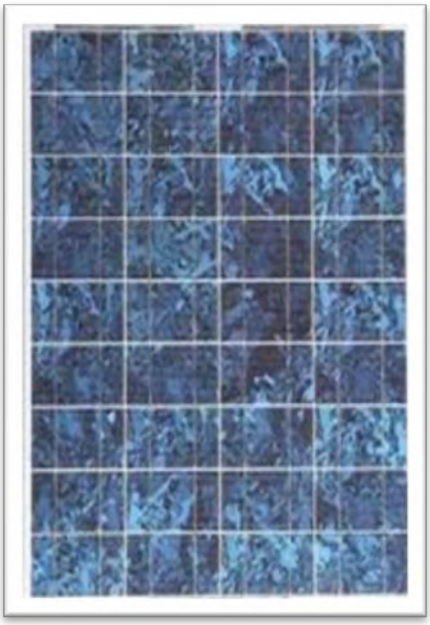
Comparative Assessment of Crystalline and Thin-Film PV Technologies in India

—A Guide for Policy & Business Decisions—



Crysatlline Silicon PV

Thin Film Silicon PV

Research Report

by

World Institute of Sustainable Energy, Pune

April 2012

Citation
WISE 2012. "Comparative Assessment of Crystalline and Thin-Film PV Technologies in India - A Guide for Policy & Business Decisions". World Institute of Sustainable Energy, 57pp.

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Abbreviations

CERC	Central Electricity Regulatory Commission
CUF	Capacity Utilisation Factor
DSCR	Debt Service Coverage Ratio
EVA	Ethylene vinyl acetate
FiT	Feed in Tariff
NOCT	Normal Operating Cell Temperature
IC	Integrated Circuit
IEC	International Electro-technical Commission
JNNSM	Jawaharlal Nehru National Solar Mission
NAPCC	National Action Plan on Climate Change
NVVN	NTPC Vidyut Vyapar Nigam
SERC	State Electricity Regulatory Commission
SPV	Solar Photovoltaic
Ipm	Maximum Power Current
IRR	Internal Rate of Return
Isc	Short Circuit Current
STC	Standard Test Condition
TFSC	Thin Film Solar Cells
Voc	Open Circuit Voltage
Vpm	Maximum Power Voltage

Executive Summary

The World Institute of Sustainable Energy (WISE) conducted a research study for comparative assessment of two solar technologies, namely crystalline PV and thin film. The study is neutral with respect to technologies, companies, lenders, institutions and societal interests; the assessment is meant to help all the stakeholders and to contribute to healthy growth of solar power in India. The assessment looks at the two technologies from four perspectives: equity investors; debt investors (lenders); various institutional entities including central and state govt bodies; and societal perspective. The following are the findings of the study:

- Thin films do not have a cost advantage in terms of initial investment costs over crystalline solar cells, which is important from both equity and debt perspectives. (Refer to the Section on Comparison of Investment Costs: The Equity Investors perspective, Chapter 4)
- The return on equity is higher for crystalline PV, which is important from both equity and debt perspectives. (Refer to the Section on Comparison of Financial Returns: Equity Investors Perspective, Chapter 4)
- The Debt Service Coverage Ratio (DSCR) is greater for crystalline PV. Projects based on crystalline technology will have a lower technology risk than those based on thin film technology. Both these are important from debt perspective. (Refer to the Section on Comparison of Financial Returns: Equity Investors Perspective, Chapter 4)
- Given the higher degradation rate of thin film modules (3%/year) compared to that of crystalline modules (0.5%/year), if a 1 MW crystalline PV project is replaced by thin film project of the same capacity, there will be a loss of 9,634,282 units over 25 years. That translates into a loss of 4,817 MUs in 25 years for the present scenario in the country with 1000 MW installed capacity with a 50% share for the thin film. (Refer to the Section on Policy and Regulatory Aspects: The Institutional Perspective, Chapter 4)
- Projects based on crystalline technologies can probably continue to generate power beyond 25 years, making them more attractive. (Refer to the Subsection on Life of the Modules, Chapter 4)
- Crystalline technologies require practically half of the land required by thin film technologies. This is important from a policy perspective for both central and state governments. (Refer to the Subsection on Land required for power generation, Chapter 4)
- Thin film technology (e.g. CdTe) has higher environmental externalities (potential health hazards) due to the presence of heavy metals. This is important from the societal perspective and policymakers need to take serious cognisance of this. (Refer to the Section on Environmental Externalities: The Societal Perspective, Chapter 4)
- Solar power projects based on crystalline modules will generate scrap of 100 tonnes per MW after their useful life. Since the mounting structures for thin film are almost double that of crystalline PV, the scrap generation will also be double in the case of thin film. Moreover, thin films are expected to have a shorter life and hence will generate scrap sooner. None of these life-cycle related costs is internalized into the current cost calculations. (Refer to the Subsection on Scrap Generation, Chapter 4)

- The popular notion that thin film technology performs better in warmer climate has proved to be wrong; thin film glass modules are liable to break at high ambient temperatures and hence require additional 1% amount as a warranty to be set aside. (Refer to the Subsection on Breakage and Replacement, Chapter 4)

- Power output from any kind of solar cell decreases with increase in temperature. It is reported that the temperature coefficient of thin film modules is lower (–0.3%/ºC) than that of crystalline modules (–0.4%/ºC). Hence it is claimed that they are more suitable for warm climates and will generate more for equivalent capacities of power projects. However, the most potential areas of Gujarat and Rajasthan also have winters that are favourable for creating low Normal Operating Cell Temperature (NOCT). Therefore, low output in summers will be compensated for by higher output in winters. (Refer to the Subsection on Temperature Coefficients of the Two Technologies, Chapter 4)
- Crystalline module manufacturers now offer a warranty for 10% degradation in output in 12 years and 20% in 25 years, which indicates greater confidence. Interestingly, thin film module manufacturers also now provide warranty for 10% degradation in output in 10 years and 20% in 25 years. The warranties have been increased because the manufactures have to compete with those of crystalline silicon modules. However, they provide the basis of IEC 61646 certification, which carries out an accelerated degradation test under simulated situations. There are doubts whether thin film will actually show this trend under field conditions. (Refer to the Subsection on Warranty Periods, Chapter 4)
- Crystalline and thin film technologies are basically different in terms of technical parameters and financial implications and need separate treatments (Refer to the Section on Policy and Regulatory Aspects: The Institutional Perspective, Chapter 4). However, the regulatory bodies in the country do not differentiate between the two technologies while determining the tariff, which is likely to misguide solar developers while taking investment decisions.
- As regards policy aspects, the state and central governments are responsible to the society for: a) efficient land utilization; b) long-term and reliable supply of power; c) avoiding large-scale dumping of less-efficient technologies; d) dissemination of correct information to investors; e) minimizing the health hazards; and f) declaration of PV as e-waste and efficient management of waste from power projects after useful life.
- While taking policy decisions, though the central government accords similar status to both the technologies in technical and financial aspects, a paradox lies in the import policy under JNNSM i.e. while thin films are freely allowed to be imported, crystalline modules have restriction of domestic content; resulting into large scale dumping of thin film modules in India without considering the future national, societal and environmental implications. Moreover, there is danger of state governments treading on similar line.

Overall, it appears from the comparative research study that crystalline PV is a comparatively better technology in all aspects and should be considered as a sustainable investment option.

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Preface

Why this study?

The Jawaharlal Nehru National Solar Mission (JNNSM) was announced in 2009 as a follow-up of the objectives laid in the National Action Plan on Climate Change (NAPCC). The JNNSM aims to promote development of solar energy for grid connected and off-grid power generation. The ultimate objective is to make solar power competitive with fossil based power projects by 2020. The solar power purchase obligation for each state is specified as 0.25% of all power consumed in the country going up to 3% by 2022.

Under Phase I Batch I of JNNSM, approval has been accorded for installation of 29 SPV power projects of total 145 MW and to 7 solar thermal power plants of total 470 MW with promoters selected through tariff reverse bidding. Recently NVVN has allocated 350 MW of SPV power projects under Batch II of Phase I of JNNSM. By March 2012, under JNNSM scheme more than 200 MW SPV and 2.5 MW CSP projects are commissioned and commercially running. In addition, different states announced their own solar policies which provided the Feed-in-Tariff in accordance with the respective SERC order. Gujarat is the leading state in this regard whose pro-active action has resulted into commissioning of 604 MW SPV projects in the state by March 2012. Therefore the total installed capacity of solar projects in the country is around 800 MW by March 2012.

Grid-connected solar power projects in India today use either crystalline or thin-film solar PV technologies. The choice is influenced mainly by the initial cost; technical aspects, environmental implications. However, we feel that certain other vital technical issues are not given adequate thought. Whereas crystalline PV has been in the market for the last two decades, thin film is a new entrant in the market, and authentic technical information about and operating experience of thin-film technology are relatively scarce. As a result, contradictory claims are being made by different stakeholders, which present a confusing picture to investors, developers, and banks.

This report is an independent and critical evaluation of the two technologies – crystalline and thin film with respect to their techno-commercial aspects with a long-term perspective along with other aspects such as their contribution to energy security, government policies, business sustainability, employment generation, and environmental implications.

We hope that the findings of this study- which is a mix of field and academic research will be an eye opener for policy makers, investors, developers, regulators, utilities, and other stakeholders in the SPV solar sector to enable them to take right decision and make correct technology and investment choices.

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Photovoltaic Principles and Physics

Introduction

Solar cell is an electronic device which converts solar energy directly into electrical energy through the photovoltaic effect. It is a typical semiconductor p-n junction device. When the light falls on the device, the light photons of certain wavelengths are absorbed by the semiconducting material and electrical charge carriers, electrons and holes, are generated. These carriers diffuse to the junction where a strong electric field exists. The electrons and holes are separated by this field and produce an electric current in the external circuit (Fig. 1).

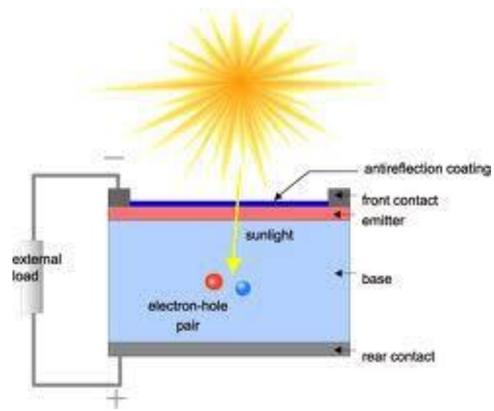

Figure-1.1 Typical p-n junction solar cell

The Semiconductor nature:

Semiconductors used in solar cell fabrication are elements such as Silicon (Si) and Gemanium (Ge) or compounds such as Gallium Arsenide (GaAs), Cadmium Sulphide (CdS), Copper Indium Diselenide (CIS), Cadmium Telluride (CdTe) and so on.

Silicon is the most commonly used solar cell material. To understand the semiconductor nature in solar cells, a simple model of two-dimensional lattice structure of silicon can be considered (Fig. 2). Each silicon atom has 14 electrons in the atomic structure and four of them are in the outermost orbit, which are weekly-bound to the nucleus. These four electrons are called 'valence electrons' which form 'covalent bonding' with the four nearest-neighbour atoms. i.e., each valence electron of a silicon atom is shared by one of its four nearest neighbours. In 'pure' or 'intrinsic' silicon, all electrons are bound through covalent bonding and there is no free electron available for conductivity, and hence, it behaves like an insulator.

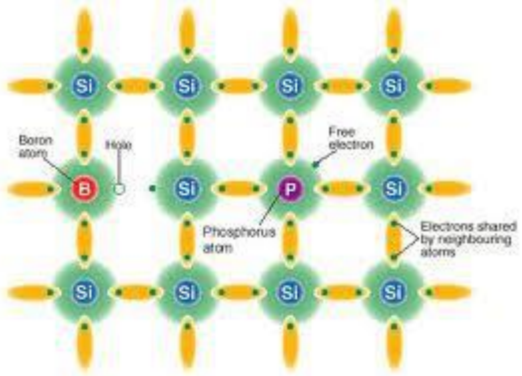

Figure-1.2 A simple model of two-dimensional lattice structure of silicon

Consider a situation where a silicon atom is replaced by a pentavalent atom like phosphorous (P). Four of the five valence electrons occupy the covalent bonding and the fifth one nominally held in the bond can move freely as a carrier of current. The energy required to detach this electron is about 0.005 eV for silicon, which is very small. By adding pentavalent atoms, called n-type doping, the creation of 'extra' free electrons are achieved, the density of these electrons depending on the dopant concentration. This type of dopant is called 'donor' type.

On the contrary, a silicon atom is replaced by a trivalent atom like boron (B) with three valence electrons. Then bonding with three nearest neighbours only is complete, producing one space with no electron (i.e., hole). This is called p-type doping wherein creation of extra holes are achieved, the hole density depending on the dopant concentration. This type of dopant is called 'acceptor' type.

Small amounts of dopants introduced into the semiconductor structure can significantly increase the number of electrons available for breaking away from their atoms.

