Re-energizing Sustainable Solar Manufacturing in India:
Technology Roadmap and Recommendations

National Centre for Photovoltaic Research and Education (NCPRE)

&

Catalyst for Accelerating Sustainable Energy for Bharat (CASE-Bharat)

Version 1.2

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CASE-Bharat
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Technology Roadmap and Recommendations

A White Paper presented to MNRE by

National Centre for Photovoltaic Research and Education (NCPRE), IIT Bombay
&
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Abbreviations

Al BSF	Aluminium Back Surface Field
BOS	Balance of System
CdTe	Cadmium Telluride
CIGS	Copper/Indium/Gallium/Selenium
Cz/RCz/CCz	Czochralski / Recharge Czochralski / Continuous Czochralski
DSS	Directional Solidification System
DWS	Diamond Wafer Sawing
FBR	Fluidized Bed Reactor
HIT	Heterojunction with Intrinsic Thin layer
HJT	Heterojunction Technology
IBC	Interdigitated Back Contact
LCOE	Levelized Cost of Energy
PECVD	Plasma Enhanced Chemical Vapour Deposition
PERC	Passivated Emitter and Rear Cell
PERT	Passivated Emitter Rear Totally Diffused
PV	Photovoltaic
PVD	Physical Vapour Deposition
SECI	Solar Energy Corporation of India
Si	Silicon
TCO	Transparent Conducting Oxide
TCS	Trichlorosilane
TOPCon	Tunnel Oxide Passivated Contact

Contents

1. Background and Current Status

Solar photovoltaics had its beginnings during the 1950's, when the first modern solar cell was invented at Bell Laboratories in USA. These cells became very important for use in space during the 1960s and 1970s, and indeed powered India's first satellites in the 1980s as well. During the 1990s, solar PV found off-grid terrestrial applications in remote and rural areas (including, for example, parts of Ladakh), and in the 2000s, they were used to generate clean energy even for grid-connected power plants. But until 2010, the cost of solar PV was still too high for large-scale deployment.

During the last decade, however, solar energy has emerged as the least expensive source for electricity in terms of the Levelized Cost of Energy (LCOE). This has been the result of rapidly declining costs of solar modules due to improvements in technology and manufacturing, which in turn resulted in widespread deployment of solar photovoltaics (about 580 GW worldwide in 2020). In India, too, the deployment of solar PV has proceeded apace, and at the end of 2020 approached 40 GW. India already ranks fifth in cumulative solar deployment, as shown in Fig. 1, despite a relatively late start in 2010, when the National Solar Mission was launched.

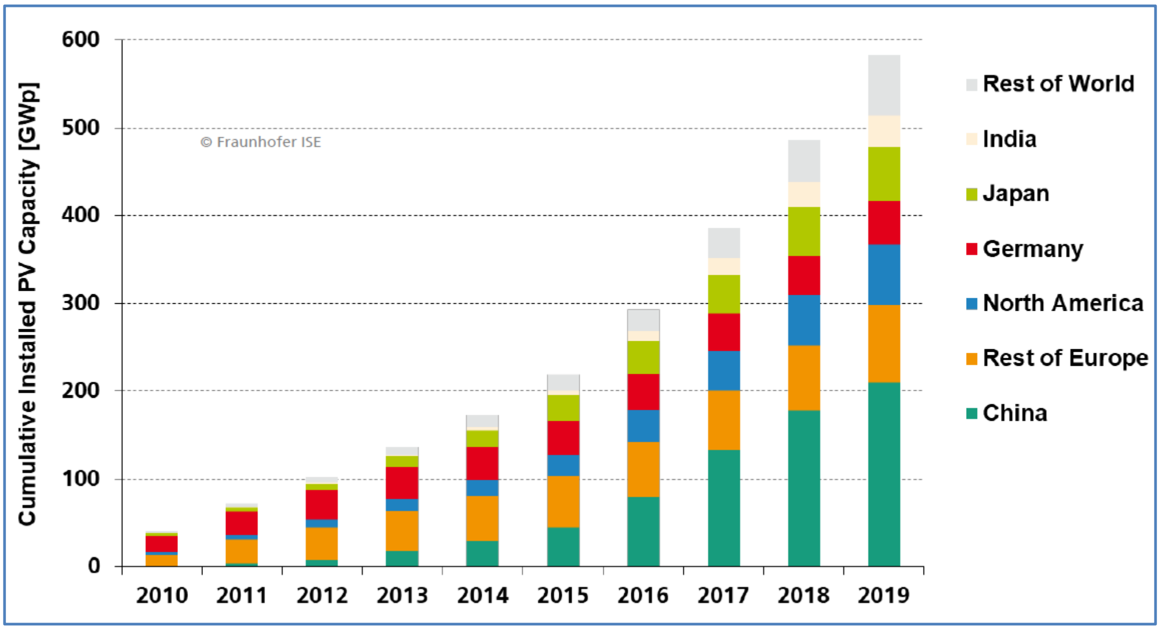

Figure 1. World-wide deployments of solar in 2020 [1]

India also has among the lowest LCOEs for solar energy, as witnessed by the recent auctions by SECI which yielded a power tariff of Rs. 2/kWh (about US$ 0.026 /kWh). The cost of solar installation in India ($/W) is among the lowest in the world, although the PPA is not, as shown in Fig. 2.

With the announcement of the 300 GW target for solar energy by 2030 (part of the 450 GW target for renewables), India is likely to take its place as one of the top 2 solar energy producing countries during the next decade. This very ambitious goal provides an opportunity as well as the exigency to ensure that solar manufacturing in India is pursued agressively.

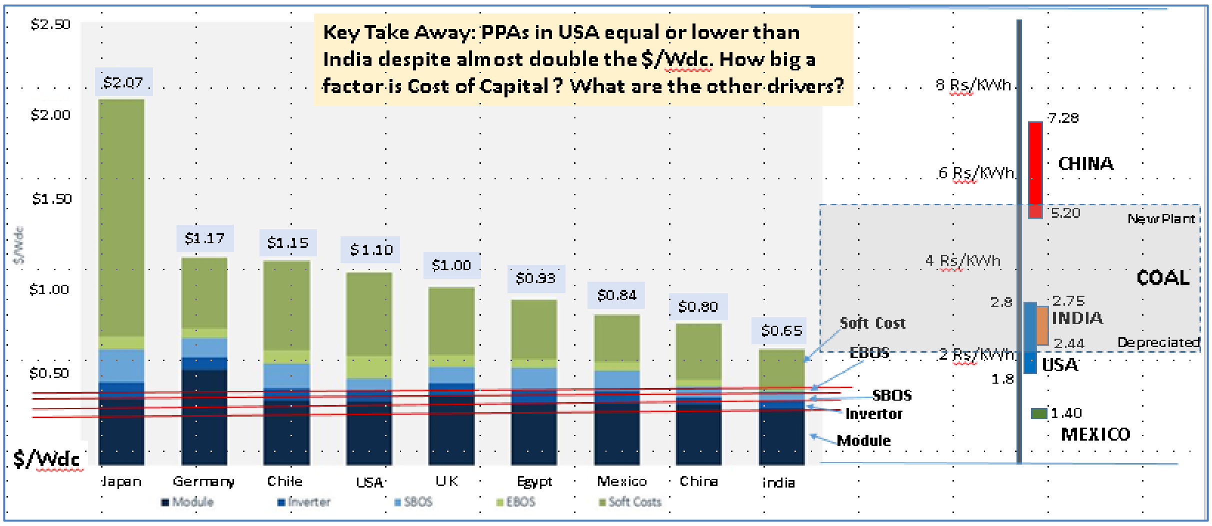

Figure 2. 2017 Utility PV System pricing in different countries (left) and solar PV PPA ranges (right)

2. The Case for Solar Manufacturing in India

Solar manucturing in India goes back a long way. Central Electronics Ltd. (CEL) began manufacturing solar cells and modules in 1978, and was followed by BHEL. Private companies like Tata BP Solar started manufacturing in 1989, and several other companies, such as Moser Baer followed in the 2000s. During the mid- and late-2000s, India was among the few countries in the world making solar cells and modules, mainly for export and for applications in remote areas. These companies manufactured both solar cells as well as solar PV modules. However, with the advent of manufacturing of solar cells and modules in China starting in about 2005, the competitiveness of the Indian companies was affected. Nevertheless, the deployment of solar PV in India during the decade of 2010-2020 grew strongly, with much of the cells and modules being imported, mainly from China. Today China produces almost 70% of global solar PV modules as shown in see Fig. 3 [1], but it produces more than 90% of silicon solar cells and silicon wafers.

