STATE OF ART OF SOLAR PHOTOVOLTAIC TECHNOLOGY

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Solar electricity is more expensive than electricity produced by traditional energy sources. But over the past two decades, the cost disparity has narrowed. Photovoltaic (SPV) technology has become a useful energy source in applications such as lightning to meet the electricity needs of villages, hospitals, telecommunications and houses. The long-term and growing dominance of crystalline silicon in the photovoltaic (PV) market is perhaps surprising given the wide range of materials that produce the photovoltaic effect. Silicon wafer-based solar has captured more than 90 percent of the market share because it is more reliable and generally more efficient than competing technologies. Crystalline silicon PV is reliable for long-term stability in the real field, but it is not economically feasible because silicon itself is expensive as a starting material. However, research into the development of versatile alternative photovoltaic technology continues. Now, solar electric technology is increasingly recognized as part of the solution to the growing energy problem and as an integral part of future global energy production. In this article, we provide a brief overview of solar energy technology, especially crystalline silicon, including global and Indian solar energy scenarios.

1. Introduction

Solar energy is the most readily available and free source of energy since prehistoric times although it is used in most primitive way. Solar energy can be used directly for heating and lighting home and buildings, for generating electricity, cooking food, hot-water heating, solar cooling, drying materials, and a variety of commercial and industrial uses [1–3].

Solar energy can be utilized through two different routes, solar thermal routes and solar photovoltaic routes [4, 5]. Solar energy can be converted into thermal energy with the help of solar collectors and receivers known as solar-thermal devices. PV-created direct current (DC) electricity that can be used as such is converted to alternating current (AC) or stored for later use. This type of solar electricity is more expensive than that produced by traditional sources. But over the past two decades, the cost gap has been closing. Solar photovoltaic (SPV) technology has emerged as a useful power source of applications such as lightning, meeting the electricity needs of villages, hospitals, telecommunications, and houses.

The long and increasing dominance of crystalline silicon in photovoltaic (PV) market is perhaps surprising given the wide variety of materials capable of producing the photovoltaic effect. PV based on silicon wafers has captured more than 90% market share because it is more reliable and generally more efficient than competing technologies [6]. But it is not economically viable due to starting material silicon itself costly. Therefore, research continues on developing a diverse set of alternative photovoltaic technology.

Now PV technology is being increasingly recognized as a part of the solution to the growing energy challenge and an essential component of future global energy production. In this paper, we give a brief review about particularly crystalline silicon PV technology including the world and Indian PV scenarios.

2. Photovoltaic Technologies

The early dominance of silicon in the laboratory has extended to the market for commercial modules. Crystalline silicon

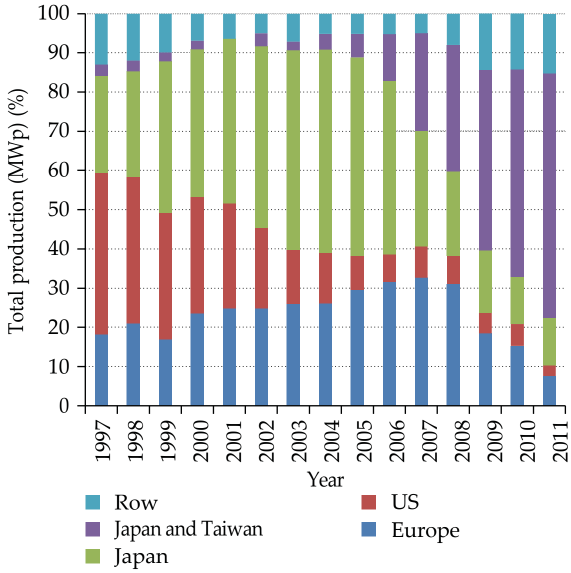


Figure 1: PV cells/modules production by region 1997–2011.

designs have never accounted for less than 80% of the market for commercial modules and nearly 15–18% of the market was not crystalline silicon. It was based on amorphous silicon-a PV technology that is almost exclusively used for consumer electronics such as watches and calculators. If we were to exclude electronics and define the market as electricity delivery system of 1 kW or more, current production is dominated by single-crystal and polycrystalline silicon modules, which represent 94% of the market. There are a wide range of PV cell technologies on the market today, using different types of materials, and an even larger number will be available in the future. PV cell technologies are usually classified into three generations, depending on the basic material used and the level of commercial maturity [7].

(i) First-generation PV systems (fully commercial) use the wafer-based crystalline silicon (c-Si) technology, either single crystalline (sc-Si) or multicrystalline (mc-Si).