Electron generation due to light absorption:

Each material, whether insulator, semiconductor or conductor; has two energy bands namely the topmost 'conduction band' and 'valence band' below it. The gap between the two bands is called band gap (E_g). If the light energy is more than the band gap, electrons from the valence band are excited and large numbers of free electrons are transferred to the conduction band, which are available for flow of electricity. That means the material with the band gap energy closely matching with that of light energy will be most ideal for solar cell. Solar light has seven colours representing seven wavelengths or seven energy values. Green light falls midway and has the wavelength of 510 nm (nanometers) with violet having lowest wavelength of 400 nm and red having the highest wavelength of 650 nm. Lower the wavelength, higher the energy. Typically green light has energy of 1.54 eV (electron volt). Any semiconductor having the band gap around this value will be ideally suited for solar cells. Some of the semiconductors used for solar cells have the band gap as given in Table-1.1

Table-1.1 Band gaps of solar cell semiconductor materials

Semiconductor	E_g (eV)
Si	1.11
GaAs	1.43
CdTe	1.44
CdSe	1.70
Cds	2.42
Cu_2Se	1.40
InP	1.27
$CuInSe_2$	1.01
$CuInS_2$	1.50

Solar cell p-n junction:

The p-n junction is the basic structure of a solar cell. The simplest structure of a solar cell is a crystalline silicon wafer in which a p-n junction is formed by doping the wafer with boron on one side and with phosphorous on the other side using appropriate doping techniques. Due to higher concentration of electrons on n-side and the holes from p- to n-side, creating a built-in potential sustained by the fixed ionized acceptors and donors at the junction.

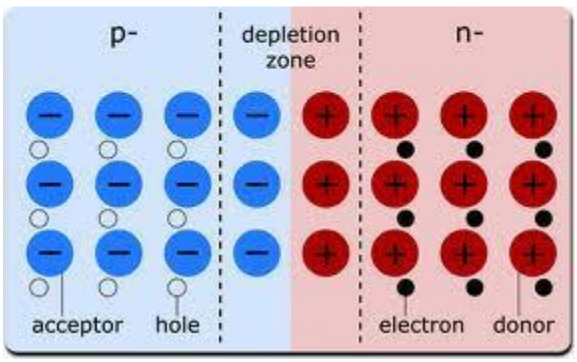

Figure-1.3 A typical p-n junction schematic

Once the p-n junction is illuminated, photo generated voltage and current are obtained. If the terminals of the junctions are shorted under illumination, 'short-circuit current' (I_{sc}) flows in the junction from p– to n-side, if the p-side is illuminated. Similarly, if the terminals of the junctions are kept open, 'open-circuit voltage' (V_{oc}) is created.

While illuminating if a load is applied in the circuit, an I-V curve is obtained, wherein the point of maximum power (P_m) represents the power output from the cell and the corresponding current and voltage to this maximum point are termed as I_m and V_m. ($P_m = V_m \times I_m$)

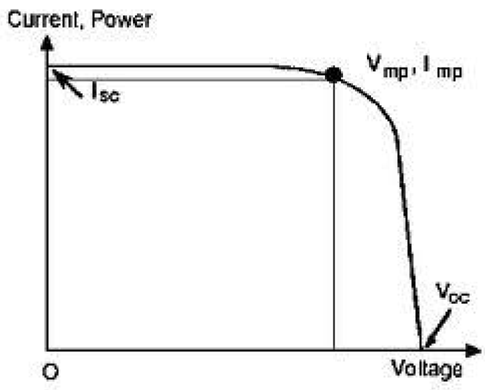

Figure-1.4 I-V curve of solar cell

Fill factor of the cell is defined as follows:

$$FF = \frac{V_m \times I_m}{V_{oc} \times I_{sc}}$$

Efficiency of the cell is defined as

$$Efficiency = \frac{V_{oc} \times I_{sc} \times FF}{\text{Incident Solar Power}}$$

A larger E_g means that a fewer photons can be absorbed because only those photons greater than and equal to E_g are absorbed, which in turn decreases the efficiency. The calculated efficiency has a maximum of about 25% at E_g equal to about 1.5 eV and falls off on either side of this value.

The semiconducting compounds, CdTe and GaAs have E_g around this value. But interestingly, silicon with E_g equal to 1.1 eV has firmly established as the prime material for solar cell fabrication. The maximum possible efficiency for silicon solar cell is 29%.

For a normal solar cell, the open-circuit voltage hardly increases with increase in solar intensity. However, short circuit current increases linearly. Therefore, the power of solar cell also changes with solar radiation.

The theoretical efficiencies are evaluated by assuming an ideal case of a cell fabricated with well-established processing and manufacturing techniques. However, for the practical purpose, there are many limitations. If we examine the available material with an appropriate band gap, the choice is limited to such materials as given in Table-1. Except for Si, all other materials by virtue of their electrical and optical properties must necessarily be in thin film form. In addition, it is also necessary that it be readily available in abundant supply in the world. If in the long term, we wish to produce 10% of total global electricity requirement, solar cells of optimum 10% efficiency will require about 10^7 kg/year of the material. Although Si is more fortunately placed in this regard, vis-a-vis other materials, owing to other technical and economical reasons, large scale thin film solar cell production using other materials are also desired.

As regards availability of solar cell materials, Si is most abundant on the earth, with the lowest cost of raw material. Ga, Ge, Te, Cd are costlier and rarely available.

Effect of temperature:

Under continued irradiation, the temperature of a solar cell increases and the power decreases with increasing solar cell temperature. The open-circuit voltage decreases by a value of approximately 3 mV for each degree centigrade rise in temperature. A solar cell with a V_{oc} of 0.6 V at 25^0 C reaches a value of 0.45 V at 75^0 C. This is a considerable reduction, which can be about 25% in practice.

The short-circuit current increases with increasing temperatures at a rate of about 0.1% for each degree centigrade rise in temperature. A solar cell with short circuit current of 2.0 A at 25^0C reaches a value of 2.1 A at 75^0C. This means an increase of 5%. The reduction in voltage is much greater than the corresponding increase in current. This affects the power, which decreases at a rate of about 0.44% per degree rise in temperature. One should, therefore, try to keep the solar cell cool. This is difficult in practice, because with increasing solar radiation the cell temperature usually increases.

Ageing Effects:

Like most other devices, ageing of a solar cell also affects its power. For commercially available mono- or poly-crystalline silicon solar cells, the problem of ageing is minor. Solar cells which are properly encapsulated have a very long life, and power from them does not reduce in any significant manner. The effect of ageing is more severe in amorphous Si-solar cells. However, recent findings show that, after an initial reduction in the power of an amorphous Si-solar cell, the power remains constant for the rest of its life. This issue has been discussed in detail in further chapters.

Reference:

1. P. Jayarama Reddy, "*Science & Technology of Photovoltaics*," BS Publications, Hyderabad, (2004).

2. K. L. Chopra & Suhit Ranjan Das, "*Thin Film Solar Cells,*" Plenum Press, New York, (1983)
3. N. K. Bansal, "*Photovoltaic Systems,*" Omega Scientific Publishers, New Delhi, (2003)

3

Types of photovoltaic cells

Introduction

Silicon is the most abundant element available on earth, and the earliest solar cell was made of crystalline silicon. Today, silicon is used in mono-crystalline, polycrystalline and amorphous nature for fabrication of solar cells. Majority of the commercial cells use mono-crystalline silicon. The polycrystalline and amorphous types of silicon are a result of engineering of silicon material where lattice perfection is sacrificed to achieve significant reduction in the cost of silicon technology for solar cell applications. Many other semi-conducting compounds have also been investigated. Solar cells based on Gallium arsenide, Cadmium telluride, and Copper indium diselenide are now commercially available. Thus based on formation of material, solar cells are grouped in three major categories namely a) Crystalline, b) Thin film and c) Emerging technologies. Each type of the solar cell is briefly described below:

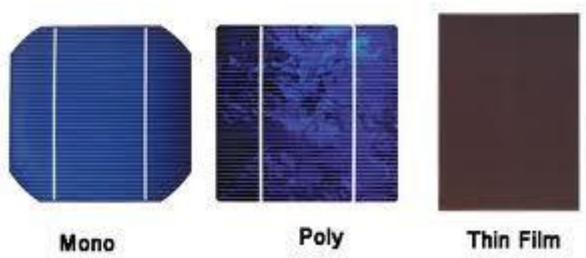

Figure 2.1 Mono-crystalline, polycrystalline and thin-film solar cells

Crystalline solar cells

Under the crystalline category, there are two types of technologies, namely, mono-crystalline and poly-crystalline technology.

Mono-crystalline silicon solar cells

The majority of solar cells manufactured today all over the world are fabricated using mono-crystalline silicon as the base. These materials have been used as semiconductors for the last hundred years in diodes, transistors, ICs etc.

The input material is SiO_2, available either in the form of quartz sand or as natural crystalline quartz converted into metallurgical grade silicon in a furnace through a reduction process using coal. Metallurgical silicon, after purification, is converted into rods of polycrystalline nature, i.e. many small crystals ordered close to each other. These polycrystalline rods are melted in a crucible and pure silicon ingots are prepared by single crystal growth on a seed pulled from the silicon melt. The principle of Czocharalski process is predominantly used for single crystal growth. In this process, a seed of single crystal silicon contacts with the melt of high purity silicon, and as the seed is slowly raised, the atoms of the molten silicon adopt to the pattern of single crystal seed as it cools and solidifies into a single crystal structure. This rod can be up to 2 m long. It is made of its own crystals and therefore the name 'mono-crystalline'. From this single crystalline ingot, wafers are sliced and textured to improve the solar energy absorption. These wafers are then fabricated into p-n junctions by high temperature diffusion of dopants, mainly boron and phosphorous that modifies the surface layer composition.

Mono-crystalline silicon solar cells have proven their credibility as source of reliable electric power both on land and in space. Practical efficiencies in the range of 14 to 17% have been measured for the mono-crystalline silicon cells. Today, the best single crystal Si solar cells have reached an efficiency of 24.7%, compared with the theoretical maximum value of 30%.

Polycrystalline silicon solar cells

After mono-crystalline silicon, polycrystalline silicon is the second most common natural substance used for the manufacture of solar cells. For solar cells one does not require silicon as pure as one needs for manufacturing semiconductors. Therefore, another approach to silicon technology is to prepare polycrystalline silicon block with no lattice perfection. The manufacturing process is simpler and cheaper. The most popular commercial process is the 'casting process' wherein the molten silicon is poured into rectangular mould and allowed to solidify into an ingot.

The ingot is then sliced into wafers. This means that the process of cutting and polishing and the waste resulting from this process are much the same as that required for single crystal silicon, and hence the cost reduction may not be very large. Nonetheless, the poly technology has lowered the costs of PV technology because the 'casting' process is relatively cheaper and less sophisticated compared to Czochralski process. Due to the presence of structural imperfections, mostly grain boundaries, the efficiencies are slightly lower, around 13 to 15%.

Both mono-crystalline and polycrystalline silicon solar cell wafers are available with the thickness of 200-300 μm.

Thin film solar cells (TFSC)

A thin film is a material created *ab initio* by the random nucleation and growth processes of individually condensing / reacting atomic / ionic / molecular species on a substrate. The structural, chemical, metallurgical and physical properties of such a material are strongly dependent on a large number of deposition parameters and may also be thickness dependent (K. L. Chopra, P. D. Paulson, and V. Dutta, "Thin-Film Solar Cells: An Overview," Prog. Photovolt: Res. Appl. 2004; 12:69–92).

Pure silicon has been conventionally an expensive material. So, continuous efforts have been made to produce cells with very little quantity of solar cell material. This type of cell technology is usually known as thin-film technology. Thin film modules are made by depositing very thin layers of photosensitive materials on to a low-cost backing. Typical inexpensive substrates used for the purpose are made of glass, stainless steel or even plastic. Three types of thin film modules are commercially available at present.

1. Amorphous silicon
2. Cadmium telluride
3. Copper indium diselenide

Amorphous silicon

In amorphous Si (a-Si), the atoms are arranged in a haphazard manner. Before 1975, it was the usual opinion that amorphous silicon could not be used to produce solar cells.

Later, it became possible for the first time to dope a-Si, in which an alloy of silicon and hydrogen from the gaseous form of silane could be separated. This product was named a-Si:H (hydrogenated amorphous silicon). It could be doped during the process of separation. There are several methods today, which can be used to deposit a-Si layers on a base substance. Already in the laboratory, efficiencies of about 12.5%, which are still very much lower than that of mono-crystalline silicon PV have been obtained.

Amorphous silicon is widely accepted as a thin-film solar cell material because: (a) it is abundant and non-toxic; (b) it requires low process temperature, enabling module production on flexible and low cost substrates; (c) the technological capability for large-area deposition exists; (d) very thin film (= 1 μm) has low material requirements, due to the inherent high absorption coefficient compared with crystalline silicon, (e) has larger band gap (it gives higher open –circuit voltage), (f) low energy consumption during manufacture, and (g) possibility of automation of the manufacturing process.

The main disadvantage is the lower efficiency and faster degradation due to higher internal resistance and therefore a smaller photon current.