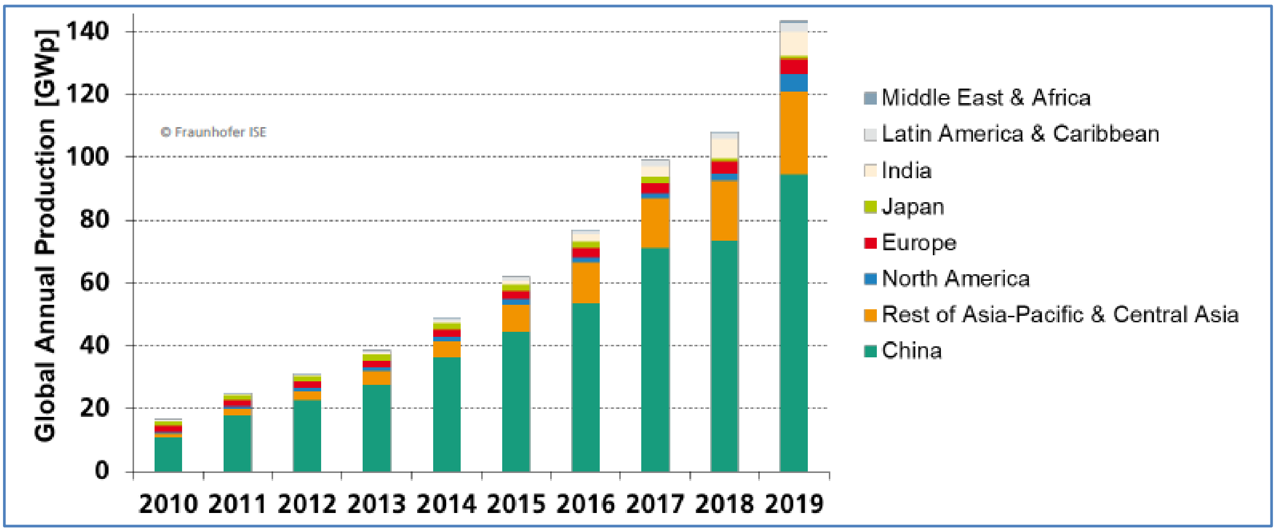

Figure 3. Global annual production of PV modules [1]

The announcement of the 300 GW solar PV target in January 2020 has significantly changed the landscape for solar manufacturing in India. Although India is quite capable of meeting this 300 GW plan, the challenge will be to ensure that all of the requirements are not imported. During the next 10 years, India would deploy between 20 to 30 GW of solar PV every year. Purely from the energy security point of view, it is important that a substantial portion of this requirement be manufactured in India. Equally important, there are also opportunities which present themselves in the challenge. Firstly, 20-30 GW is a large enough number that economies of scale come into play, and Indian companies can well set up manufacturing plants in the GW range which are necessary to be competitive. Secondly, many countries around the globe are looking for an alternate source for the supply of solar PV, and India can hope to fill that need.

The need for domestic manufacturing has indeed been recognized by the Government of India, which has made announcements about its intent to support manufacturing in India. Several workshops and conferences (for example by TIFAC in August 2020, PV EDGE by Niti Aayog in October 2020, and RE-Invest 2020 in November) have highlighted solar manufacturing in India, and the Atmanirbhar Bharat scheme has solar manufacturing as one of its key aspects. Furthermore, SECI has received bids for manufacturing-linked solar deployments from Adani and Azure. Several other companies, such as Vikram Solar and Waaree Energies (both of whom already have module manufacturing plants) have expressed their intention to expand module manufacturing and also start cell manufacturing, and possibly venture into polysilicon, ingot and silicon wafer manufacturing as well in India. ReNew Power, a major solar and wind developer, has expressed interest to invest in integrated solar manufacturing.

As the stage is being set for solar manufacturing to take off in India, this paper focuses on the technology options which are available, and which can be pursued in India.

3. The Value Chain for Solar Photovoltaic Manufacturing

Solar manufacturing has a complex value chain. The mainstream PV technology today is silicon technology, and there are two versions based on the type of silicon wafers which are used – mono and multi (sometimes also called poly). There also exists the non-silicon thin-film technology, which is less common now, but may re-emerge in future. The relative market shares of these since 1980 are shown in Fig. 4 [1]. It can be seen that mono-silicon is dominant today, and according to the International Technology Roadmap for PV (ITRPV), this dominance will increase further in the coming decade, accounting for 80% by 2025 and 90% by 2030 [2].

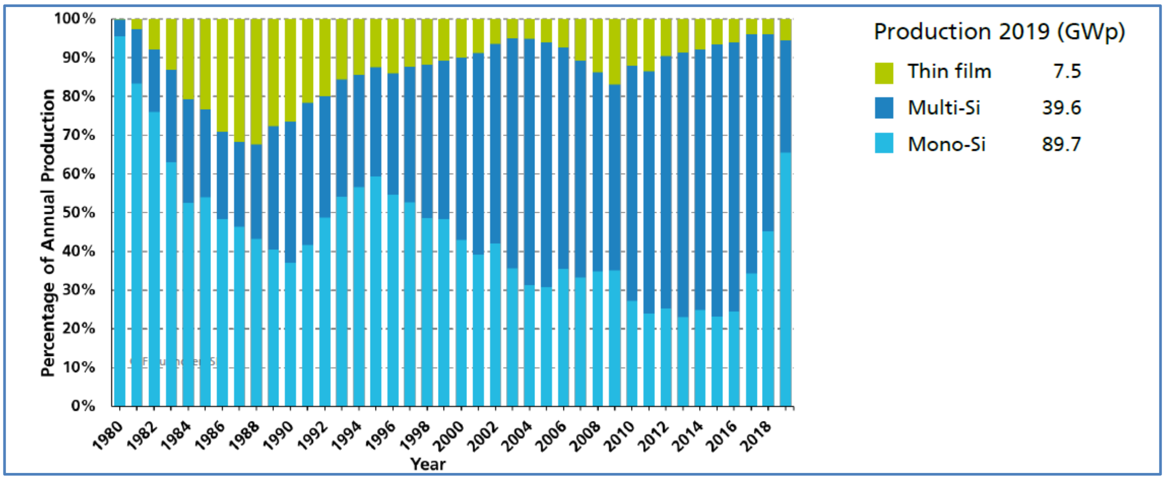

Figure 4. Market shares of mono-Si, multi-Si and Thin Film solar technologies [1]

The supply chains for the two silicon options (mono and multi) are shown in Fig. 5. They both start with polysilicon made in either a Siemens Reactor or a Fluidized Bed Reactor (FBR). The poly is then used to grow mono-crystalline ingots by the Czochralski (Cz) method or is cast into multi-crystalline bricks. These are then wafered, typically by Diamond Wafer Sawing (DWS). The wafers are used to make the solar cells. There are various silicon solar cell technologies available, the most common today being PERC (Passivated Emitter and Rear Cell) which is fast replacing the earlier Al-BSF cell. (PERC and other cell technologies are discussed in more detail in Section 4.3.) Finally, 60 or 72 individual cells are assembled together to make the solar PV module.

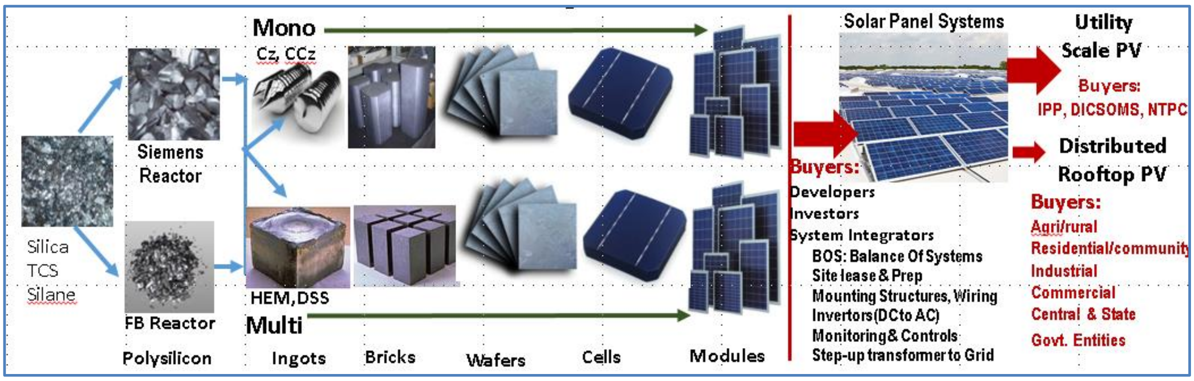

Figure 5. Supply chain for mono- and multi-silicon solar PV manufacturing

The processes described relate to the main semiconductor part of solar PV manufacturing. However, it is important to note that the manufacturing ecosystem requires various other inputs, such as semiconductor-grade chemicals and gases. Furthermore, the modules also require, besides the cells themselves, other components such as the glass, backsheet, ribbons, junction box, aluminium frame, and so on. All of these put together constitute the full value chain for silicon solar PV manufacturing. Note also that besides the modules themselves, the full solar PV system requires, in addition, 'Balance of System' (BOS) components such as wiring, switches, mounting systems, solar inverters, and, increasingly, battery banks. This report does not consider BOS components, nor many of the non-semiconductor parts of the module mentioned above.

