerous benefits. These centers would typically comprise factories that produce solar cells and modules. Inputs needed for the actual production of solar cells include silver paste, high-purity gases and chemicals, and silicon. In addition, the fabrication of modules necessitates a few other previously mentioned components. For supply chain consolidation, it would be beneficial to have a large number of these production facilities situated near a hub or cluster for solar manufacturing. A few BOS component manufacturers also produce solar microinnai. These sites are either already equipped to produce solar energy or will probably have a sizable number of manufacturing facilities operational soon. Given that the second phase of the PLI plan has the stated goal of turning India into an export hub for PV, it would make sense to concentrate directly on the production of equipment in the long run and ancillary components in the medium term.

8. Solar R&D and education in India

It's expected that the first technology for solar manufacturing will reach Indian enterprises through production line integration or partnerships with international laboratories. However, for further expansion in the upcoming years, the presence of strong solar PV operations in Indian universities and R&D facilities would be essential. It would be essential to concurrently build an ecosystem of research and education as India becomes a significant solar manufacturing nation. Thankfully, the base has been there for a long time in this regard, as was previously indicated. Research on semiconductors and solar energy has been undertaken by a number of prominent universities, including the Indian Institutes of Technology (IITs), the Indian Institute of Science (IISc), the Indian Institutes of Science Education and Research (IISERs), the Indian Institute of Engineering Science and Technology (IIEST), and several others. Established in the 1970s at IIT Delhi, the Centre of Energy Studies collaborated with the Indian Association for the Cultivation of Science (IACS) and the Tata Institute of Fundamental Research (TIFR) to conduct groundbreaking research in thin-film photovoltaics (PV) from the 1980s to the 2000s. Concurrently, other institutions, including IIT Bombay and IISc, established first-rate facilities for silicon-based research, mostly focused on MOS technology and sensors. In addition to establishing the National Institute of Solar Energy under its own auspices, MNRE established the National Centre for Photovoltaic Research and Education at IIT Bombay in 2010. In 2020, the MNRE and the Department of Science and Technology (DST) established the Solar PV Hub at IIEST. Additionally, there were events at significant national laboratories including the ARCI, which is funded by DST, and the National Chemical and Physical Laboratories. There is a great deal of activity in the field of perovskite and organic solar cells at numerous organizations, with good outcomes in terms of attained efficiency, deposition on flexible substrates, and encapsulation. A 2020 NCPRE report [37] examines the state of solar PV R&D worldwide and places the current Indian efforts in context. Table 5 provides a partial list of locations in India where research and development is being conducted. Numerous of these groups have also participated in significant bilateral initiatives, such as those between the UK and the US and Norway and the UK and the UK, that have been funded by two countries. Industry and research groups currently collaborate to some extent, but if the latter are to become more prominent in the future growth of India's solar manufacturing sector, this must happen dramatically. Research between academic institutions and business must be conducted collaboratively from the outset. To ensure that well-defined and focused research projects are taken up by relevant centers and jointly sponsored by government and industry, the optimal course of action will be to establish a consortium of academia, industry, and government to coordinate research and development. These kinds of industry-university collaborations have been effective in the USA, Taiwan, and Europe. An organization akin to Fraunhofer ISE might be established, for instance, so that equipment and material producers can assist in scaling up the technologies and materials being produced by universities and research facilities. This will make it possible to better use the limited government R&D resources and focus the research of India's accomplished but little R&D community on long-term issues with industrial relevance. Industry must, of course, have a robust internal research and development program that may also engage in one-on-one interactions with academic and research groups. A qualified and trained labor force will be needed for India's push into solar manufacturing. Numerous IITs and universities offer graduate-level courses in solar photovoltaics and programs in renewable energy. They must be reinforced and draw in a lot more pupils than they do at the moment. It will be feasible to integrate silicon IC with silicon PV technology as many of their fundamentals are similar. Creating online courses that engineers hired by the solar manufacturing countries can enroll in is a crucial endeavor that has to be undertaken. Both the fundamental and practical components of the technology would be covered in these courses. For engineers and technicians, specialized on-site training sessions will be quite helpful. The government (MNRE and the Ministry of Education), business, and academics must collaborate to develop these initiatives.