Cadmium telluride solar cell

Cadmium telluride is an excellent solar cell material with highest theoretical conversion efficiency. Several preparation techniques such as vacuum evaporation, spraying, screen-printing and electro-deposition have been initially used to produce good solar cells.

Owing to its optoelectronic and chemical properties, CdTe is an ideal absorber material for high efficiency, low cost thin film polycrystalline solar cells. CdTe is a direct band-gap material with an energy gap of 1.44 eV, and an absorption coefficient of around 10^5/cm in the visible region, which means that a layer thickness of a few micrometers is sufficient to absorb ~90% of the incident photons.

Lab solar cells efficiency is up to 16%, whilst the commercial type efficiency is up to 6 to 10% have been reported by a few manufacturers. The cells are relatively stable although humidity affects to some extent. The spraying and screen-printing are the techniques with high economic potential. The toxicity of cadmium raises two main problems, possibility of production hazards and environmental pollution. In spite of these demerits, there has been significant progress in developing low-cost manufacturing processes for rapid commercialization of CdTe cells. One problem with CdTe is that p-type CdTe films tend to be highly resistive electrically, which leads to large internal resistance losses.

Copper-indium di-selenide

$CuInSe_2$, having a band gap of 1.53 eV is considered an ideal material for photovoltaic application. The difficulties in controlling the sulphur during deposition and the relatively rapid diffusion of metals and impurity species, even at low temperatures, slow down the development of this material. However, devices with efficiency 11.4% have been reported.

An increase in the band gap and improved process conditions resulted in the fabrication of high-performance solar cells with efficiencies of 19.2% for small-area and 13.1% for a large area. Even though the efficiency and stability of the device are very promising, there are several factors that are less favorable for large-scale production of such devices. The increasing number of alloy components makes the multiple processes extremely complex and thus intelligent processes are required for precise control of the composition during deposition. The use of expensive and rare metals such as In and Ga adds to the cost of manufacturing.

Emerging technologies

In addition to the above solar cells which are either commercialized or are on the verge of commercialization, there are other materials attracting large scale attention of researchers with potential of commercialization in future. Some of them are explained below:

Gallium arsenide

Mostly used in space application due to high cost, Gallium arsenide (GaAs) and its variants Gallium aluminium arsenide (GaAlAs) and Gallium indium arsenide phosphide (GsInAsP) are the most efficient solar cell materials reported till today. These cells are generally combined in multiple junctions to achieve high efficiencies. These materials are highly suited to multiple band-gap cell designs because the band gaps are adjustable by changing the relative compositions of the components. Cell efficiencies of about 30 to 34% are obtained for these structures which are extremely high, though they are too expensive to be used for terrestrial applications.

Organic semiconductors

Organic materials are attractive for photovoltaics primarily through the prospect of high throughput manufacture using processes such as reel-to-reel deposition. Additional attractive features are the possibilities for ultra thin, flexible devices which may be integrated into appliances or building materials, and tuning of colour through chemical structure. The field has made impressive progress since the late 1990s. Solar power conversion efficiencies of over 3% have been reported. A growing range of new photovoltaic materials have been studied and increasing numbers of research groups and companies have declared an interest in 'soft' solar cells.

Organic semiconductors can be classified into three categories, depending on their chemical properties, as insoluble, soluble and liquid crystalline. They can be further classified as monomers, such as dyes, pigments and polymers. Doping of organic semiconductors can be done by introducing foreign atoms or molecules, or by electrochemical oxidation/reduction processes. Organic solar cells have a stability problem common to conjugated polymers. However, these may not be very serious problems and may be overcome in the near future.

Dye-sensitized cells

The dye-sensitized cells are also considered as thin film cells. The principle of working is based on photosensitization of wide-band-gap semiconductors. A wide-gap semiconductor with a large surface area is covered with dye molecules. When the light is incident, the light is absorbed in the dye molecules which are excited and the electrons from their excited state are directly injected into the semiconductor, without the need for transport of photo generated carriers within the dye. The ground state of the molecules has to be filled again so that the process goes on. Since the technology does not require high-purity semiconductors, this type of cells are highly promising. In Germany, the company, INAP GmbH has been working on the development of dye-sensitized TiO_2 cells, and efficiencies of 7% on 30 cm x 30 cm areas have been reached. There has been a lot of research activity and new photosensitizing chemicals are developed. This is considered as a potential and low-cost PV technology.

Nanotechnology solar cells

Nanotechnology might be able to increase the efficiency of solar cells, but the most promising application of nanotechnology is the reduction of manufacturing cost. Chemists at the University of California, Berkeley, have discovered a way to make cheap plastic solar cells that could be painted on almost any surface. These new plastic solar cells achieve efficiencies of only 1.7 percent. These new plastic solar cells utilize tiny nanorods dispersed within in a polymer. The nanorods behave as wires because when they absorb light of a specific wavelength they generate electrons. These electrons flow through the nanorods until they reach the aluminum electrode where they are combined to form a current and are used as electricity. This type of cell is cheaper to manufacture than conventional ones for two main reasons. First, these plastic cells are not made from silicon, which can be very expensive. Second, manufacturing of these cells does not require expensive equipment such as clean rooms or vacuum chambers like conventional silicon based solar cells. Instead, these plastic cells can be manufactured in a beaker.

(http://www.tahan.com/charlie/nanosociety/course201/nanos/MP.pdf)

Other nanotechnology applications under development are a) Titanium dioxide nanotubes filled with a polymer to form low cost solar cells, b) Combining lead selenide quantum dots with titanium dioxide to form higher efficiency solar cells and c) Combining carbon nanotubes, bucky-balls and polymers to produce inexpensive solar cells that can be formed by simply painting a surface.
(http://www.understandingnano.com/solarcells.html)

Present status

Global status

According to "Renewables 2011 Global Status Report", The PV industry had an extraordinary year, with global production and markets more than doubling in 2010. An estimated 17 GW capacity was added worldwide (compared with just under 7.3 GW in 2009), bringing the global total to about 40 GW – more than seven times the capacity in place five years earlier. The EU dominated the global PV market, led by Italy and particularly Germany, which installed more PV in 2010 than the entire world did the previous year. The trend toward utility-scale PV plants continued, with the number of such systems exceeding 5,000 and accounting for almost 25% of total global PV capacity. Cell manufacturing continued its shift to Asia, with 10 of the top 15 manufacturers located in the region. Industry responded to price declines and rapidly changing market conditions by consolidating, scaling up, and moving into project development.

As per EPIA market report 2011, globally, PV systems connected to the grid rose from 16.6 GW in 2010 to 27.7 GW in 2011. The number of markets reaching more than 1 GW of additional capacity during 2011 rose from 3 to 6. In 2010 the top 3 markets were Germany, Italy and the Czech Republic; in 2011 Italy leads the ranks and Germany, China, the USA, France and Japan follow, each with over 1 GW of new capacity (**Fig. 2.2 and 2.3**).

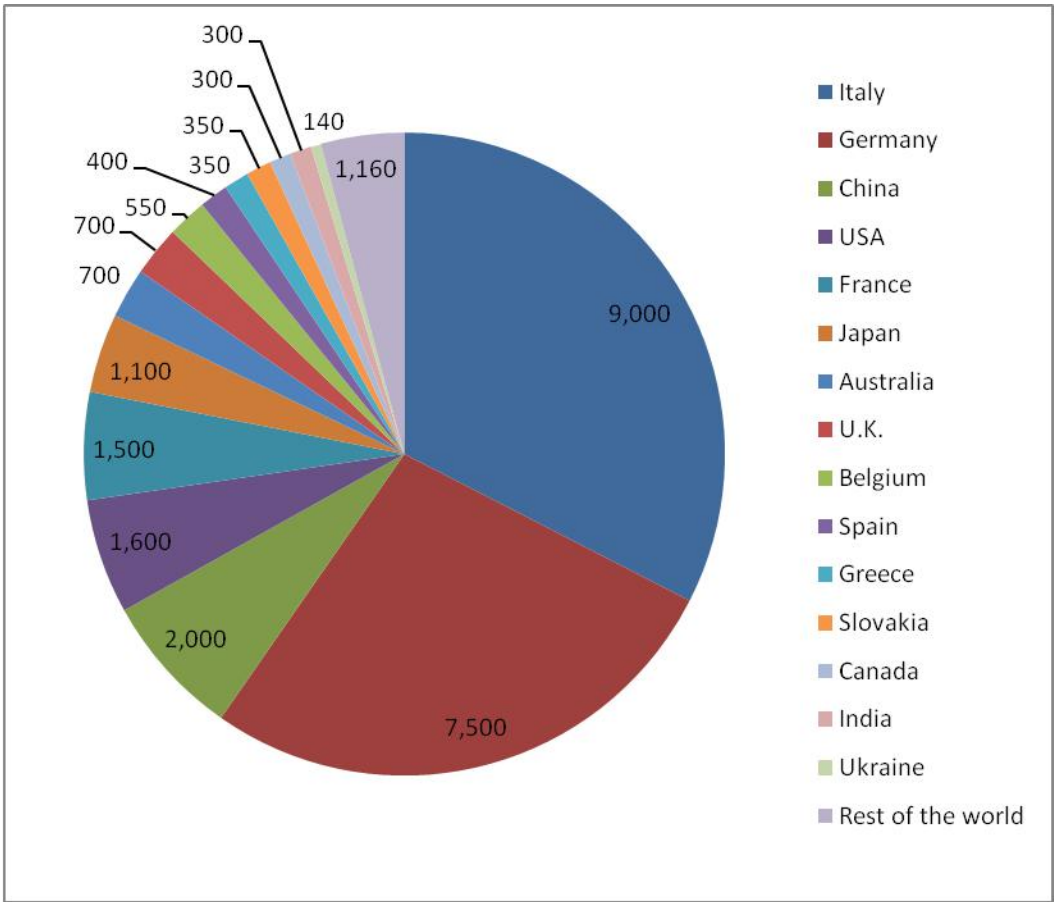

Fig. 2.2 Newly connected installed capacity in 2011

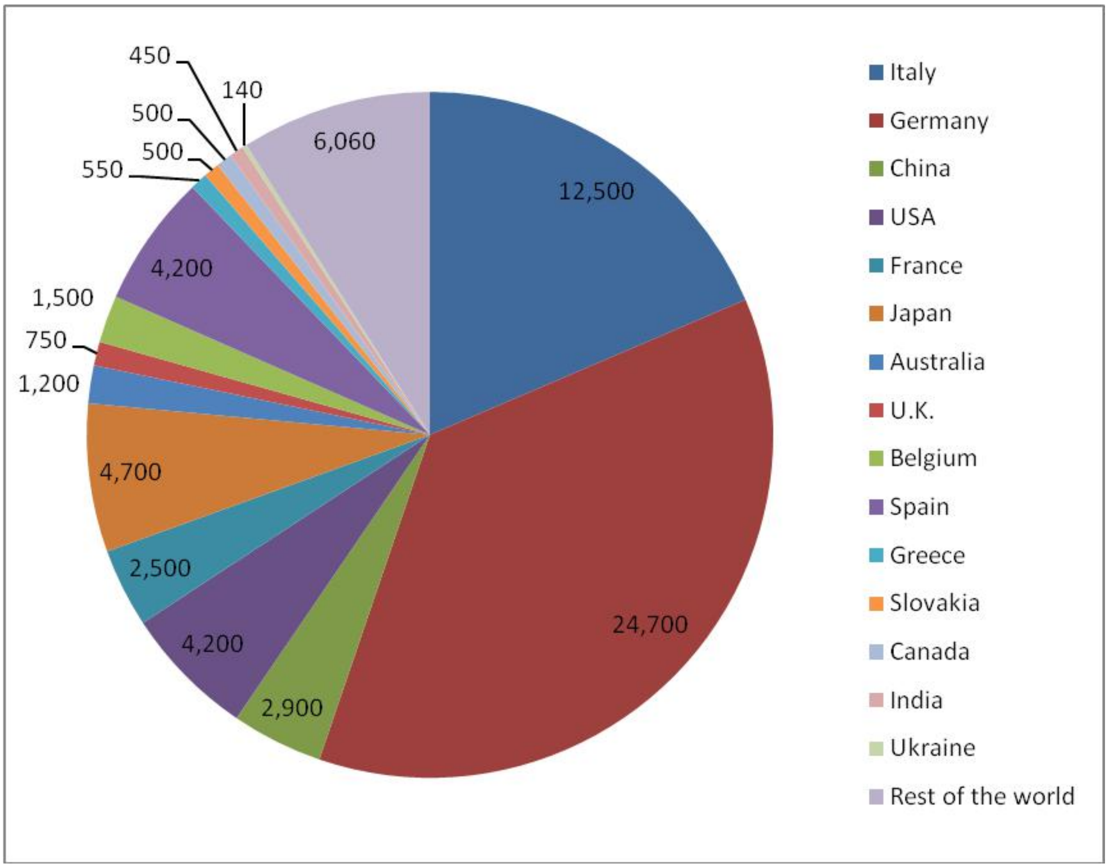

Fig. 2.3 Cumulative installed capacity in 2011

Total installed PV capacity world-wide reached over 67.4 GW at the end of 2011. PV is now, after hydro and wind power, the third most important renewable energy in terms of globally installed capacity. The growth rate of PV during 2011 reached almost 70%, an outstanding level among all renewable technologies. The total energy output of the world's PV capacity run over a calendar year is equal to some 80 billion kWh.