(ii) Second-generation PV systems (early market deployment) are based on thin-film PV technologies and generally include three main families: (1) amorphous (a-Si) and micromorph silicon (a-Si/□c-Si); (2) cadmium telluride (CdTe); and (3) copper indium selenide (CIS) and copper indium-gallium diselenide (CIGS).

(iii) Third-generation PV systems include technologies, such as concentrating PV (CPV) and organic PV cells that are still under demonstration or have not yet been widely commercialized, as well as novel concepts under development.

Commercial production of c-Si modules began in 1963 when Sharp Corporation of Japan started producing commercial PV modules and installed a 242 Watt (W) PV module on a lighthouse, the world's largest commercial PV installation at the time (M.A. Green 2001). Total PV cells/modules production by region 2007–2011 (data: Navigant consulting graph: PSE AG 2012) is shown in Figure 1. It has been observed that Japan attributed to increase their PV cells/modules production capacity from 1997 to 2004 and then drastically reduced their production capacity after 2004. Same trend was observed in PV cells/module production in Europe also but up to year 2008, and then they reduced their production capacity. On the other hand in year 1997, PV cells/module production capacity of US was the highest, and after then they reduced their production capacity every year. Whereas PV cells/modules production scenarios of China were just the reverse compared to US. Given the vast potential of photovoltaic technology, worldwide production of terrestrial solar cell modules has been rapid over last several years, with China recently taking the lead in total production volume as shown in Figure 1. Another interesting picture related to the global cumulative PV installation until 2011 was noticed as shown Figure 2. It was observed that still Germany including other European country contributed to major role towards the global cumulative PV installation until 2011, that is, 70% of global PV installation. So PV installation market in Europe is too much promising till now compared to other countries.

Figure 3 shows the PV production development by technology in the year 2011. It was from this global PV production scenario in the year 2011 that almost more than 85% of the solar cell production was based on crystalline silicon. Even it was observed that even PV installation scenario, crystalline silicon solar cell, dominated the world market as indicated in Figure 4.

The year wise efficiency record of solar cell fabricated under different technological approaches is shown in Figure 5. From this record, it is evident that laboratory monocrystalline silicon solar cell efficiency was still higher

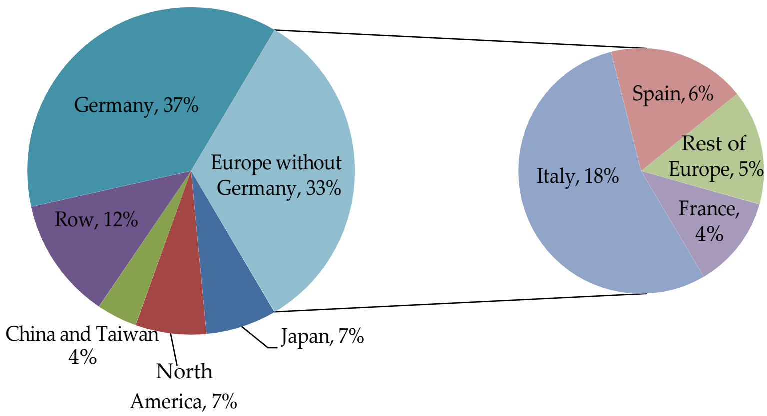


FIGURE 2: Global cumulative PV installation until 2011 (data: EPA Graph: PSE AG 2012). All percentages are related to the total global installation.

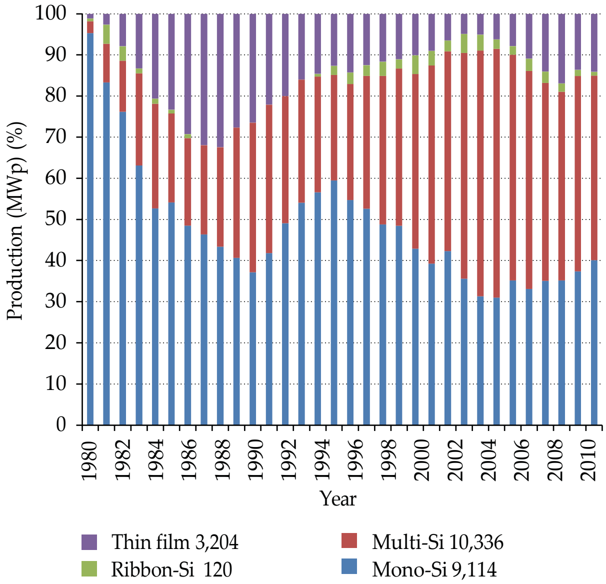


FIGURE 3: PV production development by technology (data: Navigant Consulting Graph: PSE AG 2012).