The thin film solar cell manufacturing process is considerably simpler (and so potentially cheaper). Thin film technologies include CdTe, CIGS, and perovskites. The CdTe process is shown in Fig. 6 as an example. A thin film of CdTe (and other materials) are directly deposited on a glass substrate to produce the solar PV module in a single-pass integrated process instead of multiple discrete steps needed for silicon based technolgies discussed above. The CdTe process consumes lower energy and is much less time consuming. Compared to its counterpart CIGS production process, which also uses an integrated 'glass in module out' process, CdTe production is more forgiving, hence continuous cost improvements can be made to extract higher yields and higher effeciencies.

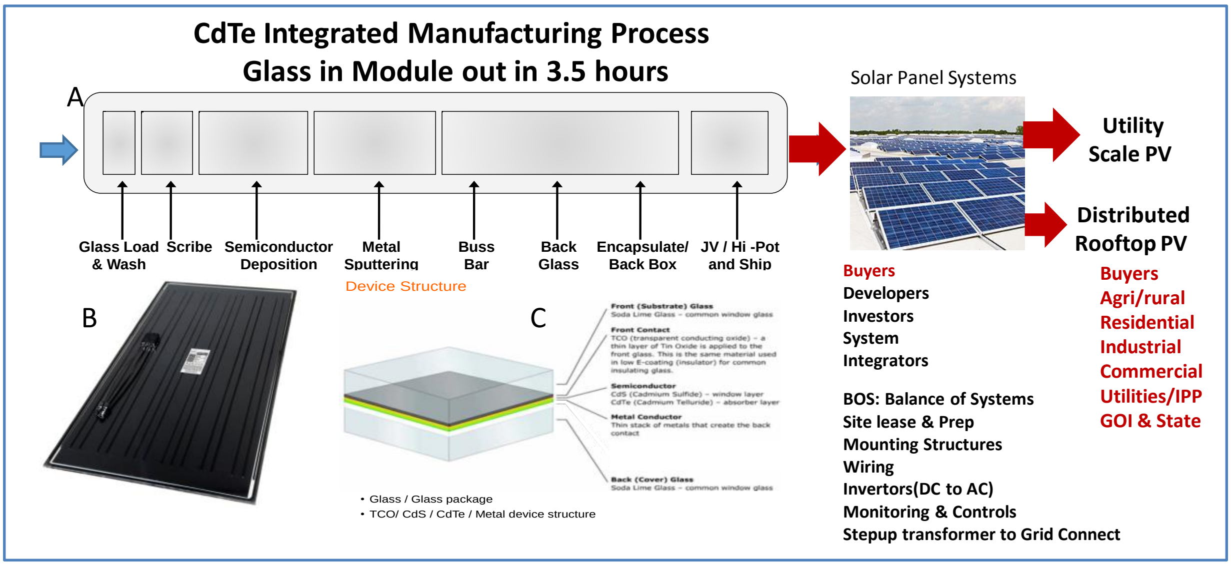

Figure 6. Thin film CdTe manufacturing process

4. Technology Options for Solar Photovoltaic Manufacturing in India

This section describes the technology options available for India for solar PV manufacturing, and gives the pros and cons of these options. It also proposes tentative recommendations. Of course, it should be noted that the final decision by the manufacturer would depend on several other aspects, such as terms and conditions of technology purchase, tie-up with a JV partner, risk appetite of the promoter, etc.

4.1 Polysilicon

The Siemens or Modified Siemens reactor remains the time-tested dominant technology to produce high-quality mono grade Polysilicon (of purity '11 nines') from Trichlorosilane (TCS) and Silica. Since producing polysilicon is very capital intensive and consumes a lot of energy, this is an oligopoly where a handful of players dominate 90% of the market [3]. While China has increased its share of the manufacturing capacity from 60% in 2017 to 74% in 2020 and has improved its quality significantly, there are still 3 major manufacturers outside China. Wacker Chemie AG (Germany) produces perhaps the best quality polysilicon as of date, and Daqo New Energy (China) claims to have to the lowest cost of production. Polysilicon used to be the weak link for China before 2020, but this is increasingly not true anymore.

India has two options to produce polysilicon via the Siemens route. First, acquire or form a strong JV with one of the three companies outside China to transfer the plant to India, and provide low-cost power, capex and manpower. If an acquisition is not viable, then Maharatna PSUs in the traditional energy sector such as NTPC, BHEL, IOC, ONGC or Coal India along with a large private conglomerate could form a coalition and partner with a reputed company like Wacker to set up a time tested Modified Siemens plant of at least 10K tons/year.

In addition to the Siemens route, India can also explore the Fluidized Bed Reactor (FBR) route. FBR holds the promise of reducing power consumption by more than 50% and even capex and opex can be reduced by 30-40% compared to Siemens based reactors. Therefore this technology is very germane to India. FBR also produces superior quality polysilicon. However, being a relatively untried technology, this route does carry a moderate amount of risk.

While many key players in the industry and some start-ups have been testing FBR pilots for several years, GCL-Poly Energy Holdings in China which acquired the FBR technology in 2017 from USA-based SunEdison (earlier MEMC), finally announced this year that FBR technology is ready for rapid commercialization and announced that they will be investing USD 640M to install a 30K ton plant in Phase 1 by mid-2021 and expand the capacity to 100K tons by end-2022 [6].

If India is to opt for the FBR route, the options available are: (1) Get a JV or licensing deal with GCL Poly who owns the patent acquired from SunEdison, and replicate their 6K ton/year FBR module by mid-2022 and expand it to 24 K ton/year by end-2023. The minimum size of the plant may be dictated by the economically viable TCS processing plant needed as input to making polysilicon. (2) Partner with other players like REC (headquartered in Europe) which will need investment in R&D before a pilot can produce higher quality and higher yield consistently. (3) Set up a full-fledged R&D team to design and develop a 3-5K ton pilot. Our team has identified very qualified person(s) of Indian origin to evaluate all 3 options and select and lead the best option for India. Option 1 can be a green arrow while the other two options will remain as yellow arrows in Fig. 7 (in Section 4.5) as it involves R&D to design and develop to get to a pilot plant.

4.2 Silicon Ingots and Wafers

Polysilicon is melted, and the molten silicon is either pulled into mono-crystalline ingots or cast into multi-crystalline bricks. As described earlier, the silicon solar cell industry is rapidly consolidating around mono-Si (either p-type or n-type), so India should only look at this option. Mono results in better efficiencies, and as the cost difference between mono-Si and the cheaper multi-Si wafers diminishes, mono becomes more attractive on LCOE basis and ultimately on a per watt basis as.

China produces more than 95% of the world's ingots for making high-quality mono wafers for the PV industry. While the PV industry was focused on cell development and manufacturing, there was a quiet revolution going on in China on the ingot manufacturing value chain for PV. LONGi from China is the dominant player in this sector with a current 30 GW manufacturing capacity, planning to expand to 100 GW by 2022. While most mono plants are batch type Czochralski (Cz) and rechargeable Cz (RCz), a few have started to move towards continuous Cz (CCz). CCz produces better quality wafers, especially in terms of variability. It needs high-quality granular polysilicon that the emerging FBR technology can provide [4].

Ingot manufacturing options for India include: (1) For fast time-to-market with high reliability, form a JV with GCL Poly or LONGi or one of its alliance partners in China to set up a 5 GW ingot and wafer plant (typically installed together so that kerf waste can be recycled back). (2) Partner/JV/acquire companies like Norsun or Norwegian Crystal in Norway to set up a mono ingot plant in India. The issue can be price and ability to produce M10 (182 mm^2) and M12 (210 mm^2) size wafers. That can be addressed by partnering with entities like Linton Crystal Technologies (LCT), who had presented their capabilities at PV EDGE in October 2020.

The ingot would then be sliced to obtain wafers. The industry has transitioned from slurry cut wafer technologies to the much more efficient Diamond Wire Saw (DWS) technology, and this is the obvious option for India. The plant to be set up in India should be aware of the increasing size of silicon wafers, transitioning from M1-M2 (158 mm^2) to M6 (166 mm^2). More recently, an alliance among China based companies are promoting M10 (182 mm^2) and M12/H12 (210 mm^2) sizes to achieve 600+ W output from a larger form factor module. The change in cell sizes can cause major disruptions to not only the existing cell and module plants but also cause disruptions among upstream ingot production investments, as well as shipping, tracker compatibility, and a host of other performance related issues. This is an important point to consider always, as a major impact of Chinese dominance is being seen in product standardization. If China shifts from M1-M2 to the larger format M6/M10/M12 wafers (as already announced by few large China based players), the India-based wafer, cell and module manufacturers must be set up to make the transition also, else the lines will go defunct. The dominant player in wafer manufacturing is LONGi who is rapidly expanding their manufacturing capacity to 100 GW/yr [5].