9. Conclusions

An outline of the recent year or so's advancements in solar manufacturing in India has been provided in this report. There has been a rise in interest as a result of multiple significant government programs, and numerous businesses are beginning or increasing their manufacturing capacity. The fact that many of these companies plan to have partially or fully integrated upstream manufacturing is particularly interesting. We have examined and evaluated the main policy incentives that were implemented. We have also looked over the various technological options and evaluated them using India's needs as a guide. We have evaluated the production costs for each link in the value chain. The cost of manufacturing in India in comparison to other nations would be crucial. Our findings indicate that while manufacturing costs in India are higher than in certain other nations, such as China, the difference will only amount to a mere 5–10%. This discrepancy is more than offset by the basic customs charge that is imposed on the import of cells and modules, and in fact, the tariff structure may be reviewed after a few years. In India, a thriving solar ecosystem would be facilitated by the establishment of solar manufacturing clusters, whether through government planning or organic growth. The Indian industrial sector should be careful not to fall behind in keeping up with the swift advancements in technology. To guarantee that Indian solar manufacturing thrives in the long run, well-funded and directed R&D in industry, universities, and research labs will be essential. The following is a list of specific suggestions for India to support end-to-end photovoltaic production. A few of these probably also apply to a number of other nations hoping to establish robust domestic PV manufacturing ecosystems.

1. Access to cheaper interest financing has a major impact on bringing down domestic manufacturing costs.
2. By removing the large disparity in electricity prices, a 24 × 7 dedicated power supply for industrial facilities powered by solar and storage may soon contribute to even lower manufacturing costs.
3. Using FBR-based polysilicon manufacture is advised for Si-based manufacturing chains since it requires less energy. Other cutting-edge direct wafer technologies might also be investigated.
4. Choosing a thin-film option and collaborating with top thin-film manufacturers could be a simpler way for nations without an established Si-based manufacturing chain to set up end-to-end PV manufacturing.
5. To entice capital markets to participate in domestic manufacturing, a manufacturing strategy that is predictable, consistent, and long-term in outlook is important.
6. Production hubs, such as those for auxiliary components, may serve as a catalyst for the expansion of domestic end-of-sale PV production.
7. For the manufacturing ecosystem to remain sustainable over the long run, investments in manufacturing should be matched with parallel, similar expenditures in domestic R&D. By 2025, it is predicted that India will produce 40 GW of solar modules annually, with a significant portion being backward integrated. This will guarantee energy security and allow India to fulfill its 2030 COP-26 pledges and energy needs. Ultimately, this manufacturing boom offers India the chance to become into a significant global provider and exporter of solar components.

References

[1] REN21, Renewables 2021 Global Status Report (2021). Paris: REN21 secretariat, ISBN 978-3-948393-03-8. Available online at https://www.ren21.net/wp-content/uploads/2019/05/GSR2021_Full_Report.pdf

[2] J. Chase, View from the solar industry: we don't need COP26 to shine, but what should we worry about? *Joule* **6** (2022) 495.

[3] Fraunhofer Institute for Solar Energy Systems, Photovoltaics report. Available online at https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf

[4] A. Parthasarathi, D. Madhavan, V.K. Kaul, Solar photovoltaic energy products: from semiconductor physics to advanced energy technology, *Curr. Sci.* **69** (1995) 974–985.