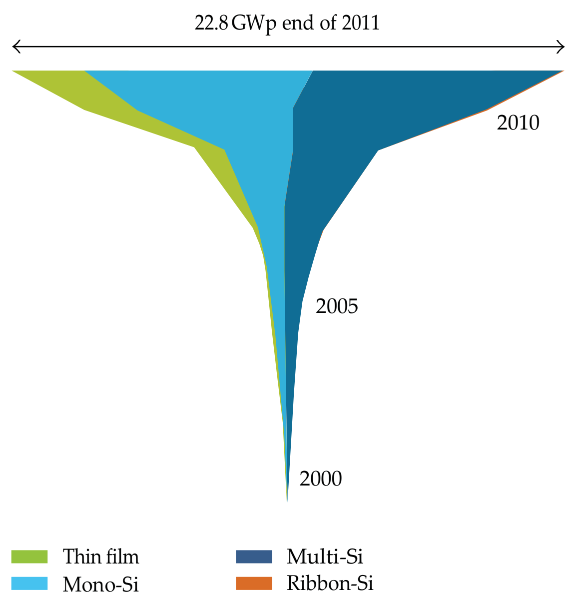


FIGURE 4: Global annual PV installation by technology at end of 2011 (data: Navigant Consulting Graph: PSE AG 2012).

compared to other existing solar cell technology except III-V multijunction concentrator solar cell and monocrystalline concentrator solar cell, respectively.

Best laboratory cell versus best laboratory module fabricated under different PV technology is also given in Figure 6. It is observed from Figure 6 that the lab. made monocrystalline solar cell and module efficiency were 25% and 22.9%, respectively, whereas multicrystalline solar cell and module efficiency were 20.4% and 18.2%, respectively. One important point to be noted is that the efficiency of thin film CI(G)S solar cell was 19.6% (area 0.42 cm²). So there is enough scope of work related to CI(G)S solar cell technology.

After more than 20 years of R&D, thin-film solar cells are beginning to be deployed in significant quantities. Thin-film solar cells could potentially provide lower cost electricity than c-Si wafer-based solar cells. However, this is not certain, as lower capital costs including lower production and materials costs are offset to some extent by lower efficiencies and very low c-Si module costs make the economics even more challenging.

Thin-film solar cells comprised successive thin layers, just 1 m to 4 m thick, of solar cells deposited onto a large, inexpensive substrate such as glass, polymer, or metal. As a consequence, they require a lot less semiconductor material to be manufactured in order to absorb the same amount of sunlight (up to 99% less material than crystalline solar cells). In addition, thin films can be packaged into flexible and lightweight structures, which can be easily integrated into building components (building-integrated PV, BIPV).

Third-generation PV technologies are at the pre-commercial stage and vary from technologies under demonstration (e.g., multijunction concentrating PV to novel concepts

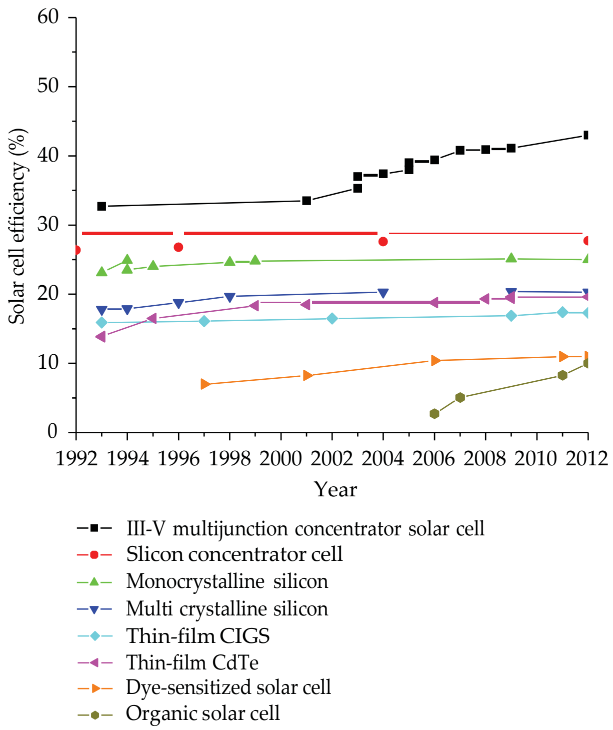


Figure 5: Development of laboratory solar cell efficiency (Data: Solar Cell Efficiency tables (version 1-40), Progress in PV: Research and Applications, 1992–2012, Graph: Simon Philipps, Fraunhofer ISE).