There are emerging wafer technologies which go directly from gas or molten silicon to wafer, without the intervening stages of polysilicon and/or ingots. These are processes in which the polysilicon is molten and made directly to a multi (or mono) wafer, or in which the TCS gas is used to directly deposit silicon to grow silicon wafers. Such processes can potentially be cheaper both in terms of cost as well as time. Some of the companies which are exploring these options are 1366 and Crystal Solar based in USA, and Nexwafe in Germany. However, none of these are yet into large-scale production. Nevertheless, it would be worth-while for India to consider these technologies, as they provide a potential cost advantage which can make Indian manufacturing competitive with respect to China, and also use technologies which are not mastered by China. India's options for these emerging technologies include: (1) Fund the next generation Epi Wafer Plant that can produce high quality wafer directly from TCS/Silane, using technologies from 1366 or Crystal Solar. It may require an R&D team, and we have identified key people of Indian origin who have deep knowledge in this area. (2) Partner with a company like Nexwafe from Germany [7] who are piloting an epi-wafer plant.

4.3 Silicon Solar Cells

The solar cell itself is at the heart of the PV solar value chain. There are a variety of silicon solar cell technologies. For many decades, the Al BSF (Aluminum Back Surface Field) was the standard;

however, since 2015, the PERC solar cells have started to become the dominant mainstream technology. Besides the standard PERC, there are many upcoming variants, including PERT and TOPCon, as well as the use of n-type wafers instead of the traditional p-type wafers. There are also other important and competing silicon-based technologies like Heterojunction Technology (HJT, also called HIT), Interdigitated Back Contact (IBC) cells and bifacial cells. In addition, there are several thin film competitors using materials like CdTe and CIGS. An emerging class of materials is the perovskite, which show excellent efficiency, and have the potential to team up with silicon to make ultra-high-efficiency tandem solar cells. Any company wanting to enter the manufacturing arena today must carefully explore all these options.

Advancement in cell efficiencies, maximizing output, manufacturing process improvement and automation are the focal points for a majority of R&D spending, resulting in rapid incremental innovation. Currently there are dizzying arrays of developments and alliances happening in this space, most of it led by China. While a majority of the current 3 GW cell manufacturing capacity in India is still based on multi-Si based Al BSF technologies using M1-M2 (156.75 mm^2) size cells, the rest of the world led by China has essentially transitioned to p-type mono-Si PERC technologies.

The logical sequence for the silicon cell technology is to transition to TOPCon [8] from mono PERC, where China has overpowering scale and process knowhow dominance. The TOPCon process has the advantage of being able to use a PERC line with only a few modifications. For an Indian company, a good strategy may be to first adopt the mainstream mono PERC technology for Atmanirbhar Bharat (perhaps using n-type wafers), with the potential to transition rapidly to TOPCon, which can make it globally competitive. If India cannot find a differentiating competitive edge through TOPCON knowhow, India will have to explore other technology options.

The HJT technology not only provides high efficiencies but also has low temperature coefficient and low degradation, both of which are important for India. It has many other advantages as well, such as high bi-facial coefficient and suitability for tandems. It leverages a hybrid technology using thin film knowhow for passivation through a PECVD process to apply an amorphous ‘intrinsic’ silicon layer on both sides on an n-type wafer, and PVD coating of a transparent conducting oxide (TCO). The first step, surface cleaning and texturing of the wafer surface, continues to be a big challenge for HJT in production lines. China has not mastered HJT technologies fully as yet and there are enough global HJT PV equipment suppliers and manufacturers such as REC, Hevel (Russia), Panasonic (Japan) and Kaneka (Japan). There are also experts of Indian origin whom India can leverage and do a due diligence to see if India can establish a competitive advantage in this area.

Another important upcoming area is bifacial cells and modules which can potentially boost the output of a module by 5-30% depending on albedo and bifaciality factors [10]. HJT Bifacials should have an advantage over mono PERC Bifacials. This is another reason why India may wish to pursue HJT technology.

IBC technology is another area China has not mastered as yet. Besides Sunpower in USA, a new player, Violet Solar [9] in USA, is planning to set up an integrated value chain to produce a differentiated IBC technology. Because all contacts are at the back, the efficiency of IBC cells is very high; however, the complexity of IBC process makes the technology expensive. It is not obvious whether this will ever become a mainstream technology or remain a niche product for high-cost high-efficiency silicon solar cells suitable for area-constrained rooftop applications. Cell manufacturing companies in India, in our opinion, need not consider this option very seriously.

4.4 Thin Film and Tandem Solar Cells

Thin film solar cell technology has always been attractive because of the potentially low cost of production. Thin film PV had attracted a lot of investments 10-15 years ago, but most of the companies were wiped out during the 2011-2013 PV market price disruption after China entered the market (see Fig. 4). However, two thin film companies, First Solar and Solar Frontier, using CdTe and CIGS respectively, continue to exist. CIGS based thin film led by Solar Frontier (Japan), while making decent efficiency improvements, is not price competitive with c-Si. CIGS does have the advantage that it can be deposited on flexible plastic substrates. Flexible CIGS PV is an exciting area to do the next level of due diligence. While the current generation of flexible CIGS companies like Flisom (started by a PIO in Switzerland) and Hanergy (China) tend to be focused on BIPV, transportation, defense and special applications, this market segment can be a multi-GW scale market. In the longer term, flexible thin film with scale and process improvements could break the price barrier and out-compete glass based PV.

First Solar (FSLR, headquartered in USA, with manufacturing plants in USA, Malaysia and Vietnam) continues to thrive and is an important player today. Their CdTe Series 6 is a significant step-up from Series 4 and can be a serious contender for countries like India who wish to cut dependencies on a single country or source. Furthermore, CdTe technology has a low temperature coefficient, which is important for India's tropical climates, and their technology also shows extremely low degradation rates. First Solar has strong financials and the 2020 Q2 earnings statement shows that there is significant demand for Series 6 modules. First Solar is looking at expanding their production capacities from the current 6.5 GW to 10 GW. It can be a win-win opportunity for both India and First Solar if a mutually acceptable agreement is reached to replicate their Vietnam plant (their most productive and cost efficient plant) in India. A First Solar integrated value chain set up in India can potentially offer the highest domestic content compared to any c-Si based option. A techno-commercial due diligence should be done on a priority basis, and this technology should be explored as part of the diversified portfolio for India.

Finally, no discussion of thin films today is complete without a mention of perovskites. These very exciting organic-inorganic hybrid materials have shown rapid increases in cell efficiency over the last 6-7 years, which now approach those of silicon. Equally exciting are tandem solar cells, which use perovskite deposited on top of a silicon HJT cell, thereby using both cells to generate larger voltages and hence higher efficiency. In December 2020, Oxford PV announced a record efficiency of 29.52% for a small 1.1 cm^2 tandem cell [11]. Oxford PV is targeting large-scale production in 2022. Technologists believe such tandems will soon cross the 30% efficiency barrier, and the focus will be on overcoming rapid degradation and addressing other material and chemistry issues of perovskites that need to be resolved (for example eliminating lead in their composition) before they can scale beyond pilot plants. Though these tandems are still in pilot R&D stage, they present a disruptive technology which may replace pure silicon. The perovskite part of the technology is not very expensive, so it is likely that perovskite-silicon tandems will not be much more costly than silicon, while offering significantly higher efficiencies. For these reasons, India should invest in this technology and the R&D required, despite the fact that the large-scale deployment of this technology is contingent upon resolving issues noted above.

4.5 Photovoltaic Modules and Manufacturing Hubs

Silicon solar cells are then assembled into PV modules. Of course, for thin film technologies like CdTe, the product is directly a module. The module-making process for silicon is basically an assembly process with low cost of entry, and therefore there are several companies in India which already do module manufacturing using imported (or domestic) cells. It is transitioning to high automation, required for large multi- GW capacity, good throughput and high yield. Although the technology involved in module assembly is not as sophisticated as in cell making, advances in manufacturing have greatly affected module assembly. Furthermore, advances and changes in module structures have contributed to the reduction in the cell-to-module (CTM) losses, resulting in improvements in module efficiency.

Some of the new developments in module assembly include the emergence of bifacial modules, use of 4-, 5-, and multi-BusBar, use of half-cells and quarter-cells instead of full cells (which can increase power output), and use of different sizes of solar cells from M2 to M12. A new module manufacturing plant in India will need to be highly automated and flexible in order to respond to changes in technology.

Going into the module manufacturing process are several other components besides just the solar cell. This includes the glass, backsheet, encapsulant, ribbons, aluminium frame and junction box. At present, many of these components are imported. This poses logistics problems of ensuring that supplies are available well in time. The technology for the manufacture of these items is not as sophisticated or capital-intensive as cells, and it is very possible to have these made in India. If the full supply chain for solar manufacturing has to be present in India, all of these need to be available as well. A detailed description of the manufacture of these other items is beyond the scope of this White Paper.

It is pertinent here to point out the advantages of having solar manufacturing hubs. This would include solar cell manufacturing as well as module manufacturing plants. As mentioned earlier, solar cell manufacturing itself requires many inputs besides silicon – high-purity gases and chemicals, silver paste, etc. Furthermore, module manufacturing requires several other components listed above. It would be advantageous to have many of these manufacturing units located at a solar manufacturing hub or cluster for consolidation of supply chains. In addition, some of the BOS component manufacturing like solar inverters could also be located in such a hub. This would reduce transportation costs and time, which will go some way in reducing the overall cost of the final product. For an industry where profits can be razor-thin, this can provide a significant advantage. It is well known that China has been successful in solar manufacturing partly because of its tightly coupled and proximately-located supply chain.