The market share of the world's top 10 markets is highlighted in **figure 2.4**. These top 10 markets make up over 90% of the entire PV growth world-wide.

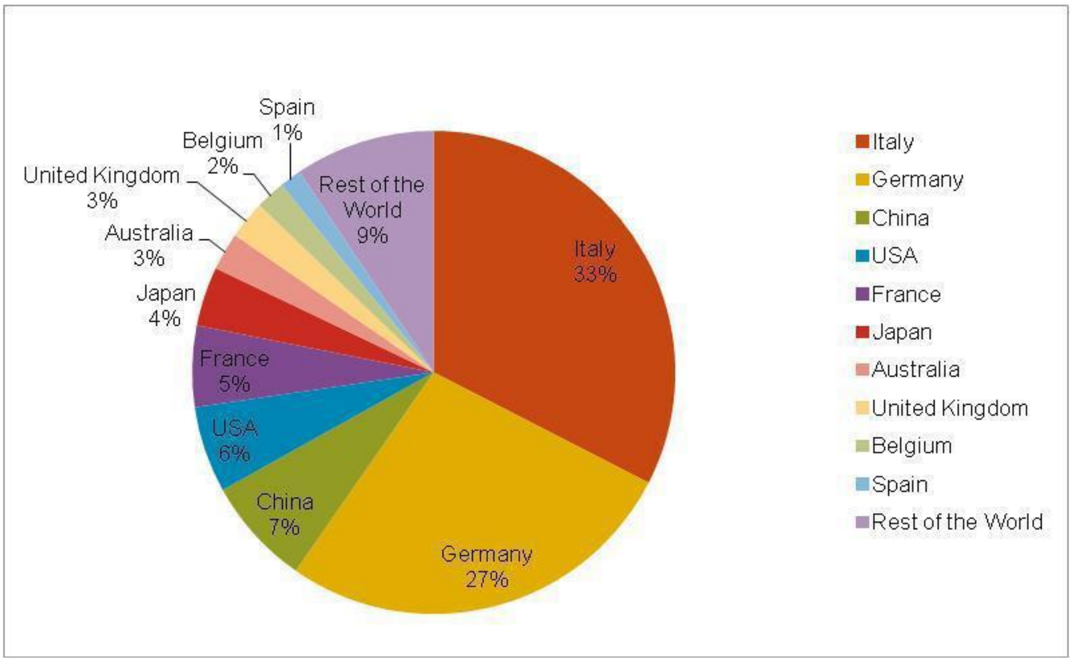

Fig. 2.4 Market share of the world's top 10 markets

More thin film companies are now increasing their production capacities and the status available for 2008 is as follows (**Fig. 2.5**):

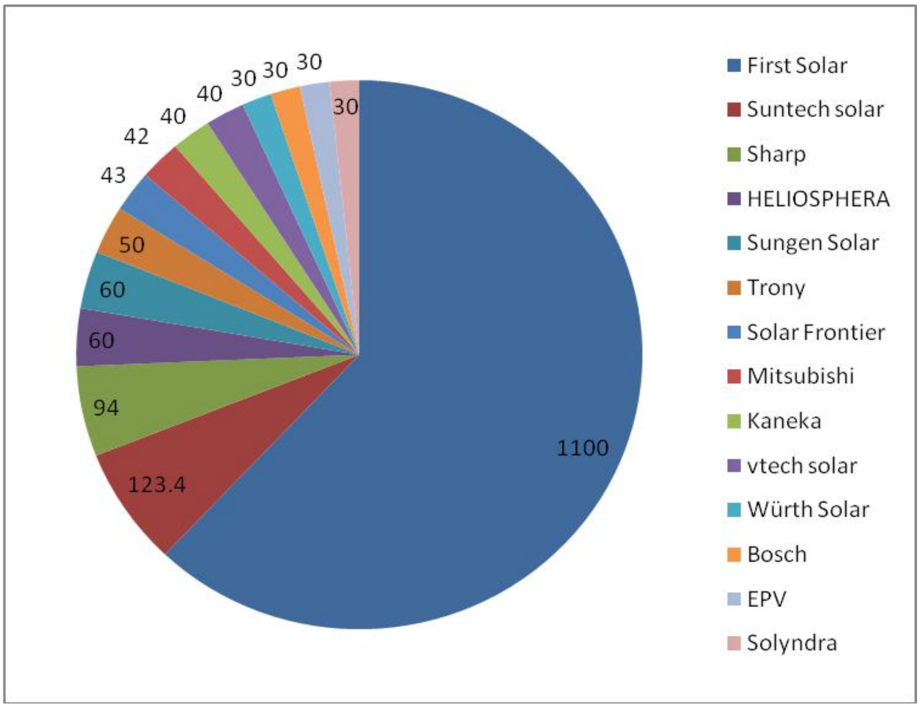

Fig. 2.5 Production capacities of various thin film companies

According to EnergyTrend (http://www.energytrend.com/), 2011 global top ten solar cell manufacturer by capacity are as follows (**Fig. 2.6**) :

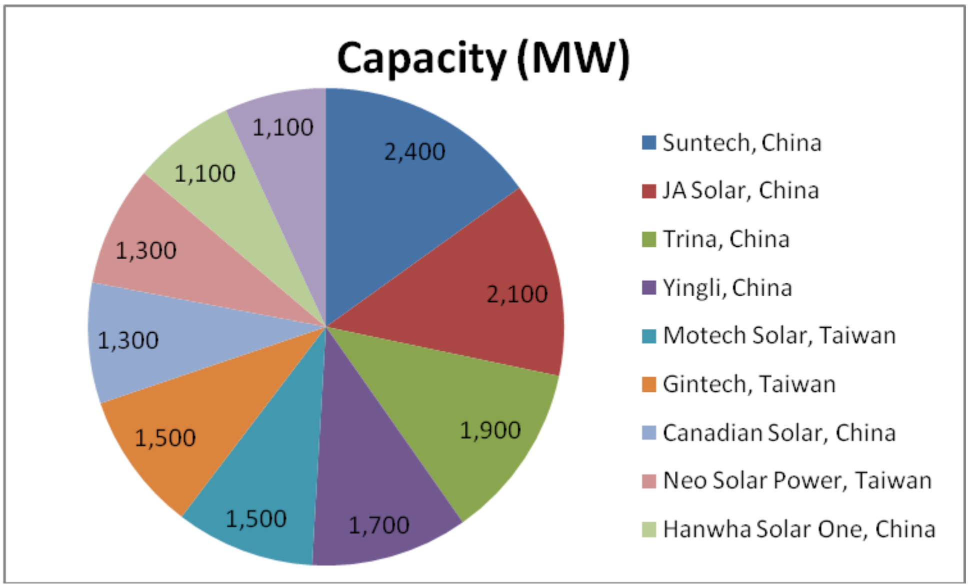

Fig. 2.6 Top ten solar cell manufacturer in the world

According to an annual market survey by the photovoltaics trade publication Photon International, global production of photovoltaic cells and modules in 2009 was 12.3 GW. The top ten manufacturers accounted for 45% of this total. In 2010, a tremendous growth of solar PV cell shipments doubled the solar PV cell market size. According to the solar PV market research company, PVinsights, Suntech topped the ranking of solar cell production. Most of the top ten solar PV producers doubled their shipment in 2010 and five of them were over one gigawatt shipments.

National status

India has witnessed a steady growth in solar photovoltaic of the sector in last two decades. SPV power sector got fillip after announcing JNNSM in year 2009. This has resulted into growing number of PV module manufacturers/suppliers and the major players are tabulated below (**Table 2.1**):

Table 2.1 Major manufacturers / suppliers of SPV module

S. No.	Name of Company	Technology	Business (2010-11) in MW	Power Range	Website
Crystalline					
1.	Ajit Solar	Crystalline Si	12	75-280	www.ajitsolar.com
2.	Alpex Solar	Crystalline Si	10	195-260	www.alpexsolar.com
3.	Access Solar Ltd.	Crystalline Si	15	3-300	www.accesssolar.co.in
4.	Emmvee Photovoltaic	Crystalline Si	52	80-300	www.emmveesolar.com
5.	Green Brilliance Energy	Crystalline Si	40	185-270	www.greenbrilliance.com
6.	HHV Solar Technologies Pvt. Ltd.	Crystalline Si	18	225-315	www.hhvsolar.com
7.	KCP Solar Industry	Crystalline Si	16	3-210	www.kcpsolar.com
8.	Kotak Urja	Crystalline Si	15	10-270	www.kotakurja.com
9.	Novergy	Crystalline Si	24	50-280	www.novergy.co.in
10.	PLG Power Ltd.	Crystalline Si	18	10-280	www.plgpower.com
11.	Reliance solar	Crystalline Si	32	3.3-280	www.resolar.com
12.	Solar Semiconductor	Crystalline Si	160	130-270	www.solarsemiconductor.com
13.	Sun Energy Systems	Crystalline Si	12	3-290	www.sunenergysystems.in
14.	Surana Ventures Ltd	Crystalline Si	30	3-230	www.suranaventures.com
15.	Tapan Solar Energy P Ltd.	Crystalline Si	25	80-290	www.elecssol.com
16.	Tata BP Solar India	Crystalline Si	100	0.3-280	www.tatabpsolar.com
17.	Titan Energy Systems	Crystalline Si	100	20-300	www.titan-energy.com
18.	Topsun Energy Ltd.	Crystalline Si	10	10-225	www.topsunenergy.com
19.	Waaree	Crystalline Si	14	3-300	www.waaree.com
20.	Websol Solar	Crystalline Si	60	3-390	www.websolar.com
21.	XL Telecom & Energy Ltd.	Crystalline Si	160	175-280	www.sltelenergy.com

S. No.	Name of Company	Technology	Business (2010-11) in MW	Power Range	Website
Thin Film Manufacturers					
1.	Alpex Solar	Amorphous Si	10	195-260	www.alpexsolar.com
2.	HHV Solar Technologies Pvt. Ltd.	Amorphous Si	18	225-315	www.hhvsolar.com
3.	KSK Surya Photovoltaic Venture Pvt. Ltd.	Amorphous Si			www.suryapowerinc.com
4.	Moser Baer Solar Ltd.	Amorphous Si		5-240	www.moserbaerpv.in
5.	Novergy Energy Solutions P. Ltd.	Amorphous Si	24	50-280	www.novergy.co.in
6.	Powercell Energy Pvt. Ltd.	Amorphous Si			www.powercellenergies.com
7.	Vorks Energy Pvt. Ltd.	Amorphous Si			www.vorks.com
8.	Empire Photovoltaic Sys Pvt. Ltd.	CIS		130-270	www.epssolar.com
9.	Shurjo Energy Pvt. Ltd.	CIS			www.shurjo-energy.com

Source: http://www.enf.cn/database/panels-india.html

The India solar handbook, January 2012 published by Bridge to India has documented the recent development in PV sector in very articulated manner. Some of the highlights including pictorial representation taken from the report are reproduced below:

According to them, India with liberalized policies for the power sector, a high potential for solar power and a variety of central and state-level incentive systems, presents a particularly good opportunity for the solar industry. The market is supported by FiTs to provide an initial thrust. The growth is further fuelled by the REC market which is RPO driven as mandated by SERCs.