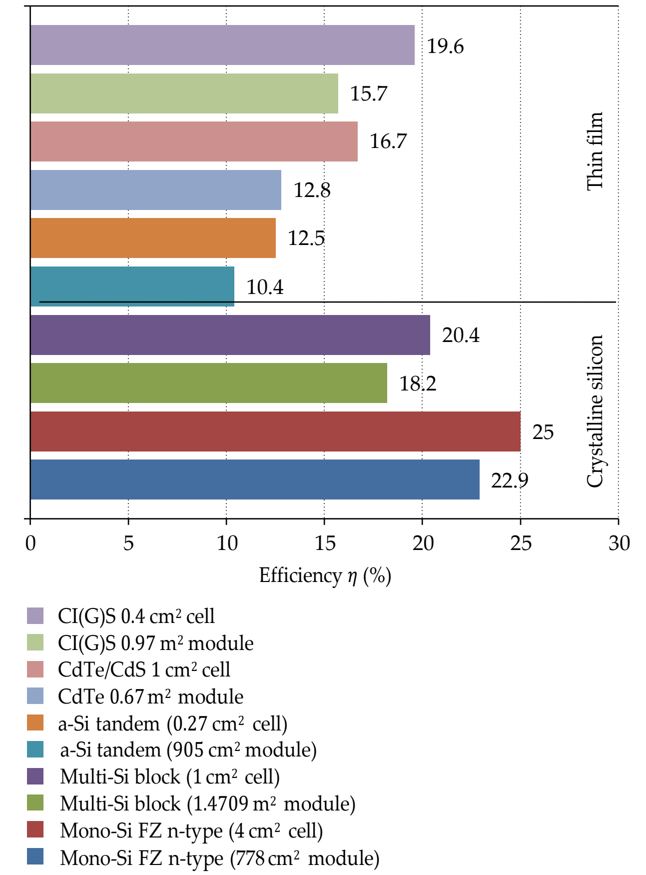


Figure 6: Efficiency comparison of technology: best laboratory cells versus best laboratory module (Data: Green et al.; Solar Cell Efficiency tables (version 1-40), Progress in PV: Research and Applications, 2012, Graph: PSE AG 2012).

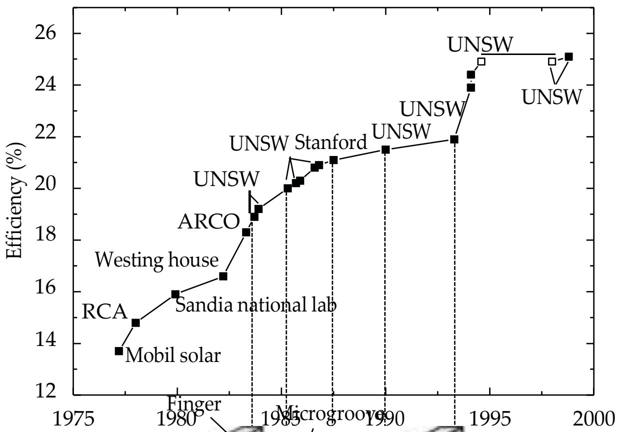
still in need of basic R&D (e.g., quantum-structured PV cells). Some third-generation PV technologies are beginning to be commercialized, but how successful they will be in taking market share from existing technologies remains to be seen.

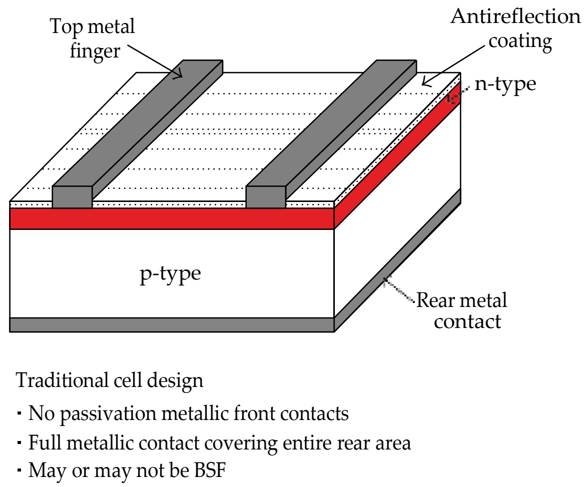
Novel and emerging solar cell concepts in addition to the previously mentioned third-generation technologies; there are a number of novel solar cell technologies under development that rely on using quantum dots/wires, quantum wells, or super lattice technologies (Nozik, 2011 and Raffaelle, 2011). These technologies are likely to be used in concentrating PV technologies where they could achieve very high efficiencies by overcoming the thermodynamic limitations of conventional (crystalline) cells. However, these high-efficiency approaches are in the fundamental materials research phase. Furthermore from the market are the novel concepts, often incorporating enabling technologies such as nanotechnology, which aim to modify the active layer to better match the solar spectrum (Leung, 2011).