An additional aspect of solar PV manufacturing should be addressed. This is the design and production of equipment to make solar cells and modules. Traditionally, such equipment came from

USA (for example Applied Materials) or Europe (for example Meyer Burger). More recently, Chinese companies have been making these equipment at much lower price, which is one reason that cells and modules from China are priced lower than ROW (Rest Of the World). India has a rich tradition of developing complex manufacturing equipment, and we can start by licensing designs from Europe and adapting the design for the Indian environment. It is worthwhile considering this aspect of solar manufacturing, though it is not directly a part of the supply chain. Such equipment manufacturing factories can also be set up in the solar manufacturing hubs, which will have many benefits both for the equipment manufacturer and the cell/module manufacturer.

We have described the various technology options for solar cells and modules in the sections above. Fig. 7 provides an overview of technology options India should focus on throughout the whole solar PV value chain. There are significant techno-economic-policy related implications, and all of these would have to be carefully considered before deciding on a final strategy.

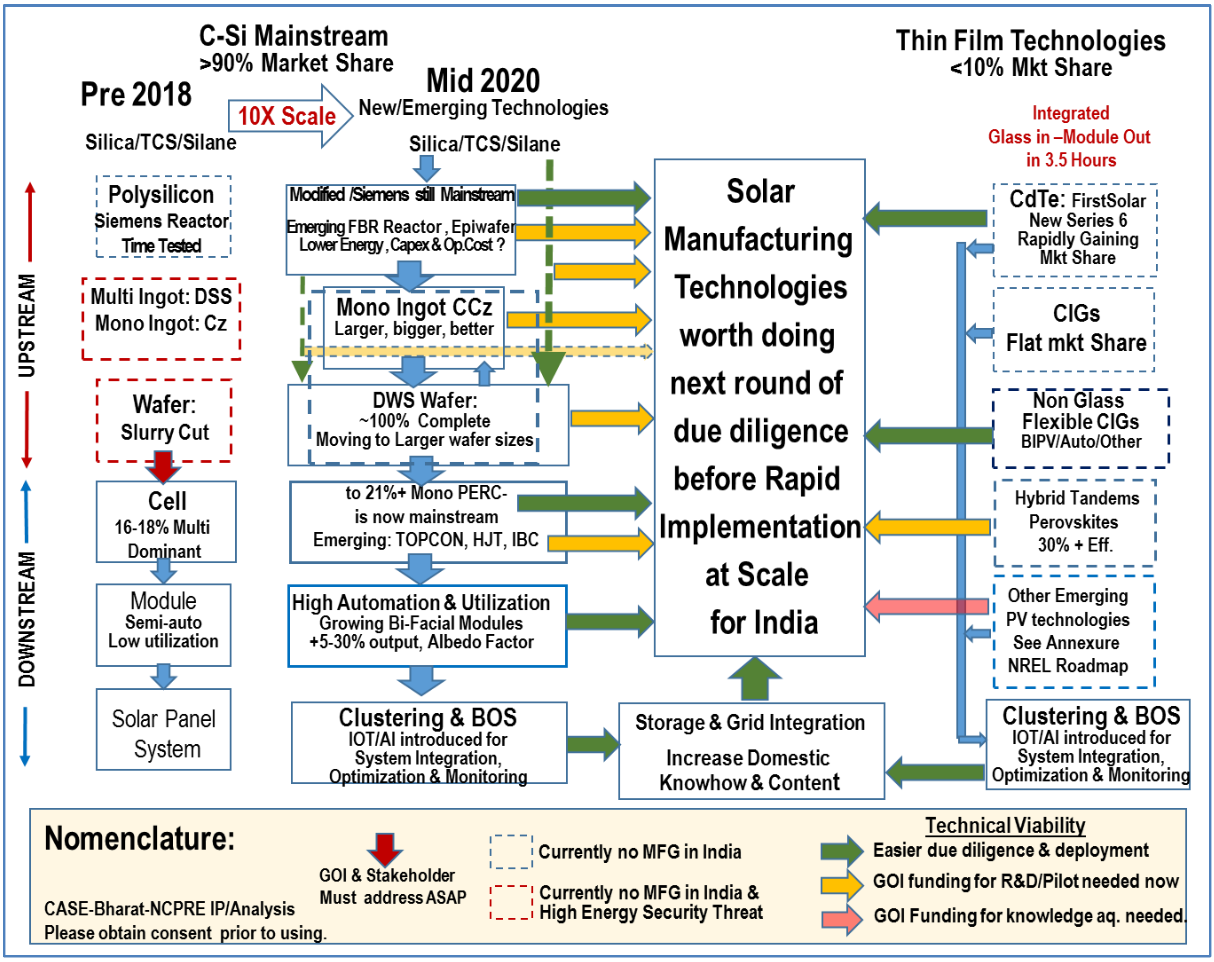

Figure 7. PV Technologies: An overview of Options available

4.6 Global Best-in-Class Solar PV Modules for Different Solar Technologies

In this section, we perform a comparative analysis of different solar technologies comparing their key performance metrics and estimated price per watt to produce this technology. Of course, it should be re-iterated that beyond this analysis, there are several other factors which would go into the final choice of a particular technology by a company.

The first part in this study is to compare the specifications and performance metrics of some of the 'best-in-class' representative modules using different cell technologies as provided in the data sheets. The key performance metrics are module efficiencies, output, and degradation over lifetime. The current trend focuses on maximizing output for each module on an M2 basis as this is directly tied to revenue generation. It is important to cross-check 'claimed' data with reliable third party certifications as well as consider local conditions where modules will be installed. Some details of each of the technologies chosen in Table 1 are given below.

Table 1: An Overview of Best-in-Class PV options as of Q3 2020

		Best in Class CSi Modules from Datasheet Sep 2020						Best in Class Thin Film	
Module Name	**Adani Encore**	**Trina Vertex**	**Longi Hi-Mo4**	**Jinergy JNHM144**	**REC ALPHA**	**SunPower A Series**		**FSLR Series 6**	**2021 Target?**
cell Mono	M1/M2?	H12 210 mm2	M6 166 mm2	166MM2?	M4?	M4 161.7mm2		CdTe	CdTe
Cell Type	Mono PERC P type	Mono N type?	Mono PERC P Type	N type HJT	N type HJT	Maxeon Gen 5 IBC cells		NA	NA
Total Half Cut Cells*	72	120	144	144	144	72		NA	NA
L in Meters	1.998	2.172	2.094	2.094	2.06	1.999		2.009	2.009
W in Meters	1.01	1.303	1.038	1.038	1.02	1.016		1.232	1.232
Area M2	2.02	2.83	2.17	2.17	2.10	2.03		2.48	2.48
Max Front Output W	345	600	455	465	450	450		450	500
Bifacial Gain Max	NA	10%	25%	30%	??	NA		NA	NA
Bi Facial Output	NA	642	556	604.5	??	NA			NA
Lab Efficiency (NREL)	**22.30%**	**26.10%**		**26.60%**	**26.60%**			**22.10%**	
Max Front Eff.	**17.10%**	**21.20%**	**20.90%**	**21.40%**	**21.30%**	**22.20%**		**18.20%**	**20.2%**
Front Output/M2	**170.96**	**212.01**	**209.33**	**213.93**	**214.75**	**221.57**		**181.81**	**202.01**
Bifacial Output/M2	NA	226.85	255.80	278.11	??	NA			
1st Year Degradation*	3%	2%	<2.00%	<2.5%		1.0%		2%	2%
Annual Degradation*	0.68%	0.45%	<0.45%	0.40%		0.3%		0.50%	0.50%
Output Warranty 25 years	81.18%	87.20%	87.20%	88.40%	92.00%	89.00%		86.00%	??
Weight Kgs	22.70	35.30	27.50	26.30	23.64	21.60		34.50	34.50
* Sun power exception: Full cells, 1st 5 years degradation per annum, then 0.3% for next 20 years.									
						CASE-Bharat Analysis & Insights			

Adani Multi c-Si cell Encore series: We have selected Encore series as a place holder representation of Best-in-Class India-based module to compare with other best-in-class PV options around the world. Even while Adani has the latest cell and module 1.5 GW integrated plant in India, it may not be a fair comparison as multi-c cell based modules still dominates the domestic demand largely due to lowest PPA driven reverse tenders. While Adani has 200 MW mono PERC cell and 50 MW bifacial cell manufacturing capabilities, capacity utilization and process improvement may be lagging due to lack of demand. Multi c-Si outputs @ 345 W and efficiency @ 17.1% lag the other best-in-class examples shown. One major reason c-Si PV manufacturing is transitioning to mono c-Si based architecture is that the efficiency for laboratory cells recorded by NREL is 22.3% for multi c-Si compared to > 26% for mono c-Si. This is a clear indication that India needs to provide incentives to adopt new mono c-Si based technologies and policies to help scale and acquire process and manufacturing competencies over the next four years.