It is interesting to note India has now many local SPV cell and module manufacturer as represented below (**Fig. 2.7 & 2.8**):

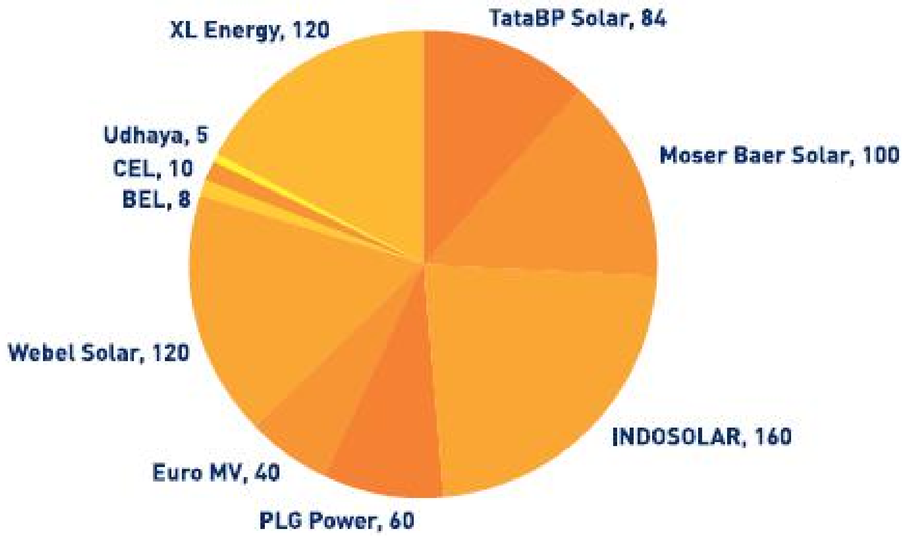

Fig. 2.7 Cell manufacturers in India (MW)

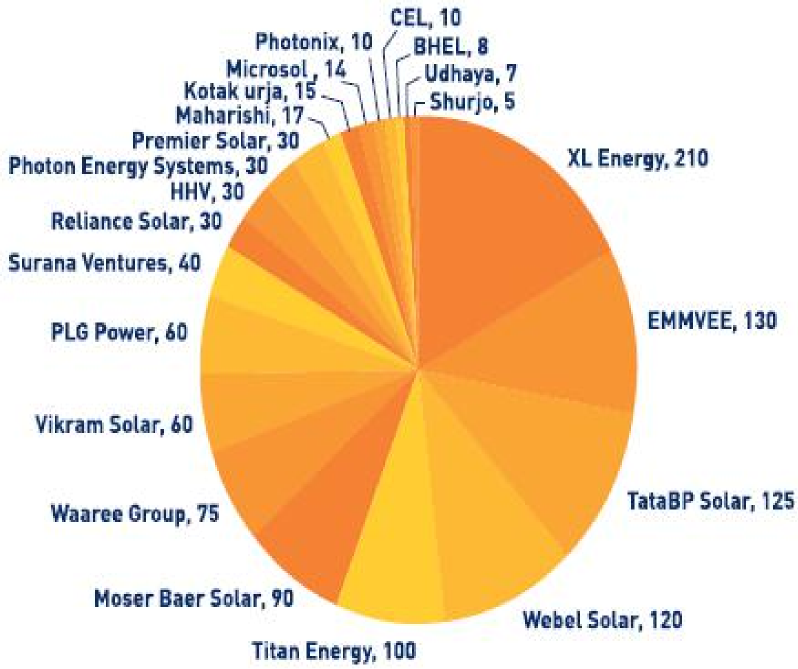

Fig. 2.8 Module manufacturers in India (MW)

For the first batch of projects in the NSM, crystalline modules being used must be manufactured in India. The second batch of projects under the NSM due to be allotted by the end of 2011 are not allowed to install modules with imported cells. Use of thin film technology is still exempted from domestic content guidelines.

Considering that projects outside JNNSM have no restriction of domestic PV module purchase, many projects are looking for imported solar PV modules. Going by the current supply contracts, India will import more than 1 GW of modules until the end of 2012. More than 60% of these will be for thin film modules, all from foreign manufacturers (**Fig 2.9 & 2.10**) .

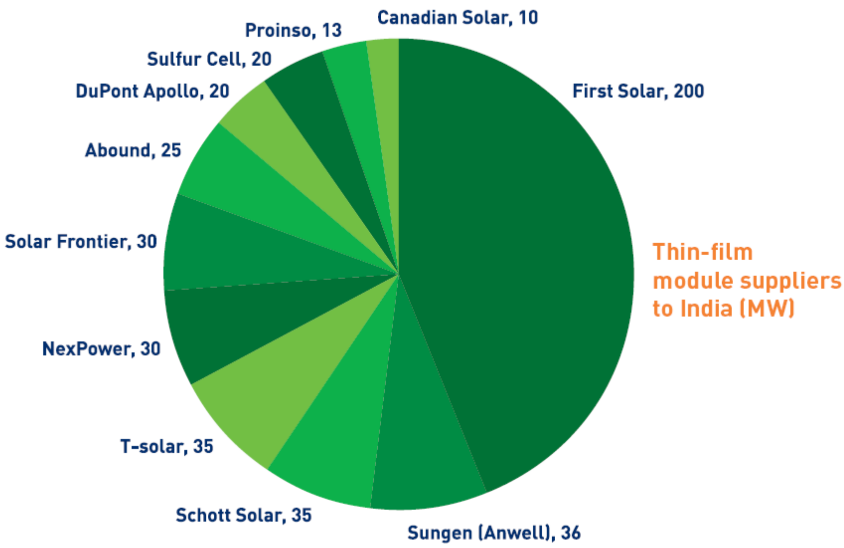

Fig. 2.9 Thin film module suppliers in India

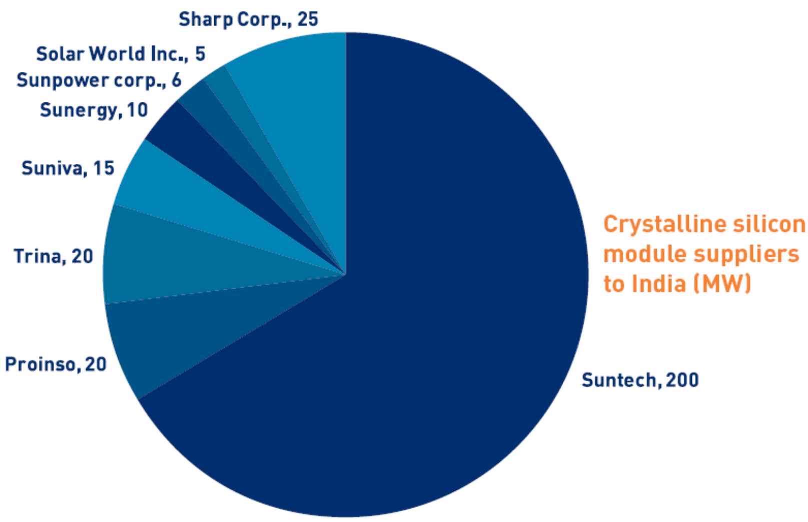

Fig. 2.10 Crystalline silicon module suppliers in India

Considering the present scenario of FiT declared by CERC and many SERCs; and the recent developing REC market, healthy growth of SPV market is expected in India (**Table 2.2**).

Table 2.2 Projected Market growth of Solar PV in India													
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Migration Policy**	2	20	50	0	0	0	0	0	0	0	0	0	0
NSM	0	40	145	460	520	1100	1600	2000	2400	2900	3500	4200	4800
Gujarat Solar Policy	0	180	350	550	800	1100	1450	1900	2400	2950	3550	4200	5000
Rajasthan Solar Policy*	0	0	0	220	450	750	1100	1500	2000	2550	3150	3850	4600
Karnataka Solar Policy*	0	0	0	40	80	130	200	320	500	720	970	1270	1600
Other States	22	40	200	300	420	550	800	1200	1650	2200	2800	3450	4200
Off-grid: Captive power plants and telecom towers	30	50	80	220	550	1100	1900	3100	3400	4000	4600	5300	6200
off-grid: Home system and minigrids	10	25	40	110	280	500	840	1300	1800	2500	3700	5200	7000
Total	**64**	**355**	**865**	**1900**	**3100**	**5230**	**7890**	**11320**	**14150**	**17820**	**22270**	**27470**	**33400**
**** Policy has been discontinued, there will be no further projects beyond 2012**													
*** New policy; capacity addition will only begin past 2012**													

The PV manufacturing industry in India has grown six-fold from under 200 MW in 2007 to 1,300 MW in 2011. In the next few years, the growth in module production will be replicated upstream as well. For the first time, Indian manufacturing industry could be seeing significant production capacities for wafers and ingots as well (Fig. 2.11).

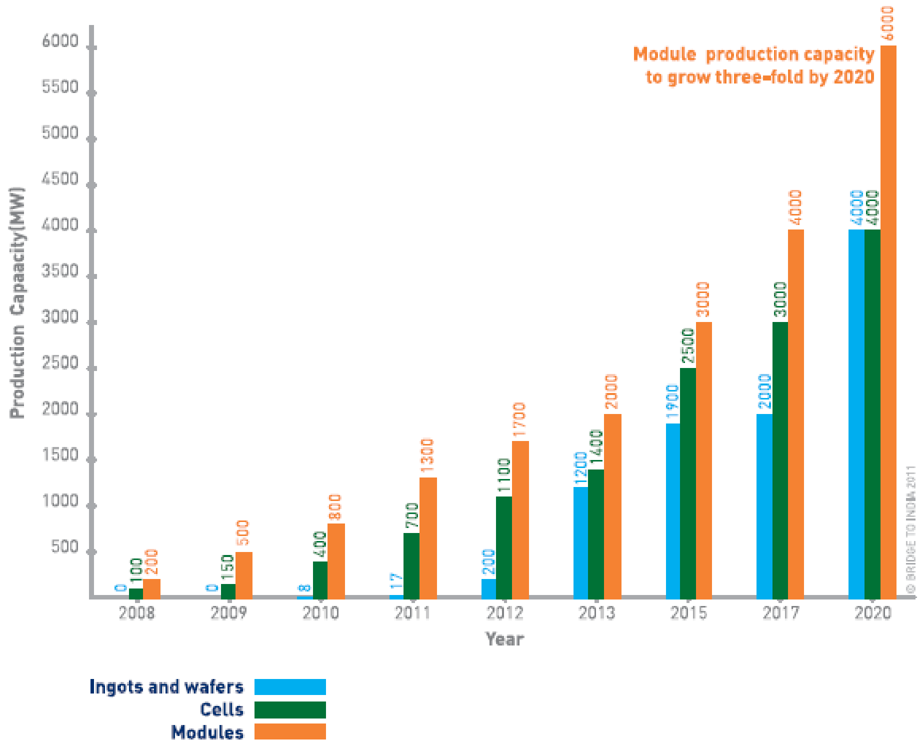

Fig. 2.11 PV manufacturing forecast- India

The picture of commissioned solar power projects in India is very encouraging. It is interesting to note that majority of the development has occurred in Gujarat state which is outside JNNSM scheme. That means the proactive policy of state government can also play a major role. There is a steady growth in other states too. According to personal communication with the Gujarat government officials, the state has achieved 604 MW by 31 March 2012. Considering this report, total installed capacity of solar power projects in the country will be around 800 MW which can be considered a great achievement by Indian solar sector.

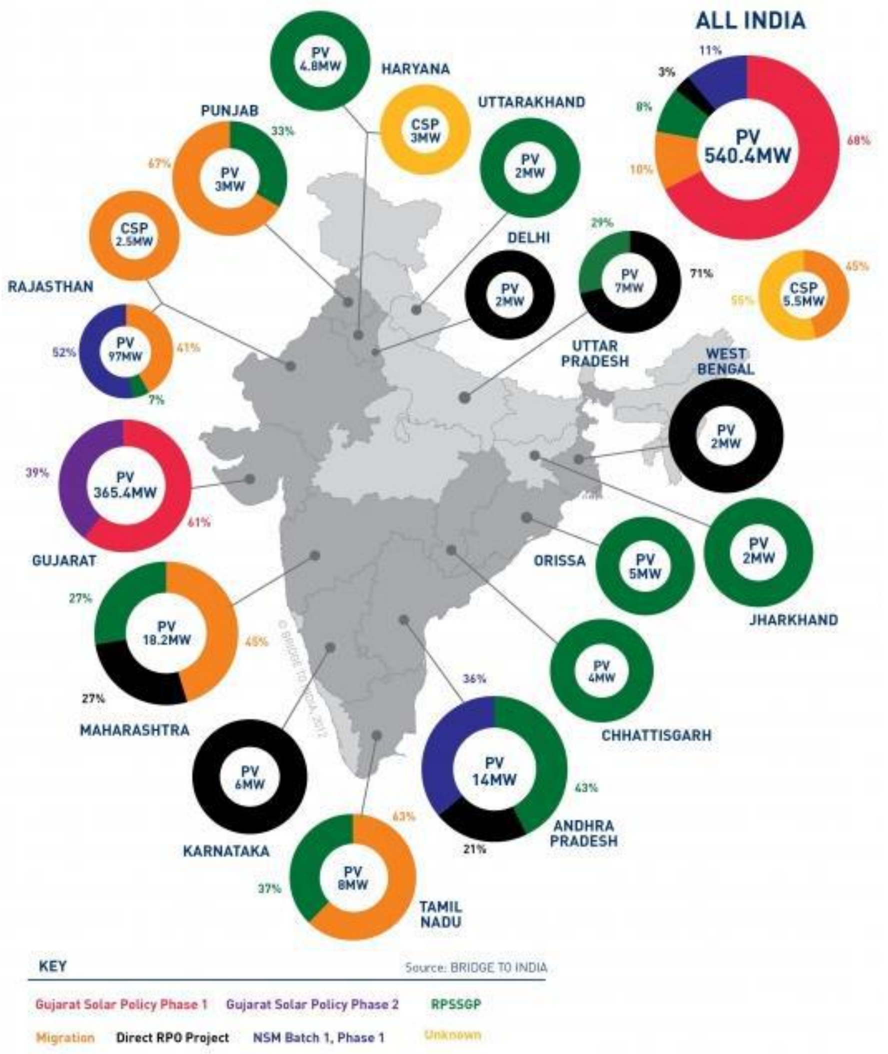

Fig. 2.12 Current total grid connected installed capacity – All India

4

Technical Specifications

Typical technical specifications

The photovoltaic modules whether crystalline or thin film, have typical technical specifications, which indicate the quality of the module that helps the user to choose the module as per his load requirement. The important parameters sought for in the technical specifications and the desired parameters are tabulated below:

Table 3.1 Technical specification in desired parameters of SPV modules

S.No.	Technical parameters	Desired requirements	Justification
1.	Model No.	Must be mentioned	Necessary for record and future reference
2.	Unique identification no.	Must be mentioned	To avoid duplication
3.	Maximum Power @ STC (Standard Test Conditions)	To know the capacity of module to generate maximum power	Necessary to design the system as per load requirement
4.	Open Circuit Voltage (Voc)	Higher the better	Indicates maximum possible voltage
5.	Optimum Operating Voltage (Vmp)	Higher the better	Indicates practically available voltage
6.	Short Circuit Current (Isc)	Higher the better	Indicates maximum possible current
7.	Optimum Operating Current	Higher the better	Indicates practically available current
8.	Operating temperature	Larger range from sub-zero to 30 deg C above room temperature desired	Flexibility to work in any environment in any season.
9.	Maximum system voltage	The modules should be able to sustain the power plant's voltage environment of not less than 1000 DC Volt	This reflects the suitability of module to work for large power projects without deterioration due to leakage current
10.	Maximum series fuse rating	Higher rating but not more than 15 amperes is expected	For better protection of the power system
11.	Cell efficiency	Higher the better	High efficiency will produce more power in lesser area
12.	Module efficiency	Closer to cell efficiency desired	The module efficiency closer to cell efficiency indicates better manufacturing quality
13.	Type of solar cell	Whether the module is crystalline or thin film must be defined	Ultimate efficiency, power output and area utilization depends upon the type of cell
14.	Dimensions	Length, width and thickness needs to be defined	Higher power output in lesser area helps deployment of lesser modules
15.	Net Weight	Lesser the better	Lighter modules reduces the bulk of power project and hence lesser requirement of support structure

16.	Frame	Weather-proof frame with minimum 30 years life is desired	Replacing the frame mid-way is practically impossible

Table 3.2 Currently available cell and module efficiencies

17.	Front glass	Highly transparent and strong glass required	Transparency allows maximum sunlight to be absorbed and toughness is needed for long life and protection from hailstorms
18.	Junction box and cables	Needs to be standard items	Latest specification must be followed, such as IP65/IP67 etc.
19.	Nominal operating cell temperature (NOCT)	Due to inherent losses, individual cell temperatures are always higher than ambient temperature	NOCT of around 50 deg C is desirable
20.	Temperature coefficient of Pmax	Lower the better	Power output reduces with increase in the ambient temperature

Cell and module efficiencies

According to the report on “Performance of Solar Power Plants in India”, dated February, 2011 (Dr. B. D. Sharma), submitted to Central Electricity Regulatory Commission, crystalline silicon (c-Si) modules represent 85-90% of the global annual market today. C-Si modules are subdivided in two main categories: i) single crystalline (sc-Si) and ii) multi-crystalline (mc-Si).

Thin films currently account for 10% to 15% of global PV module sales. They are subdivided into three main families: i) amorphous silicon (a-Si), ii) Cadmium-Telluride (CdTe), and iii) Copper-Indium-Diselenide (CIS).

The above technologies are mainly used on roof tops of commercial and residential buildings, and as large scale grid connected power plants. For optimum output, larger installations use tracking devices which change the orientation of the panels to correspond with the trajectory of the sun to focus sunlight directly onto the panels.

The current status of efficiencies at cell and module levels can be summarized in the following table:

Technology	Cell Efficiency (%)	Module Efficiency (%)	Remarks
Single crystal silicon	16-17	13-15	Highest efficiency but more expensive
Polycrystalline silicon	14-15	12-15	Slightly less efficient but no distinct cost advantage
Amorphous silicon		6-7	Very low efficiency but cheaper fabrication cost
Cadmium telluride		8-10	Moderately efficient, just beginning to make market impact
Copper indium diselenide		10-11	Most efficient amongst rest of thin films, negligible market share

Effect of ambient temperature

Module performance is generally rated under Standard Test Conditions (STC): irradiance of 1,000 W/m², solar spectrum of AM 1.5 and module temperature at 25°C. All electrical parameters of solar modules depend on temperature. The module output decreases with increase in temperature. This loss of power is defined by Temperature coefficients.

The temperature coefficient represents the change in power output with different temperatures. Typical values of temperature coefficient for solar modules are as follows:

Crystalline modules: -0.40 to 0.45%/°C

Amorphous modules: -0.20 to 0.25%/ °C

CdTe modules: -0.24 to 0.3 %/ °C

Therefore thin film modules of comparable wattage will give higher performance at elevated temperature when compared to crystalline silicon.

Life of module and degradation

The long term reliability of photovoltaic modules has been improving steadily, with manufacturers offering over 25 years guarantee on their panels. However, no power plant of MW scale has been in existence for such a long period of time, for verification of the guarantee. Some of the mono-crystalline small SPV power plants of kW scale have been reported to be working successfully even after 30 years without much degradation. The power plants based on polycrystalline are also reported to be working since last 20 years with little degradation. However, there is no such experience regarding thin films.

As the output reduces each year, so does the revenue from sale of power, and therefore accurate data must be available at the outset to ensure that the power plant design is exact and not over or under the required output. Lifetime of the module is one of the four factors besides system price, system yield and capital interest rate which decides the cost of electricity produced from the module, and this lifetime is decided by the degradation rate.

To estimate the lifetime from degradation, standard tests called ‘Type Approval Tests’ have been introduced by the International Electrotechnical Commission (IEC). These are essentially accelerated test procedures based on accelerated climatic testing. However, there is still some uncertainty as to whether these accelerated tests can accurately simulate real time long term exposure (Dr. B. D. Sharma).

Most panels are guaranteed to produce outputs of 90% after 10 years of use and 80% after 20 years of use. Recently, the manufacturers are comfortably providing guarantees of 90% output after 12 years and 80% output after 25 years.

Many long term studies have shown that module degradation for 10 years for crystalline solar cells can be in the range of 4 to 7 percent, lower than the 10% degradation currently guaranteed by most manufacturers. However, similar data for thin film solar cells are yet to be established. This information is extremely relevant during power plant design for getting an accurate estimate of the amount of power and therefore income expected each year after installation.

The silicon cells themselves have infinite life, except for the slight degradation due to thermal effects. Main reasons for degradation are the slow breakdown of a module’s encapsulant (usually ethylene vinyl acetate; EVA) and back sheet (polyvinyl fluoride films), the gradual obscuration of the EVA layer between the module’s front glass and the cells themselves. Over time, this limits a module’s ability to force out moisture. The trapped moisture eventually leads to corrosion at the cell’s electrical connections, resulting in higher resistance at the affected connections and, ultimately, decreased module operating voltage (Dr. B.D. Sharma).

IEC 61215 / IEC 61646 type approval

For crystalline solar cells, the test specifications on “Terrestrial Photovoltaic (PV) Modules with Crystalline Solar Cells – Design qualification and Type Approval” were adopted in 1993 and in April 2005 International Electro-technical Commission standard with some revision (IEC 61215) was published.

For photovoltaic thin-film modules, a comparable standard was developed in 1996. In 2008, a second edition to this standard, namely IEC 61646: “Thin-film terrestrial photovoltaic (PV) modules – Design qualification and type approval”, was released, which addresses new developments in the thin-film technologies and shall reduce testing efforts. The standard is in many aspects identical to IEC 61215. The main difference between the two standards lays in the additional test procedures to adapt to the special properties of thin-film technologies. These additional tests take the degradation behavior of thin-film modules due to irradiance exposure into account (Brochure of TÜV Rheinland Immissionsschutz und Energiesysteme GmbH, Renewable Energies, January 2009)

The overview of these specifications for crystalline and thin film solar cells are tabulated below:

Overview of IEC 61215 / IEC 61646 tests

Code	Qualification Test	Test Conditions
10.1	Visual Inspection	according defined inspection list
10.2	Maximum Power Determination	measurement according to IEC 60904
10.3	Insulation Test	1000 VDC + twice the open circuit voltage of the system at STC for 1 min, isolation resistance * module area > 40 MΩ·m^2 at 500 VDC
10.4	Measurement of Temperature Coefficients	Determination of the temperature coefficients of short circuit current, open circuit voltage and maximum power in a 30°C interval
10.5	Measurement of NOCT	total solar irradiance = 800 W/m² wind speed = 1 m/s
10.6	Performance at STC and NOCT	cell temperature = NOCT / 25°C irradiance = 800 W/m² / 1000 E/m² measurement according to IEC 60904
10.7	Performance at low Irradiance	cell temperature = 25°C irradiance = 200 W/m² measurement according to IEC 60904
10.8	Outdoor Exposure Test	60 kWh/m² solar irradiation
10.9	Hot-Spot Endurance Test	5 hour exposure to > 700 W/m² irradiance in worst-case hot-spot condition
10.10	UV-preconditioning test	15 kWh/m² UV-radiation (280 - 385 nm) with 5 kWh/m² UV-radiation (280 - 320 nm) at 60°C module temperature
10.10*	UV-Exposure according IEC 61345	Min.15 kWh/m² UV-radiation (280 - 400 nm) with 7.5 kWh/m² UV-radiation (280 - 320 nm) at 60°C module temperature
10.11	Thermal Cycling	50 and 200 cycles -40°C to +85°C
10.12	Humidity Freeze Test	10 cycles -40°C to +85°C, 85% RH
10.13	Damp Heat	1000 h at +85°C, 85% RH
10.14	Robustness of Terminations	As in IEC 60068-2-21
10.15	Wet Leakage Test	Evaluation of insulation of the module under wet conditions
10.16	Mechanical Load Test	Three cycles of 2400 Pa uniform load, applied for 1 h to front and back surfaces in turn
10.17	Hail Test	25 mm diameter ice ball at 23 m/s, directed at 11 impact locations
10.18	Bypass diode thermal test	Asses adequacy of thermal design of by-pass diodes at a current of 1.25 x Isc running through the diodes at module temperature of 75°C
10.19**	Light soaking	Light exposure of cycles of at least 43 kWh/m² and module temperature of 50°C ± 10 °C, until Pmax is stable within 2 %

* Tests can alternatively be used
** Tests only relevant for IEC 61646 qualification

Pass criteria

A module design shall be judged to have passed the qualification tests, and therefore to be IEC type approved, if each sample meets the following criteria:

• The degradation of the maximum power output at standard test conditions (STC) does not exceed 5 % after each test nor 8 % after each test sequence;

• The requirements of tests 10.3 (and 10.2) are met;

• No major visible damage (broken, cracked, torn, bent or misaligned external surfaces; cracks in a solar cell which could remove a portion larger than 10% of its area; bubbles or de-laminations; loss of mechanical integrity

• No sample has exhibited any open circuit or ground fault during the tests;
• For IEC 61646 only: the measured maximum output power after final light-soaking shall not be less than 90% of the minimum value specified by the manufacturer.

Technical specifications of commercial SPV modules

It would be interesting to have look of technical specification of existing SPV modules commercially available from each of the categories. Some of the typical cases are presented below:

Mono-crystalline modules

Table 3.3 Technical specification of typical mono-crystalline module

Electrical parameters	
Nominal Power – Pmax (Watts)	230
Voltage at Maximum Power – Vmp (Volts)	30.84
Current at Maximum Power – Imp (Amps)	7.48
Open Circuit Voltage – Voc (Volts)	37.26
Short Circuit Current – Isc (Amps)	7.96
Maximum System Voltag	1000 VDC
Temperature Coefficient – Voc	-133.26 mV / °C
Temperature Coefficient – Isc	+2.28 mA / °C
Solar Cells per Module – Units	60
Parent Solar Cell Size – mm	156 Sq. Mono Crystalline
Mechanical Details	
Dimensions – L x W x T mm	1660 x 990 x 42
Weight – Kgs	20
Mounting Holes Pitch (Y) – mm	1100 ± 2
Mounting Holes Pitch (X) – mm	953 ± 2
Area – Sq. Mtrs	1.64

Measurement Tolerance on Electrical Parameters ± 5%.

- All specified parameters are at STC 25°C cell, 100mW / cm² irradiance and AM 1.5.
- Specifications subject to change without prior notice due to product up gradations.
- All Modules will be supplied with prefixed cables and connectors.

(Two cables of 4 Sq. mm and length 0.9m each).