A newer technology, thin-film PV, accounts for 10%–15% of global installed PV capacity [8]. Rather than using polysilicon, these cells use thin layers of semiconductor materials like amorphous silicon (a-Si), copper indium diselenide (CIS), copper indium gallium diselenide (CIGS), or cadmium telluride (CdTe). The manufacturing methods are similar to those used in producing flat panel displays for computer monitors, mobile phones, and televisions;a thin photoactive film is deposited on a substrate, which can be either glass or a transparent film. Afterwards, the film is structured into cells. Unlike crystalline modules, thin-film modules are manufactured in a single step. Thin-film systems usually cost less to be produced than crystalline silicon systems but have substantially lower efficiency rates [9]. On average, thin-film cells convert 5%–13% of incoming sunlight into electricity, compared to 11%–20% for crystalline silicon cells. However, as thin film is relatively new, it may offer greater opportunities for technological improvement.

3. Monocrystalline Silicon Solar Cell Technology

Traditional c-Si cell design and its development up to year 2000 have been focused on in the Figure 7. Different types of c-Si cell structure have been used for improving the efficiency of crystalline silicon solar cell. Metal-insulator NP solar cell (MINP), passivated emitter solar cell (PESC), passivated emitter and rear cell (PERC), passivated emitter, rear locally diffused cell (PERL), and interdigitized back contact cell (IBC) are useful solar cell structures used by the different well-recognized universities or laboratories.





(b)

ll design and its development up to year 2000.

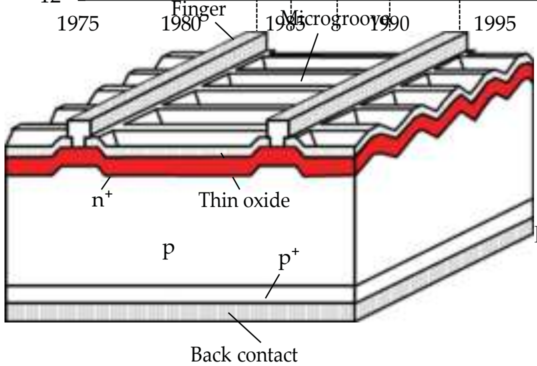


Figure 8: Passivated emitter solar cell.

In MINP structure, there was SiO_2 passivation surface underneath contact and current conduction by tunneling through the thin oxide [10].

But in PESC structure [11, 12], there was no oxide underneath contact as shown in Figure 8. Contact width is reduced by laser microgrooving as shown in Figure 9.

In PERC structure as shown in Figure 10(a), rear surface of the solar cell was passivated and contact was made by point rear contact, whereas in PERL structure [13], rear contact is made by local BSF (back surface field) at rear point contact by diffusion as shown in Figure 10(b).

Interdigitized back contact solar cell [14] is now well-known promising solar cell structure used by SUNPOWER in their solar cell production line. R.M. Swanson is a key person for the development of IBC solar cell structure [15]. In this structure, all solar cell contacts were made from rear surface. Both front and back surface fields have been implemented in this structure as shown in Figure 11.

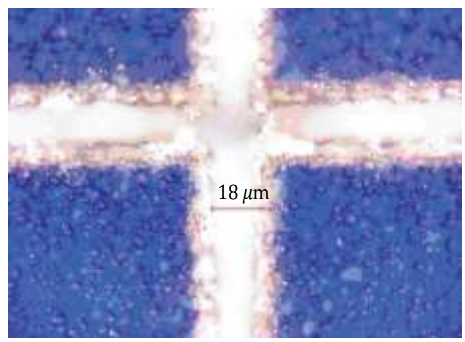


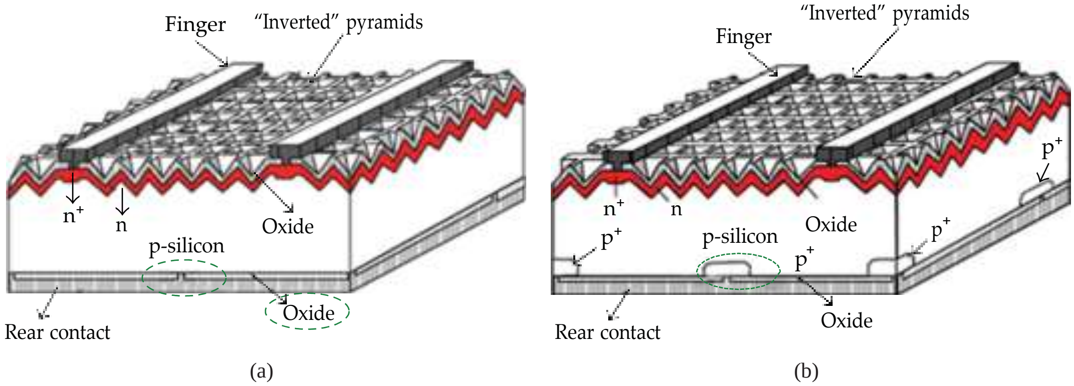
Figure 9: Laser microgrooving.