[5] Ministry of External Affairs, Government of India (2021), "National statement by prime minister Shri Narendra Modi at COP26 summit in Glasgow". Available online at https://www.mea.gov.in/Speeches-statements.htm?dtl/34466/National+Statement+by+Prime+Minister+Shri+Narendra+Modi+at+COP26+Summit+in+Glasgow

[6] J. Gulia, P. Sharma, A. Thayillam, Photovoltaic manufacturing outlook in India, JMK/IEEFA Report (February 2022). Available online at https://jmkresearch.com/renewable-sector-published-reports/photovoltaic-manufacturing-outlook-in-india/

[7] The Energy and Resources Institute (TERI), "Policy paper on solar PV manufacturing in india: silicon ingot & wafer - PV Cell - PV module " (2019). Available online at https://www.teriin.org/sites/default/files/2019-08/Solar%20PV%20Manufacturing%20in%20India.pdf

[8] Indian Chamber of Commerce (ICC), Shakti Foundation and ICF Consulting India, "SURYA to boost solar manufacturing in India," (2017). Available online at https://shaktifoundation.in/wp-content/uploads/2018/01/Solar-Manufacturing_Report.pdf

[9] Ministry of New and Renewable Energy (MNRE), "Production linked incentive scheme 'national programme on high efficiency solar PV modules " (2021). Available online at https://mnre.gov.in/img/documents/uploads/file_f-1619672166750.pdf

[10] Ministry of New and Renewable Energy (MNRE), "Imposition of basic customs duty (BCD) on solar PV cells & modules/panels," (2021). Available online at https://mnre.gov.in/img/documents/uploads/file_f-1615355045648.PDF

[11] Ministry of New and Renewable Energy (MNRE), "Guidelines for enlistment under 'approved models and manufacturers of solar photovoltaic modules (requirements for compulsory registration) order (2019). Available online at https://mnre.gov.in/img/documents/uploads/209841a146974a08860f86ebe31a440d.pdf

[12] Ministry of Electronics and Information Technology (MeitY), "Semiconductors and display fab ecosystem," (2021). Available online at https://www.meity.gov.in/esdm/Semiconductors-and-Display-Fab-Ecosystem

[13] Government of India, "Budget 2022-23 speech of Nirmala Sitharaman Minister of Finance" (2022). Available online at https://www.indiabudget.gov.in/doc/budget_speech.pdf

[14] Indian Renewable Energy Development Agency (IREDA), "Bucket-share of beneficiaries and waiting list (Dated 02-12-2021)". Available online at https://www.ireda.in/images/HTMLfiles/MNRE%20PLI%20Scheme-%20Updated%20Bucket%e2%80%90Share%20of%20Beneficiaries%20and%20Waiting%20List%20dated%2002122021.pdf

[15] P. Ghosh, J. Vasi, A. Kottantharayil, N. Shiradkar, S. Kumar, R. Arya, L.L. Kazmerski, Re-energizing sustainable solar manufacturing in india: technology roadmap and recommendations, NCPRE Report (2020). Available online at http://www.ncpre.iitb.ac.in/ncpre/research/pdf/Re-energizing_Sustainable_Solar_Manufacturing_in_India_v1.2.pdf

[16] P. Ghosh, J. Vasi, A. Kottantharayil, N. Shiradkar, S. Kumar, R. Arya, L.L. Kazmerski, Scaling sustainable integrated PV manufacturing globally, in: Proceedings of the IEEE 48^{th} Photovoltaic Specialists Conference (PVSC) (2021) p. 0472.

[17] International Technology Roadmap for Photovoltaics 2021 (ITRPV 2021). Available online at https://www.vdma.org/international-technology-roadmap-photovoltaic

[18] National Renewable Energy Laboratory (NREL) Efficiency Chart (2021). Available online at: https://www.nrel.gov/pv/cell-efficiency.html

[19] K. Pickerel, "Meyer burger chooses Arizona for U.S. Solar panel manufacturing facility" PV magazine (December 2021). Available on-line at https://www.solarpowerworldonline.com/2021/12/meyer-burger-chooses-arizona-for-u-s-solarpanel-manufacturing-facility/

[20] C. Lin, "A 200 GW solar year in 2022" PV magazine (December 2021). Available online at https://www.pv-magazine.com/2021/12/27/a-200-gw-solar-year-in-2022/

[21] B. Kafle, et al., TOPCon-technology options for cost efficient industrial manufacturing, *Solar Energy Mater. Solar Cells* **111** (2021).