Certifications: IEC 61215 / IEC 61730-1 / IEC 61730-2 & TUV Safety Class II

Polycrystalline modules

Table 3.4 Technical specification of typical polycrystalline module

Electrical parameters

Maximum Power (Pmax)*	240 W
Tolerance of Pmax	+5%/-0%
PTC Rating	216.4 W
Type of Cell	Polycrystalline silicon
Cell Configuration	60 in series
Open Circuit Voltage (Voc)	37.5 V
Maximum Power Voltage (Vpm)	29.3 V
Short Circuit Current (Isc)	8.75 A
Maximum Power Current (Ipm)	8.19 A
Module Efficiency (%)	14.7%
Maximum System (DC) Voltage	600 V
Series Fuse Rating	15 A
NOCT	47.5°C
Temperature Coefficient (Pmax)	-0.485%/°C
Temperature Coefficient (Voc)	-0.36%/°C
Temperature Coefficient (Isc)	0.053%/°C
Mechanical Characteristics	
Dimensions	39.1" x 64.6" x 1.8"/994 x 1640 x 46 mm
Cable Length (G)	43.3"/1100 mm
Output Interconnect Cable	12 AWG with SMK Locking Connector
Weight	41.9 lbs / 19.0 kg
Max Load	50 psf (2400 Pascals)
Operating Temperature (cell)	-40 to 194°F / -40 to 90°C
Qualifications	
UL Listed	UL 1703
Fire Rating	Class C

Amorphous Silicon modules

Table 3.5 Technical specification of typical amorphous silicon module

Electrical Data	
Maximum power Pmax	135 W
Tolerance of Pmax	+7%/-2%
Open-circuit voltage Voc	61.3 V
Short-circuit current Isc	3.41 A
Voltage at maximum power Vpmax	47.0 V
Current at maximum power Ipmax	2.88 A
Module efficiency η	9.6%

Temperature coefficient – open circuit voltage β	-0.3%/°C
Temperature coefficient – short circuit current α	+0.07%/°C
Temperature coefficient – power γ	-0.24%/°C
Specifications (I)	
Cell	Tandem architecture of amorphous and microcrystalline silicon
Dimensions	1001 x 1402 x 7.4 mm
Weight	26 kg
Front glass	Low iron non-tempered glass
Back glass	Tempered
Connection type	Cable with SMK connector
Specifications (II)	
Maximum system voltage	1,000 VDC
Maximum mechanical load	2,400 Pa
Series Fuse Rating	5 A
Operating temperature (cell)	– 40 to +90 °C
Storage temperature	– 40 to +90 °C
Storage air humidity	Up to 90 %
Installation orientation	Portrait or Landscape

Cadmium Telluride modules

Table 3.6 Technical specification of typical Cadmium Telluride modules

Rating at STC	
Nominal Power(+/-5%) P_{MPP} (W)	70
Voltage at PMAX V_{MPP} (V)	65.5
Current at PMAX I_{MPP} (A)	1.07
Open Circuit Voltage V_{OC} (V)	88.0
Short Circuit Current I_{SC} (A)	1.23
Maximum System Voltage V_{SYS} (V)	1000 (600 UL2)
Temperature Coefficient of PMPP TK(P_{MPP})	-0.25%/°C
Temperature Coefficient of V_{OC}, high temp (>25°C) T_K(V_{OC}, high temp)	-0.25%/°C
Temperature Coefficient of V_{OC}, low temp (-40°C to + 25°C) T_K(V_{OC}, low temp)	-0.20%/°C
Temperature Coefficient of I_{SC} T_K(I_{SC})	+0.04%/°C
Limiting Reverse Current I_R(A)	2
Maximum Series Fuse I_{CF}(A)	2

Rating at 800W/m2, NOCT3 45°C, AM 1.5*	
Nominal Power(+/-5%) P_{MPP}(W)	52.5
Voltage at P_{MAX} V_{MPP}(V)	61.4
Current at P_{MAX} I_{MPP}(A)	0.86
Open Circuit Voltage V_{OC}(V)	81.8
Short Circuit Current I_{SC}(A)	1.01
Mechanical Description	
Length (mm)	1200
Width (mm)	600
Weight (mm)	12
Thickness (mm)	6.8
Area (Sq. m)	0.72
Lead-wire	4.0 mm^2, 610 mm
Connectors	Solarline 1 type connector
Bypass Diode	None
Cell Type	CdS/CdTe semiconductor, 116 active cells
Frame Material	None
Cover Type	3.2mm heat strengthened front glass laminated to 3.2mm tempered back glass
Encapsulation	Laminate material with edge seal

Copper Indium Di-selenide modules

Table 3.7 Technical specification of typical Copper Indium Di-selenide modules

Data measured under standard test conditions (STC)	
Electrical Specifications	
Nominal power P_{nom}	135 W
Tolerance of nominal power ΔP_{nom}	-0/+4 %
Module efficiency η**	12.8 %
Aperture efficiency η	14.2 %
Open-circuit voltage V_{oc}	61.5 V
Short-circuit current I_{sc}	3.14 A
Voltage at mpp V_{mpp}	47.4 V
Current at mpp I_{mpp}	2.84 A
Limiting reverse current I_r	5.0 A

Max. system voltage V_{sys} (IEC)	1000 V
Max. system voltage V_{sys} (UL)	600 V
Data measured at nominal operating cell temperature (NOCT)* and AM 1.5	
NOCT	40.0 °C
Nominal power P_{nom}	100.7 W
Open-circuit voltage V_{oc}	57.8 V
Short-circuit current I_{sc}	2.48 A
Voltage at mpp V_{mpp}	44.4 V
Temperature Corfficient	
Temperature coefficient P_{nom}	-0,39 %/°C
Temperature coefficient V_{oc}	-170 mV/°C
Temperature coefficient I_{sc}	0,1 mA/°C
Temperature coefficient V_{mpp}	-140 mV/°C
Mechanical Specifications	
External dimensions	1587 x 664 mm²
Thickness	39,6 mm
Weight	16 kg
Junction box protection class	IP65
Dimensions of the junction boxes	70 x 64 x 13 mm³
Cable lengths (-plug / +socket)	170 / 300 mm
Cable cross section	2,5 mm²
Connector type	LC4

5

Comparative Assessment of Technologies: Crystalline PV vs. Thin Film Solar

Overview

This comparative assessment of the two technologies: crystalline PV and thin film solar is neutral with respect to technologies, companies, lenders, institutions and societal interests. Presently, all stakeholders in this sector are on a learning curve. While carrying out this comparative assessment exercise, many organizations, individuals, scientists, government officers, promoters, manufacturers and financiers have been contacted. Their views along with supporting documents provided by them, while subject to confidentiality, have been very helpful in enriching the study. Therefore, the names of individuals have not been included. Only references already available in the public domain have been incorporated for the sake of transparency and independent evaluation. The objective of this study is to help all the stakeholders, so as to result in the healthy growth of the solar power sector in India.

This comparative assessment looks at the two technologies from four different perspectives: the perspectives of equity investors, the perspectives of debt investors (lenders), the perspectives of various institutional entities including central and state govt bodies, and also the societal perspective towards environmental externalities. Hence the two technologies are judged from these differing perspectives in arriving at a balanced conclusion with respect to the technologies.

Comparison of Investment Costs: The Equity Investors perspective

This section of the study has been carried out for comparing the investment costs of crystalline and thin film PV technologies. This comparison is important from the equity investors' perspective. It also has relevance in the debt investors' perspective. A sample case of 1 MW each power project has been considered.

A cost break-up has been prepared considering the present module cost as of 11th April 2012 (www.pvinsights.com) and latest forex conversion rate of RBI. The project cost break-up accordingly for both the technologies is given below:

Table 4.1 Comparative Project cost of crystalline & thin film SPV power project (1 MW)

	Crystalline	Thin film
Cost Component	**Rs in lakhs**	
Land (3.2 Lakh/ acre)(1)	14.4	28.8
PV module (2)	447	383
Civil and General Work(3)	90	135
Mounting Structures(4)	100	150

Power conditioning unit[5]	98	98
Preliminary and pre-operative expenses including IDC and contingency[6]	80	80
Additional cost towards degradation & auxiliary (ref CERC guidelines)[7,8,9,10]	66	66
Evacuation Cost up to Inter-connection Point (Cables and Transformers)[11]	100	120
Total capital cost	**995.8**	**1060.9**
Please refer the following subsections (1-11) for the basis of cost estimation		

(1) Land required for power generation

Land requirement for crystalline technology is assumed to be 4.5 acres/MW and for thin film technology is 9.0 acres/MW, considering the difference in their efficiencies Due to low efficiency, the thin film technology needs almost double the area required by crystalline technology for the same capacity of power plant. A comparative statement given below is self explanatory. This will have a detrimental effect on the economics of projects in the areas where land is a scarce commodity. Recent trend has shown that even waste land costs have sky rocketed in the case of wind power projects and in some cases in solar power projects. In near future, with the rush of the green investors, there will be severe shortage of land and this factor deserves serious attention.

Type of module	Area requirement (per kW_p)
Single crystal silicon	~ 7m²
Polycrystalline silicon	~ 8m²
Amorphous silicon	~15m²
Cadmium telluride	~11m²
Copper indium diselenide	~10m²

(2) Cost of Modules

Cost of Crystalline module $ 0.87/Wp (Rs. 44.74)
Cost of Thin Film module $ 0.745 /Wp (Rs.38.31)
Source: (*www.pvinsights.com*), USD 1 = Rs. 51.42 (*Reserve Bank of India*)

(3) Civil and General Work

In case of thin film, additional provision of 50% in civil and general works compared to crystalline has been considered, due to the larger area of works.

(4) Mounting Structures

For mounting structure and cabling an additional cost of 50% and 20% respectively compared to crystalline has been considered, due to larger area.

(5) Power Conditioning Unit

This cost is assumed equal for both technologies

(6) Pre-Operative Expenses

This cost is assumed equal for both technologies

(7) Module degradation

As stated in the technical chapters, module degradation on exposure to sunlight is the inherent property of solar modules of all types whether crystalline or thin film. Thin films are by nature such that there is initial drop in power output due to light soaking up to 1000 hours of exposure to radiation and thereafter it stabilizes for long term. No such effect is observed in crystalline solar cells. Therefore in the case of thin film one must ask about the "stabilised output" rather than "initial output". Although, different manufacturers claim their own performance indicators, actual measurements at the sites after 10-20 years of installation is the only way to get the true picture. Some of the observations of WISE research team in this regard are as follows:

- NREL study of various kinds of 10 years old SPV modules installed at Solar Energy Centre, New Delhi has shown that the degradation in thin film modules is 2% or more per year. Moisture seepage through edges has been observed. Many of the thin film modules had "bar graph corrosion".
- Mono-crystalline solar modules used for off-grid applications at the Solar Energy Centre have shown amazing results. These modules are referred to as champion modules wherein only 10% degradation has been observed in more than 20 years old mono-crystalline solar modules. (A Sinha et al. "Performance of champion's module of PV lighting systems in India", Oral presentation).
- A close study of percentage-degradation of various kinds of modules has shown maximum degradation in thin film modules and the losses in power were observed primarily due to material degradation. While, mono and multi crystalline modules have shown power reduction from the rated output of 1-10%, amorphous silicon recorded 16-30%. The same value for CdTe module was 19% and that for CIS module 36%. None of the modules had any visual defects (as seen with naked eyes) and appeared normal. However, electroluminescence and thermal imaging have shown the degradation spots very clearly. Amorphous silicon modules have shown electrochemical degradation of SnO_2 layers. (O S Sastry et al. "Degradation in performance ratio and yield of exposed modules under arid conditions", 26th European photovoltaic solar energy conference and exhibition).

Figure 4.1 CIS modules under field condition

- A performance ratio comparison has shown that thin film modules have better performance ratio in general. Further, amorphous silicon performance was 16% higher in the months of April and May and 12% less during December as compared to multi-crystalline modules.
- Even IEC certified mono-crystalline modules have degradation in certain cases. However, these were mainly due to degradation of encapsulant materials rather than the basic cell degradation. Therefore, certification of only sample modules is not sufficient and occasional testing of sample field modules is also recommended for larger power projects.
- Out of a series of different modules studied at the ambient temperature of 40 ^{o}C, a failure of 70% of thin film modules and 25% of crystalline silicon modules were observed. The extent of degradation has not been reported. Govindasamy Tamizh Mani, TÜV Rheinland PTL & Arizona State University, Tempe, Arizona, USA, which appeared in the eighth print edition of Photovoltaics International journal, on "Testing the reliability and safety of photovoltaic modules: failure rates and temperature effects",
- A study by European Commission, DG JRC, Institute for Energy, Ispra, Italy has shown that mono-crystalline silicon modules are still working perfectly with very low degradation rate of maximum 0.8% per year. This is one of the best performances for mono-crystalline modules till date. According to them they have found no statistically significant difference in poly and single crystalline modules.
- In 1990, the Schatz Energy Research Center (SERC) installed a nominal 9.2 kWp photovoltaic (PV) array at Humboldt State UniversityÕs in Trinidad. A degradation study has shown that mono-crystalline SPV modules have shown only 4% degradation in 11 years even under the corrosive environment of seashore.

All the above studies indicate that thin film module degradation is much faster than crystalline modules. Mono-crystalline and probably poly-crystalline silicon modules have shown very good stability with time.

A sensitivity analysis regarding generation of energy using a sample case of 1 MW for crystalline and thin film each has been carried out CUF 19% for 1st year as per CERC norm and degradation factors of 0.5% and 3.0% for crystalline and thin film technologies respectively. A comparative picture is shown in **figure 4.2**, which indicates that if 1 MW crystalline PV project is replaced by same capacity thin film project, there will be loss of 9,634,282 units over a period of 25 years.