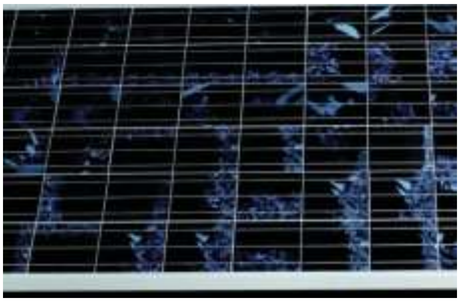
Researchers in the area of crystalline silicon continuously tried to find out a new simple route by which large area high efficiency can be achieved. In 2011, Lai [16] already achieved 19.4% efficient planar cells on CZ silicon using simple cell technologies. Figure 12 is the structure used during fabrication by Lai.

One key to the development of any photovoltaic technology is the cost reduction associated with achieving economies of scale. This has been evident with the development of crystalline silicon PVs and will presumably be true for other technologies as their production volumes increase. Price trend of crystalline installed PV in the world market is shown in Figure 13.

4. Indian PV Scenarios

Developing countries, in particular, face situations of limited energy resources, especially the provision of electricity in rural areas, and there is an urgent need to address this constraint to social and economic development. India faces





(c)

Figure 10: (a) PERC and (b) PERL solar cell structure. (c) PERL design cell marketed by SunTech as PLUTO technology cell.

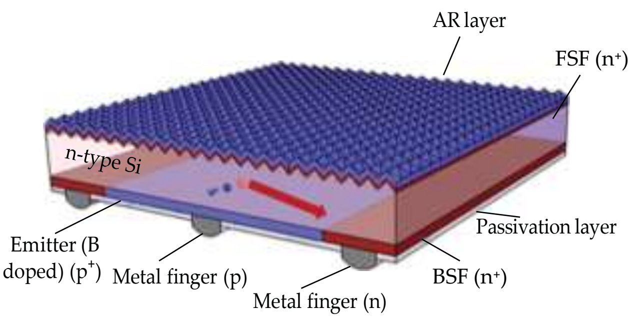


Figure 11: Interdigitized back contact solar cell.

a significant gap between electricity demand and supply. Demand is increasing at a very rapid rate compared to the supply. According to the World Bank, roughly 40 percent of residences in India are without electricity. In addition, blackouts are a common occurrence throughout the country's main cities. The World Bank also reports that one-third of Indian businesses believes that unreliable electricity is one of their primary impediments to do business. In addition, coal shortages are further straining power generation capabilities.

India is endowed with rich solar energy resource. The average intensity of solar radiation received on India is 200 MW/km square (megawatt per kilometer square). With a geographical area of 3.287 million km square, this amounts to 657.4 million MW. However, 87.5% of the land is used for agriculture, forests, fallow lands, and so forth, 6.7% for housing, industry, and so forth, and 5.8% is either barren, snow bound, or generally inhabitable. Thus, only 12.5% of the land area amounting to 0.413 million km square can, in theory, be used for solar energy installations. Even if 10% of this area can be used, the available solar energy would be 8 million MW, which is equivalent to 5 909 mtoe (million tons of oil equivalent) per year.

In order to meet the situation, a number of options are considered. Power generation using freely available solar energy is one such option. Fortunately, India is both densely populated and has high solar insolation, providing an ideal combination for solar power in India. Jawaharlal Nehru National Solar Mission is one of the major global initiatives in promotion of solar energy technologies, announced by the Government of India under National Action Plan on Climate Change. Mission aims to achieve grid tariff parity by 2022 through the large-scale utilization and rapid diffusion and deployment of solar technologies across the country at a scale which leads to cost reduction and promotes the research and development activity to local manufacturing and infrastructural support. Table 1 shows the road map of Jawaharlal Nehru National Solar Mission.

Under the plan, solar-powered equipment and applications would be mandatory in all government buildings including hospitals and hotels. The scope for solar PV growth in India is massive, especially growth in distributed solar as over 600 million people—mostly in rural areas—currently do not have access to electricity. It is useful for providing grid quality, reliable power in rural areas where the line voltage is low and insufficient to be catered to connected load.