Trina Vertex: Trina's most advanced mono PERC module is based on H12 (210 mm^2) cell size that can produce maximum 600W output from the front surface @ 21.2% efficiency. Most likely it uses n-type cells to get a higher efficiency than mono PERC with p-type cell. This is yet to be commercialized at scale. Note that the size of the module is 30% more and so is the weight.

LONGi Hi-MO4: This is a 144 half-cut mono PERC p-type cell based on M6 (166 mm^2) size. Max Output is 455W @ 20.9% efficiency that can increase up to 556W if a 25% increase from back surface can be achieved. Output/m^2 is 209W/m^2 front, 256W/m^2 bifacial. Weight is 27.5 kg. LONGi Hi-MO4 is currently a high volume multi GW mainstream product. Output rating/warranty after 25 years: 87.2%.

Jinergy n-type HJT 144 (half-)cell Module: Since the size is exactly same as LONGI HiMO 4, we assume it is using a M6 size cell. Max Output is 465W @21.4% efficiency that can increase up to 605W if a 30% increase from back surface can be achieved. Output/m^2 is 214W/ m^2 front, 278W/m^2 bifacial @25%. Weight is 26.3 kg. Output rating/warranty after 25 years: 88.4%.

REC Alpha 144 cell HJT Alpha Series: REC has set up a 600 MW plant with most of its equipment from Meyer Burger. The unit got commissioned in early 2020. Max Output is 450W @21.3% efficiency. Output/m^2 is 215W/m^2. Weight is 23.6 kg. Output rating/warranty after 25 years: 92%, best in Industry.

SunPower A Series with Maxeon Gen 5 IBC cells: SunPower A Series with Maxeon Gen 5 IBC 72 cells module produces the highest efficiency at 22.2% and highest output per m^2 at 222 W/m^2. However the current design does not permit bifaciality and high price limits IBC cell based modules primarily for space-constrained rooftop markets in residential and C&I space.

First Solar (FSLR) Series 6 CdTe Module: First Solar is the only Thin Film manufacturing company that is listed in the top 10 module shipment companies currently. While their current max output is 450 W/module and max efficiency is 18.2%, they are on track to get to 20.2% efficiency and 500 W/module output with the same form factor. Currently their normalized output per m^2 is 182 W/m^2 and that is expected to improve to >200W/m^2 by 2021. While their output warranty after 25 years at 86% seems to be lower than many best-in-class c-Si base module manufacturers listed in this table, NCPRE and many other global testing companies have found consistently that their output degradation is the lowest among all the different modules tested. The current format of Series 6 cannot offer bi-facial capabilities.

We now review the current and potential estimated pricing by YE 2024 of different c-Si based options as well as First Solar's CdTe, and explore what can be the potential roadmap for getting there. The component pricing for poly/multi c-Si and mono PERC are extracted from PV Insights (September 2020). The pricing for each of the components for HJT and IBC are estimates based on our analysis and insights gleaned from several analysts and research papers. PV Insights records high, low and average prices. Average prices for multi and mono PERC components tend to be much closer to low prices shown. China price variance between high and low have narrowed significantly after China moved away from FIT and have adopted lowest price tenders similar to India where this initiative was pioneered. We show here only the low/average price (Fig. 8).

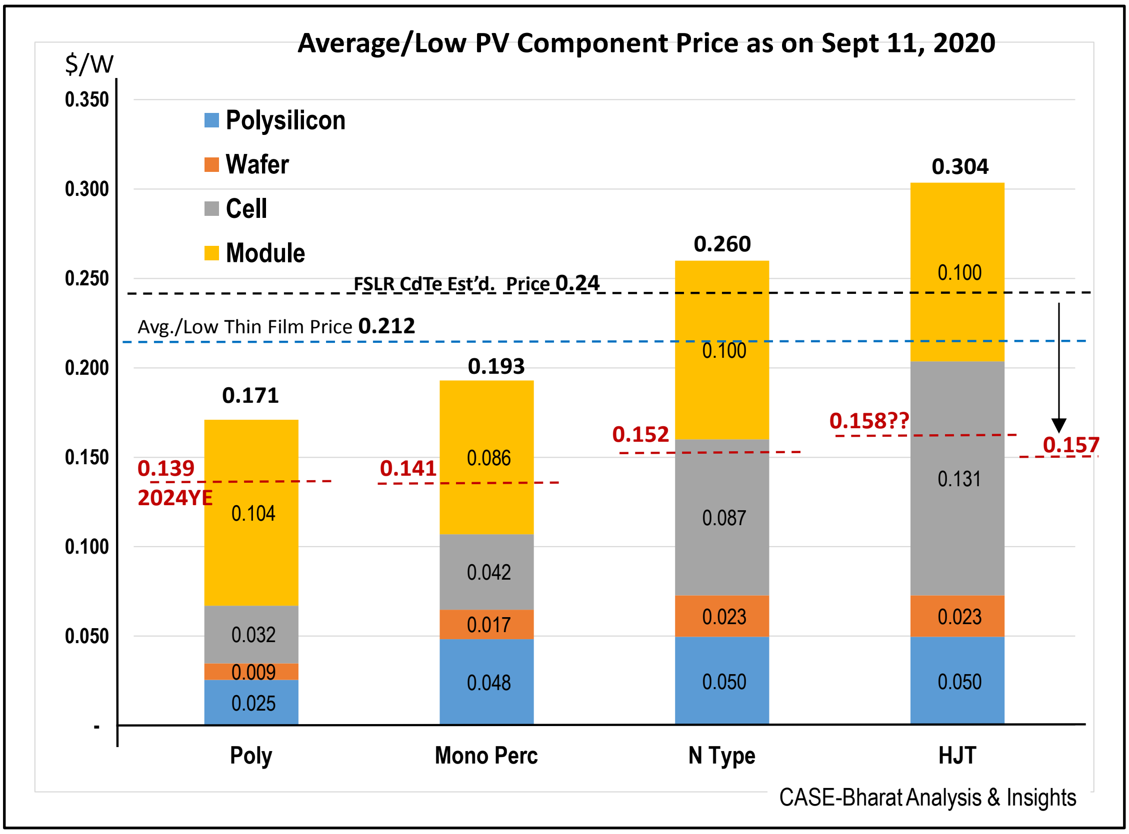

Figure 8. c-Si Component Prices ($/W) in September 2020 and Future Trend (2024) Implications. Also shown are the Thin Film: CdTe potential price points for 2024.

The estimates for 2024 have been obtained by our calculations based on inputs from various sources. These details are not given here, and will be presented in the expanded version of this White Paper. The highlights of the analysis, however, are presented here.

It can be seen that the price differential between multi (poly) and mono will almost vanish by 2024. It will become almost impossible to make any money as an investor for an integrated multi based Polysilicon-to-Module plant in the future. There may be a short term opportunity for multi-based module makers if they can have access to very low fire-sale prices of wafers and cells in the near future. n-type mono technologies such as TOPCon PERC will reduce considerably in price and approach p-type PERC. Because of superior performance of n-type (including lower degradation), this becomes an attractive technology. HJT technology also approaches standard p-type PERC, making this also an attractive option, especially since it is particularly suitable for bifacial and tandem. Finally, CdTe will remain competitive with PERC and HJT, and will continue to play a role in future deployments. The bottom line is that Indian companies can invest in p-type mainstream PERC (but must be able to compete aggressively with Chinese companies eventually), and can invest in n-type TOPCon-like PERC and HJT (where competition may be less intense). A tie-up with a thin film company producing CdTe is also likely to yield positive returns.

Figure 9 sums up a potential cell manufacturing roadmap for each of the c-Si architectures we have discussed above. The output shown is from the front surface, and bifacial output from the rear surface can be additional output. A more in-depth analysis is beyond the scope of this White Paper and this will be addressed at an appropriate point in the future.