[22] A. Richter, et al., Design rules for high-efficiency both-sides-contacted silicon solar cells with balanced charge carrier transport and recombination losses. *Nat. Energy* **6** (2021) 429–438.

[23] IEC TS 63126:2020, "Guidelines for qualifying PV modules, components and materials for operation at high temperatures". Preview available online at https://webstore.iec.ch/publication/59551

[24] R. Dubey, et al., Comprehensive study of performance degradation of field-mounted photovoltaic modules in India, *Energy Sci. Eng*. **5** (2017) 51.

[25] Y.R. Golive, et al., Analysis of field degradation rates observed in all-India survey of photovoltaic module reliability 2018, *IEEE J. Photovolt*. **10** (2020) 560.

[26] U. Gupta, Reliance Industries to Invest $29 Million in Nexwafe, PV Magazine (2021). Available online at https://www.pv-magazine.com/2021/10/13/reliance-industries-to-invest-29-million-in-nexwafe/

[27] B. L. Smith, M. Woodhouse, K. Horowitz, T. Silverman, J. Zuboy, R. Margolis "Photovoltaic (PV) module technologies: 2020 benchmark costs and technology evolution framework results" NREL Technical Report NREL/TP-7A40-78173 (2021). Available online at: https://www.nrel.gov/docs/fy22osti/78173.pdf

[28] U. Gupta, "First solar goes to India ". PV magazine, Issue 9 - 2021 (September 2021). Available online at https://www.pv-magazine.com/magazine-archive/first-solar-goes-to-india/

[29] E. Bellini, "Swiss scientists achieve 21.4% efficiency for flexible CIGS solar cell" PV magazine (September 2021). Available online at https://www.pv-magazine.com/2021/09/07/swiss-scientists-achieve-21-4-efficiency-for-flexible-cigs-solar-cell/

[30] E. Bellini, "Helmholtz center achieves 29.80% efficiency for perovskite/silicon tandem solar cell," PV magazine (November 2021). Available online at https://www.pv-magazine.com/2021/11/22/helmholtz-center-achieves-29-80-efficiency-for-perovskite-silicon-tandem-solar-cell/

[31] C. Messmer, et al., How to make PERC suitable for perovskite–silicon tandem solar cells: a simulation study, *Prog. Photovolt. Res. Appl.* (2022).

[32] S. Mariotti, et al., Monolithic perovskite/silicon tandem solar cells fabricated using industrial p-type polycrystalline silicon on oxide/passivated emitter and rear cell silicon bottom cell technology, *Solar RRL* (2022).

[33] H. Mizuno, et al., Integration of Si heterojunction solar cells with III–V solar cells by the Pd nanoparticle array-mediated 'smart stack' approach, *ACS Appl. Mater. Interfaces* **14** (2022).

[34] M. Woodhouse, B. L. Smith, A. Ramdas, R. Margolis, "Crystalline silicon photovoltaic module manufacturing costs and sustainable pricing: 1H 2018 benchmark and cost reduction road map" NREL Technical Report NREL/TP-6A20-72134 (2019). Available online at https://www.nrel.gov/docs/fy19osti/72134.pdf

[35] U. Gupta, "India's Borosil to expand solar glass production capacity to 2,000 tons per day" PV magazine (February 2022). Available on-line at https://www.pv-magazine.com/2022/02/14/indias-borosil-to-expand-solar-glass-production-capacity-to-2000-tons-per-day/

[36] CRISIL Press Release (2022), "Solar module making capacity set to soar 400%" available online at https://www.crisil.com/en/home/newsroom/press-releases/2022/01/solar-module-making-capacity-set-to-soar-400-percent.html

[37] NCPRE, "Global R&D in solar PV" (2020). Available online at http://www.ncpre.iitb.ac.in/ncpre/uploads/Global_R_D_in_Solar_PV.pdf

Publisher's Note: Research Plateau Publishers stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.