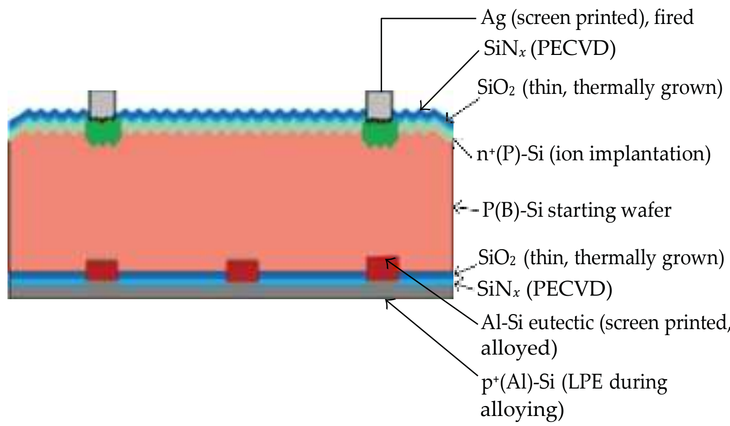


FIGURE 12: 19.4% efficient planar cells on CZ silicon using simple cell technologies.

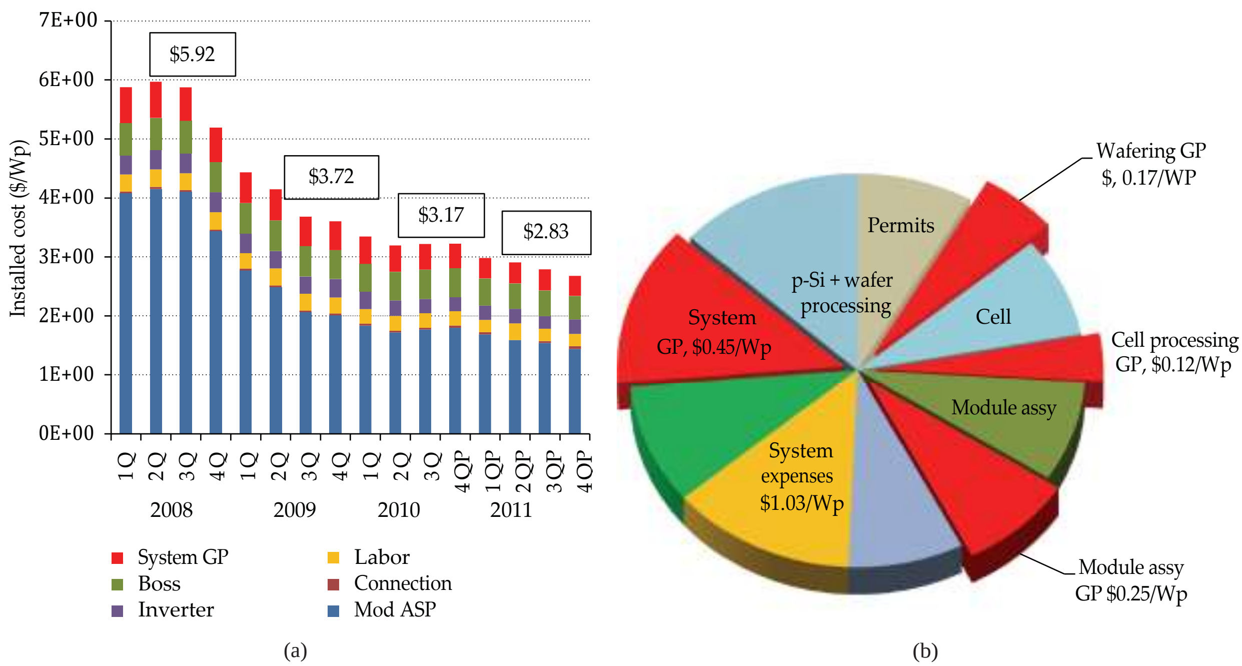


FIGURE 13: Price trend of crystalline installed PV in the world market.

TABLE 1: Road map of Jawaharlal Nehru National Solar Mission.

Application segment	Target for phase I (2010–13)	Cumulative target for phase 2 (2013–17)	Cumulative target for phase 3 (2017–22)
Grid solar power including roof top and distribution grid connected plants	1,000 MW	4,000 MW	20,000 MW
Off-grid solar applications	200 MW	1,000 MW	2,000 MW
Solar collector	7 million sq.meters	15 million sq.meters	20 million sq.meters

The Government of India is planning to electrify 18,000 villages by year 2012 through renewable energy systems especially by solar PV systems. This offers tremendous growth potential for Indian solar PV industry.