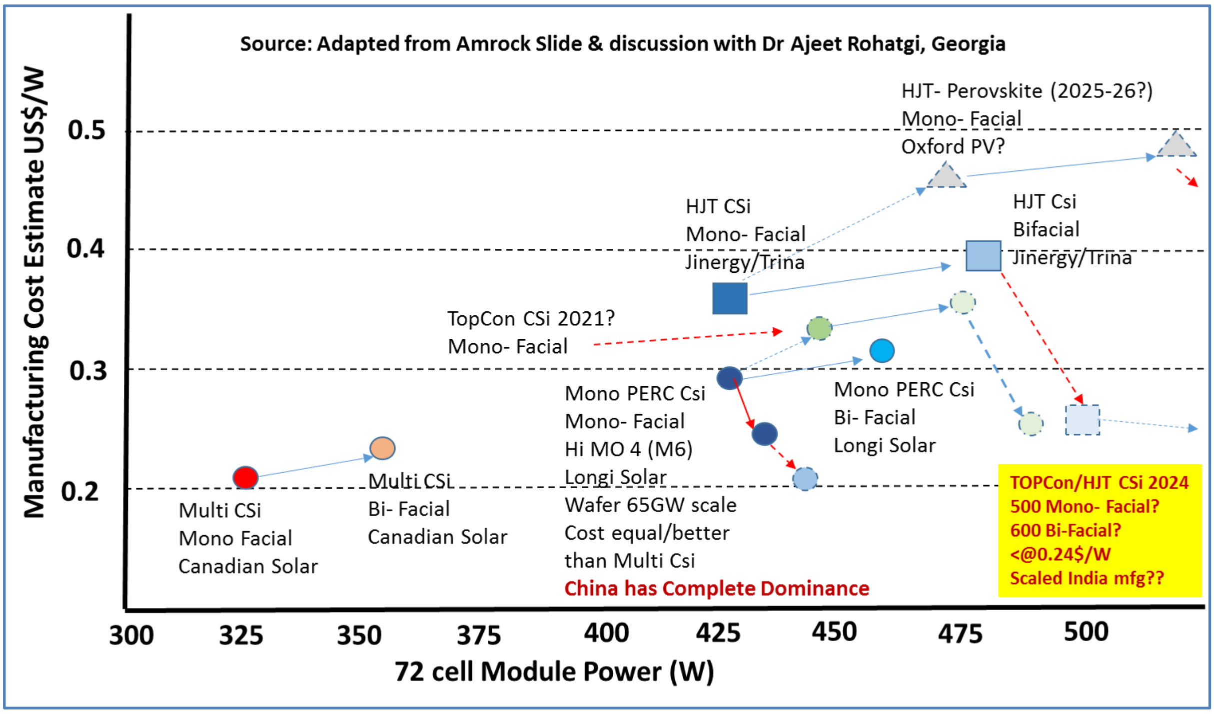

Figure 9. Cell Manufacturing Options for India

A majority of R&D investments for the solar value chain go to incremental but rapid innovations in different mainstream cell technologies. China has excelled in this area in the last decade through close interaction between R&D centers, manufacturing and equipment suppliers. There is a need for continuous R&D, and this is addressed next.

4.7 The Need for R&D

Solar technologies advance very rapidly. Many of the technology changes are incremental, but disruptive changes can also occur. We have already seen a couple of such disruptive changes during the last decade and a half, and another (perovskite-silicon tandems) may be around the corner.

Although Indian companies may initially have a tie-up or purchase a technology from a global player, it must eventually have access to an R&D facility where new ideas, whether incremental or disruptive, can be explored. This R&D facility can be in-house, or can be an independent R&D facility. If India is to become truly self-sufficient in solar manufacturing in the long run, there must be a continual emphasis on R&D.

NCPRE has submitted to MNRE two reports – one on Global R&D in Solar PV [12] which gives a review of the current research activities being pursued world-wide, and another on a more focused review of Solar R&D required in India [13] to achieve the ambitious 300 GW target by 2030. The latter report describes the following activities which will be critical for India in the coming decade: solar manufacturing and hubs; next generation utility scale PV power plants, and digital analysis of their performance and reliability; reliable and compact inverters; grid management and storage integration; new and 'space-efficient' applications for solar PV; solar for water-food-energy nexus; novel testing methods, new standards and certification; and futuristic solar PV technologies. The emphasis is on R&D which is particularly relevant for India and Indian conditions, and much of such R&D is unlikely to be undertaken elsewhere. It can be seen that this is a large portfolio of research activities which would involve many academic and R&D organizations.

Government can help by providing long-term support to independent research centres, including research centres at academic institutions, where innovative and promising ideas can be tried out. Young research students like to explore new avenues, and an increasing number want to pursue a career in entrepreneurship. This is now turning out to be a fruitful way to convert ideas into start-up companies. Many of the recent international companies, including Oxford PV, 1366 and Flisom had their origins in university laboratories. Government should also provide tax and other incentives for companies to carry out research. An excellent way will be to provide funding to research centres to work on specific applied projects in collaboration with a company to explore the next stages in technology development. Another important way would be to ensure that the R&D centres are well networked (and possibly jointly funded), so that they work in unison.

5. Self-Reliance and Competitiveness in Solar Manufacturing

5.1 Country-wise cost of manufacturing

Individual countries have different costs for manufacturing various items. This is, of course, the reason why global trade exists, with each country exporting what it does or makes most efficiently, and importing things that other countries make better or more economically. However, there are limits to global trade for several reasons, which include security, local employment, trade barriers, and the need to diversify supply chains.

In the case of solar PV technology, China has emerged as the dominant global player, and many other countries which used to manufacture solar cells and modules, including Germany, USA, India, S. Korea, Taiwan and Japan have had difficulty competing. It is useful to compare the relative costs of manufacturing various components of the silicon value chain. This was done recently by NREL and is presented in their Technical Report entitled *Crystalline Silicon Photovoltaic Module Manufacturing Costs and Sustainable Pricing: 1H 2018 Benchmark and Cost Reduction Road Map* [14]. It is instructive to examine the data presented there for various countries, and use it to estimate production costs in India. The NREL Report looks at all the steps in the silicon manufacturing chain, starting from polysilicon, and going up to the final module. We examine only two of these steps, namely manufacture of silicon solar cells and manufacture of solar modules.

Figure 10 shows the cost model results for mono-Si PERC cells made in different countries in 1H 2018, assuming that the silicon wafers and polysilicon were also made in the same country. The model breaks up the final cost into several parts, including the wafer cost, plus all the additional costs, including electricity, labour, depreciation, maintenance, R&D, and administrative. However, it should be noted that costs related to tariffs, transportation (shipping), and interest on capital are not included. It can be seen from the figure that costs for PERC cells vary significantly from $ 0.33/W in Germany to $ 0.18/W in 'Lowest Cost' China.

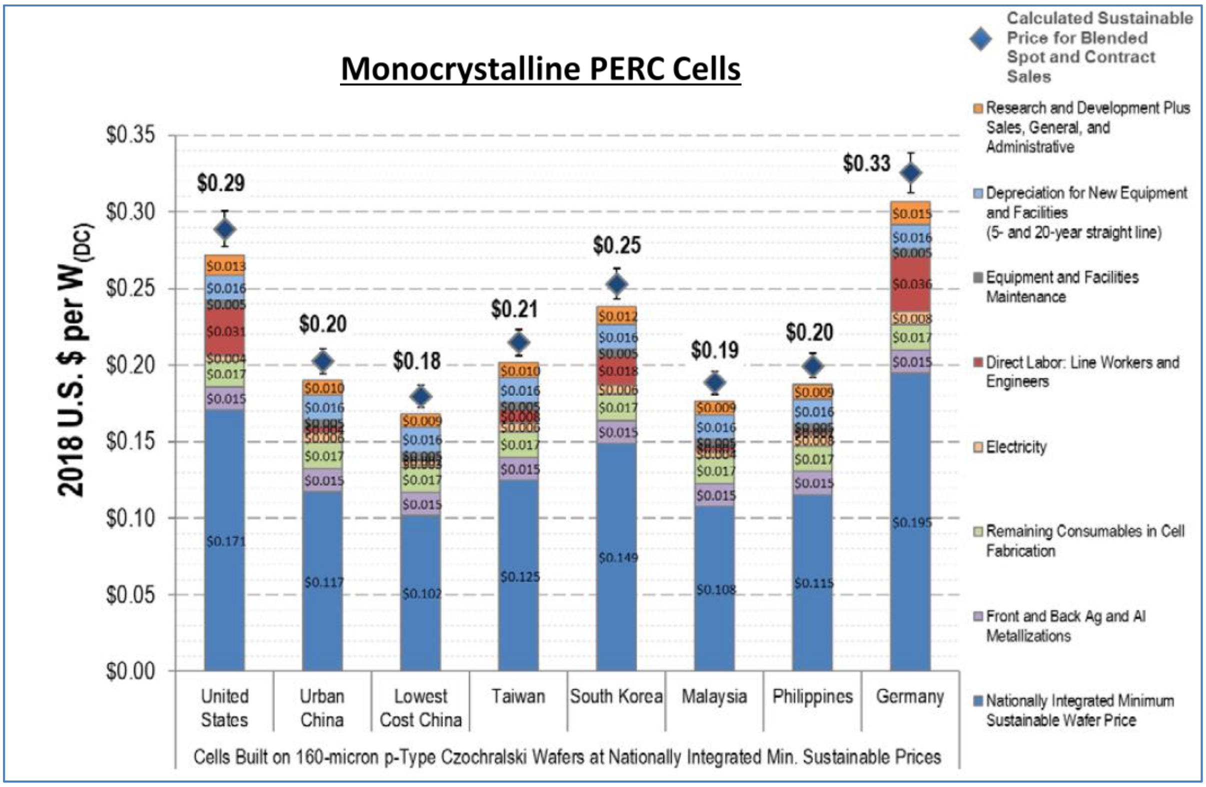

Figure 10. Cost of manufacture of monocrystalline PERC cells in different countries [14].