The growth of Indian PV is shown in the Figure 14 indicating that the increase of module production up to year 2011 was significant compared to solar cell production by the Indian manufacturer. This may be due to availability to solar cell with much lower prices from Chinese solar cell manufacturer and initial investment of the module plant with lower CAPEX compared to setting up new solar cell plant in India. But the status of Indian PV is related to the application in different areas by installing 53,00,000 systems (~2600 MW) up to 2012 as shown in Figure 15.

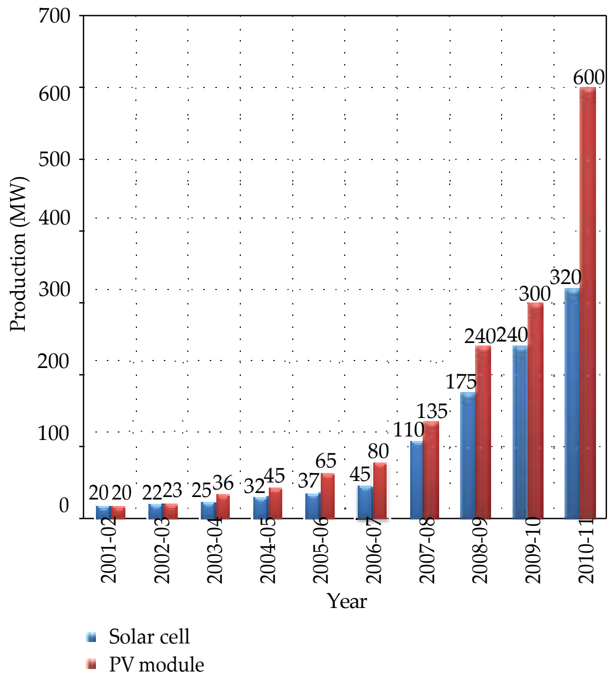


FIGURE 14: Growth in Indian PV production.

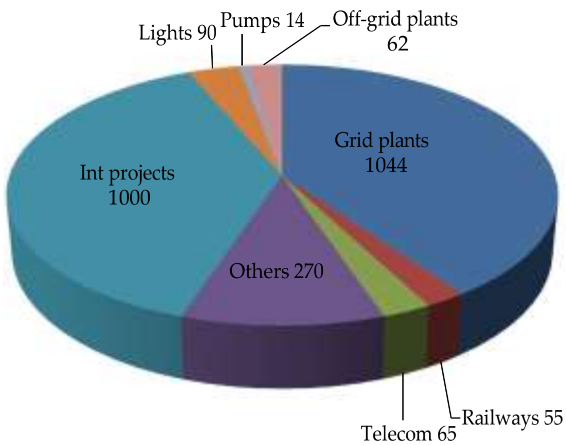


FIGURE 15: Status of PV in India.

Another important achievement in the Indian PV area is 1044 MW capacity new Grid Solar Power projects commissioned by September, 2012 in 16 States as indicate state wise in Figure 16. From this pictorial presentation, it is clear that Gujarat state much ahead compared to the rest of other state as far as installation of Grid Solar PV Power Plant in India.

5. Conclusion

One key to the development of any photovoltaic technology is the cost reduction associated with achieving economies of scale. This has been evident with the development of crystalline silicon PVs and will presumably be true for other technologies as their production volumes increase. Given

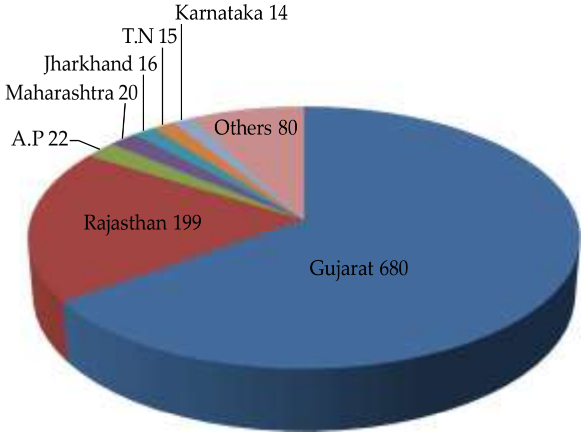


FIGURE 16: Grid solar PV power plants in India.

the vast potential of photovoltaic technology, worldwide production of terrestrial solar cell modules has been rapid over the last several years, with China recently taking the lead in total production volume.

Fortunately India is both densely populated and has high solar insolation, providing an ideal combination for solar power in India. The Government of India is planning to electrify 18,000 villages by year 2012 through renewable energy systems especially solar PV systems. This offers tremendous growth potential for Indian solar PV industry.

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