We can use a similar procedure to estimate the approximate cost of mono PERC cell fabrication in India, assuming that silicon wafers are imported from Taiwan without any duty but including a shipping cost of $ 0.01/W. Also, the electricity cost will be more in India (by $ 0.005), and we also add higher interest cost to depreciation (say $ 0.01) compared to Taiwan. On the other hand, labour and admin costs are likely to be less by about $ 0.005. Other costs are assumed to remain the same as in Taiwan. This results in a mono PERC cost of $ 0.23/W for production in India. This renders the India cost more than that of China, Taiwan, Malaysia and Singapore. However, imposition of a 25% duty makes this the cheapest of all (Lowest Cost China is $ 0.225/W, but add $ 0.01/W for shipping).

We can similarly perform the analysis for the cost of production of PV modules using mono PERC cells. Figure 11 shows the cost of manufacture in different countries from the NREL report. Again, the costs vary widely, from $ 0.53/W in Germany to $ 0.37/W in Lowest Cost China. As before, we can attempt to estimate the cost of modules manufactured in India. We assume that cells are either domestically produced in India, or imported from Lowest Cost China with a 25% duty. Then the cost of the cells would be $ 0.23/W or $ 0.235/W respectively. Accounting for higher electricity and interest costs, but lower labour and admin costs than Taiwan as earlier, we find the approximate cost of making mono PERC modules in India would be $ 0.415/W. If a 40% duty were to be imposed on modules, this would be by far the cheapest (Lowest Cost China would be $ 0.47/W, without shipping costs). According to this analysis, a 30% duty on imported modules would also serve the purpose.

It should be emphasized, however, that these preliminary estimates for India cost are very approximate. Furthermore, these data refer to 1H 2018. A more detailed and updated calculation needs to be performed, which will have to take into account various other aspects such as existence (or absence) of supply chain clusters, productivity of labour, yield, policy uncertainty, etc. which are difficult to quantify at this stage, and all of which would add to the cost of manufacturing in India compared to China or Taiwan.

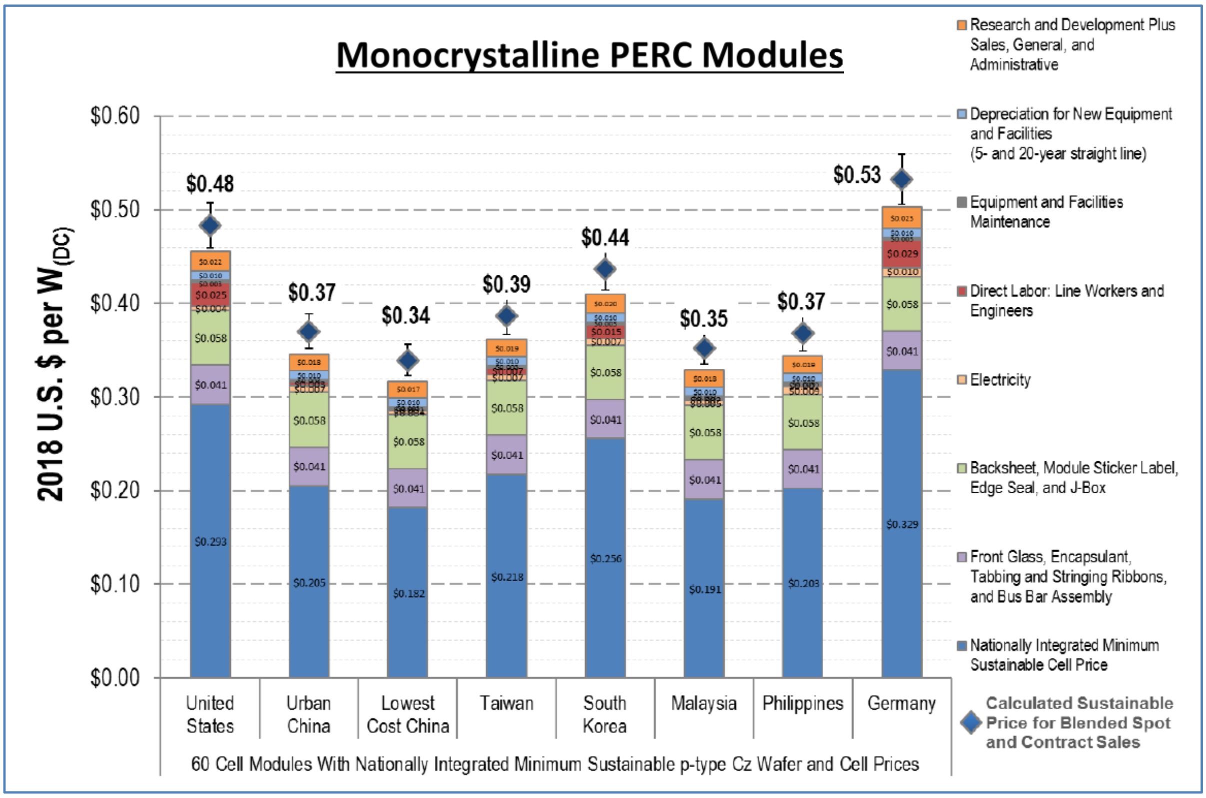

Figure 11. Cost of manufacture of mono PERC modules in different countries [14]

5.2 Self-Reliance versus Competitiveness

Self-reliance and competitiveness are often viewed as two conflicting requirements. On the one hand, self-reliance promotes security and local generation of employment, which provides significant returns in the long term, but can lead to production of uncompetitive products in the short term.

In the case of solar manufacturing, the best way forward is first to aim for self-reliance, and boost the local industry. This can be done by providing incentives or imposing duty (though avoiding violation of WTO rules). However, this cannot continue for too long, and eventually the transition has to be made for Indian industry to become competitive with other countries. This can take several years. It should be remembered that China took more than 10 years before it became the global leader in solar PV. It should also be mentioned that many other countries are now attempting to return to solar manufacturing, including Europe and USA. Europe, led by Germany, is contemplating setting up an integrated 10 GW GreenFab [15], and the new administration in USA has proposed to commit $ 2 trillion to clean energy [16]. There are obvious synergies here for India to work closely together with such countries.

6. Recommendations and Conclusions

The current status of solar manufacturing in India is about 10 GW of module manufacturing and 3 GW of cell manufacturing. As per our analysis, of the 10GW of operational module capacity, about 4 GW is being produced and sold to domestic and international customers, 2 GW is idle and as much as 4 GW is outdated and hence needs to be updated or discarded. Of the name plate 3 GW of cell capacity, only about 1GW is produced and sold to domestic and international customers, and the remaining 2 GW is idle and/or outdated/defunct.

Our recommendation is to target 20-25 GW of integrated module manufacturing capacity by 2024-25. Assuming a 75% utilization for module plants, domestic module output can be about 15 to 18 GW/ year. This will mean that some modules will be imported to meet the annual requirement of 20 to 30 GW. Cell manufacturing capacity should be targeted at 15-20 GW. As mentioned earlier, the cell technology would include mono PERC (both p- and n-type), as well as HJT and some thin film (CdTe). The exact details would need to be worked out by individual companies who will invest in the plants. In parallel, India should also plan to set up ingot/wafering facilities of capacity 12-15 GW to ensure a reliable supply for cell manufacturers. High-quality polysilicon is still available internationally, but it is necessary to have this manufacturing also in India in the near future, since China's presence in this sector is growing rapidly. The choice for India should be state-of-the-art energy efficient technologies. In parallel, epi and direct wafer technologies should also be explored. As India streamlines its integrated solar manufacturing to become globally competitive over a 4-8 year horizon, domestic content can increase and India can become a reliable option for exports.

While perovskites and perovskite-silicon tandems may not reach GW scale commercialization before 2025, it is recommended that we should invest in R&D in this area to acquire deeper knowledge and keep the options open. This will be an attractive potentially disruptive technology to pursue. India's expertise in chemistry and materials over many decades will be a plus point.

The Government should support 'directed' applied R&D in several organizations including IITs, universities and research laboratories to ensure that the solar industry is continuously updated and supplied with well-trained manpower. Encouragement should be provided to young technologists coming out or research laboratories to become entrepreneurs.

We recommend that a meeting among the leadership in GOI be held in the near future before this White Paper is released to the industry and other key stakeholders. Policy and budget implications may dictate the next level of due diligence required to make large scale integrated and sustainable solar manufacturing a reality by the end of this decade.

In conclusion, solar PV manufacturing for India has become an urgent necessity as we move towards the 300 GW target in 2030, and also presents unique opportunities for advancing the 'Make in India' and Atmanirbhar Bharat programmes, and thereby rejuvenating India's manufacturing ecosystem. This White paper has presented an analysis of the technology options which are available, and which should be chosen as most suitable for India. This paper has focused mainly on the semiconductor value chain, but equal technology-based analyses are required for other materials like glass, encapsulant, backsheet as well as BOS components.

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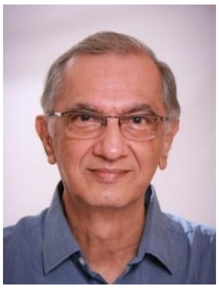

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