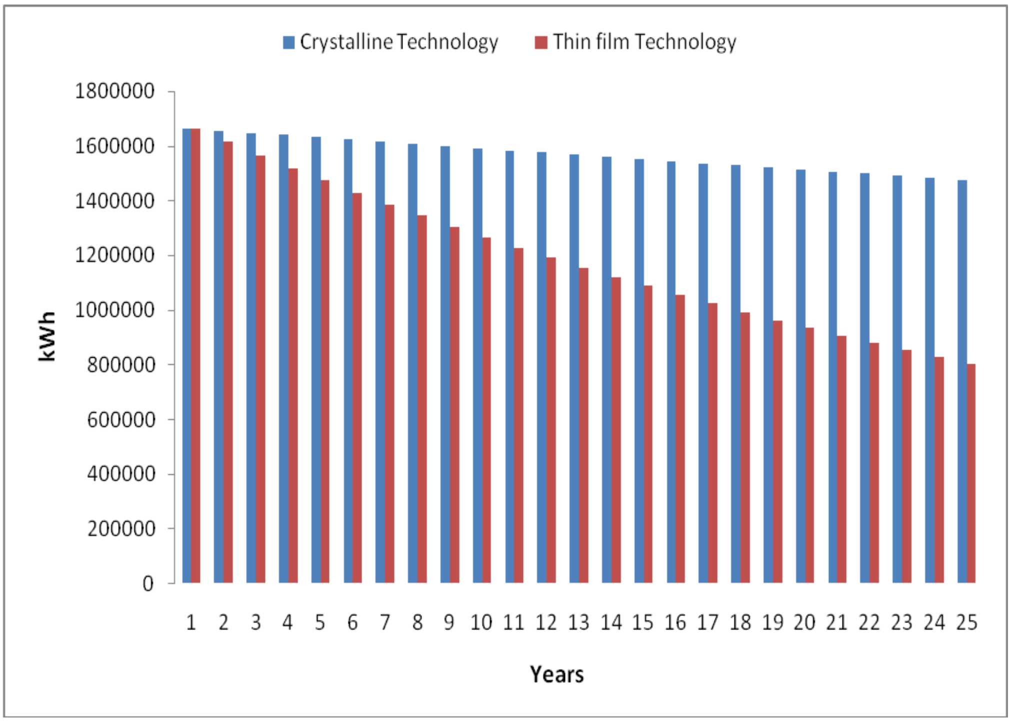

Fig 4.2 Comparative energy generation by 1 MW crystalline vs. thin film SPV power project during 25 years of lifetime

(8) Life of the modules

While all the modules manufacturers claim 25 years of life whether it is crystalline or thin film, the main question is what would be the balance capacity after 25 years considering the degradation rate. A good quality and state-of-art hermetically sealed crystalline module has been reported to be working with little degradation even after 25 years which is a bonus for the power plant owner. The experience at the Solar Energy Centre, New Delhi shows upto 40% degradation in 10 years in the case of thin films. Under such situation, the life of thin film modules is questionable and poses technology risk to the project.

(9) Breakage and replacement

The thin film modules have a double glass structure. Thin film of absorber materials are deposited either on "substrate" or on "superstrate" depending upon the side exposed to sun. Under both the situations, the thin film is sandwiched between two glass sheets.

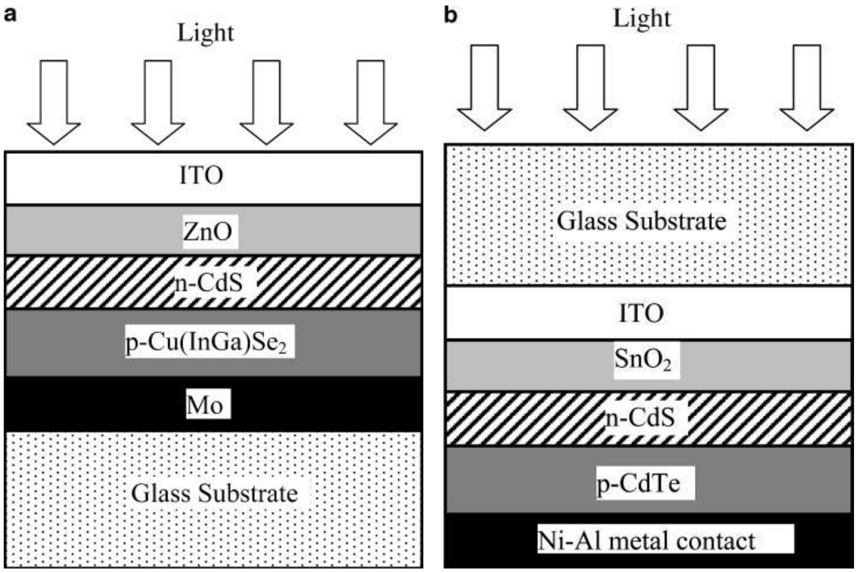

Figure 4.3 Typical Thin Film Solar Cell structures for single-junction:
(a) substrate $Cu(InGa)Se_2$; (b) superstrate CdTe;

It is well known that the due to inherent losses, the actual cell temperature is higher than the ambient temperature and many times it goes upto 25-30 deg C above the ambient temperature. This causes thermal stress not only to solar cells but to encapsulant also e.g. EVA material and glass.

In the case of thin film solar cells, the thin layer of absorber material is fixed between two glass layers of around 3mm thickness each. In the event of rise in temperature, the two rigid layers of glass face severe stress due to temperature difference between top and bottom layers. This causes micro-cracks in the top glass layer. Such a case is more prominent when the thin film modules are washed with a spray of water at around 6:00 p.m. while the whole system is yet to be stabilized to normal temperature. It has been observed that modules are generally cleaned in the evenings due to availability of labour. Eventually, the micro-cracks keep increasing resulting into complete deterioration of the solar module due to ingress of moisture.

Therefore, the thin film power plants have to compulsorily replace 1% of modules per year that leads to additional cost. However, this factor is not incorporated while calculating the financials of thin film power projects.

Figure 4.4 Micro-cracks resulting into major cracks in thin film modules

However, in case of crystalline PV modules, no such replacement of modules are reported anywhere. The crystalline PV cells are fixed between encapsulant (usually ethylene vinyl acetate; EVA) and back sheet (polyvinyl fluoride films). The top layer is toughened glass above the EVA layer. In the case of heating of cells, the top layer has higher temperature compared to bottom layer due to natural cooling on the lower side and cell heating at top layer. The thermal stress faced between the layers, as radiation increases, is managed due to flexible back sheet that avoids any crack on the top glass layer.

(10) Warranty Periods

For, crystalline modules, confidence among manufacturers has increased over time as shown by the following table.

Table 4.2 Increase in warranty of SPV modules over a period of years	
Period	**Warranty**
Before 1987	5 years
1987 to 1993	10 years
1993 to 1999	20 years
Since 1999	25 years

The crystalline module manufacturers are now offering warranty for 10% degradation in output in 12 years and 20% in 25 years which indicates higher confidence level.

Interestingly, thin film module manufacturers are also now providing warrantee for 10% degradation in output in 10 years and 20% in 25 years. The reason that the warranties have been increased is that the manufactures had to compete with crystalline silicon modules. However, they provide the basis of IEC 61646 certification which carries out accelerated degradation test under simulated situation. There are doubts whether thin film will actually show this trend in actual field conditions.

Many technical experts and financial experts have suggested that additional bank guarantee needs to be taken from the manufacturer of thin film modules to cover the field condition risks. This becomes more important when manufacturers use the term “limited warranty”. Further, the asterisk of “conditions apply” indicates that “manufacturer reserves the right to modify the specification and warranties without notice”. Moreover, the limited warranty certificates made public by the company especially for thin film solar modules are both vague and ambiguous. While limited warranty may be a comfortable position for the crystalline modules reported with minimum degradation, the same for thin film puts it into an uncomfortable position due to reported faster degradation of thin films.

As stated earlier, the thin film modules suffer from initial decay. Some manufacturers do not mention whether the rated values are post initial decay or the initial one and what is the initial decay percentage. (Recently, a news report in the 5 March 2012 issue of “The Hindu” has reported that First Solar has admitted that one of the reasons for its 4th quarter operating loss of $485.3 million was higher warranty payments.) Therefore, one needs to be careful while reading the warranty clauses and module rating under stabilised condition.

Despite the technological differences outlined in (7), (8), (9) and (10), we have assumed the same cost component for both technologies, based on current CERC guidelines which do not differentiate between the two technologies. However, these technological differences result in lower net generation from thin film technologies as compared to crystalline PV technologies. This difference shows up in the financial performance comparison of the two technologies, which is shown in section on “Comparison of financial returns” below.

(11) Evacuation Cost up to Interconnection Point

Due to the larger spread area of thin film arrays, the cabling cost consisting of both material costs of cable and labour cost of installation will be higher for thin film PV as compared to crystalline PV as shown in table 4.1.

Comparison of financial returns: Equity Investors perspective

Table 4.3 Financial viability analysis output

Parameter	**Crystalline**	**Thin film**
Project IRR (Pre Tax)	17.30%	13.43%
Project IRR (Post Tax)	15.59%	12.18%
Average Debt Service Coverage Ratio (DSCR)	1.67	1.37
Equity IRR	**19.58%**	**12.80%**

As regards financial viability analysis, major parameters have been considered as per latest CERC RE tariff order dated 27th March 2012. By keeping the above project cost, the analysis has been carried out with only variation of de-rating factor. In the case of thin film, the de-rating factor of

2% as reported in the field is considered initially. In addition, 1% de-rating in power generation has been considered to compensate the 1% modules replacement in thin film power projects. Thus, total 3% of de-rating in the case of thin film is considered for the practical purpose. The de-rating of 0.5% is considered for crystalline SPV modules based on practically observed degradation as explained in the preceding chapters. Incorporation of these parameters results in the above output in calculation of financial viability.

Temperature coefficients of the two technologies

Power output from any kind of solar cell decreases with increase in temperature. It is reported that temperature coefficient of thin film modules is lower (-0.3%/°C) as compared to crystalline (-0.4%/°C). Hence, it is claimed that they are more suitable for hot climate and hence will give more generation for the equivalent capacities of power projects. However, the most potential areas of Gujarat and Rajasthan also have winter which is favourable for creating less NOCT. Therefore, low output in summer will be compensated by higher output in winter which can be seen in the **figure 4.5** below.

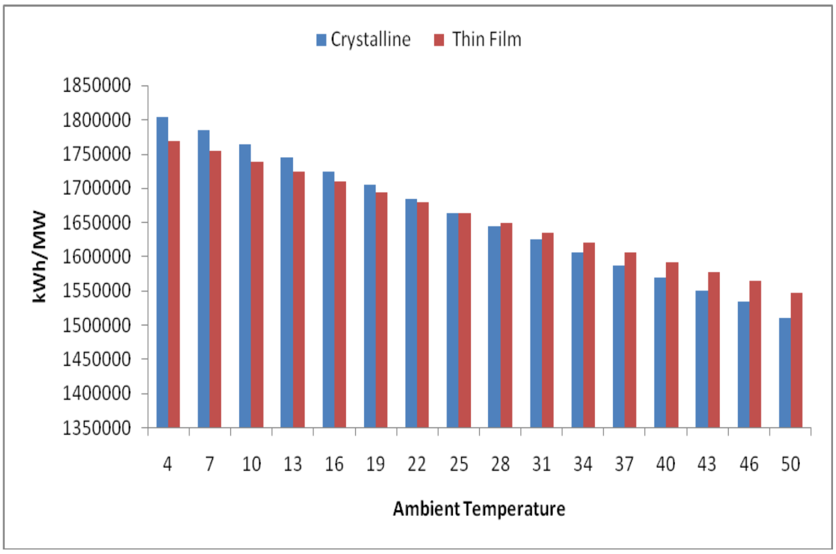

Fig. 4.5 Energy generation against ambient temperature for 1 MW crystalline and thin film PV power project

Naturally, there will be a minor effect of this difference of temperature coefficient. The higher output in hot climate by thin film based power project is yet to be ascertained in actual field conditions. (Recently, a news item in "The Hindu" dated 5 March 2012 reports "First Solar admits to unsuitability of its products to hot climate". According to them, "the company's warranty rates for hot climate are slightly higher than for temperate climates". The company is reported to keep a provision of 1% additional amount against warranty in hotter climates). Therefore, the claimed advantage of lower temperature coefficient is not valid.

Acceptance by Financial Institutions: Lenders perspective

The Financial Institutions in India are yet to show confidence in thin film technology. Majority of proposed thin film power projects in India are backed by huge soft international loans for long term (16.5 years) provided by US Exim Bank, which is the main reason for promotion of thin film in the country. This constitutes a form of technology risk coverage or hidden international subsidy to the thin film technology. Thin film technology is presently less preferred by Indian Financial Institutions. As regards power projects based on crystalline modules, many of the projects are already installed in India and have been financed by banks. As Table 4.2 indicates, both Internal Rate of Return (IRR) and Debt Service Coverage Ratio (DSCR) are higher for crystalline PV. This performance, coupled with lower technology risk and longer life, makes it more acceptable from Lenders perspective. While Lenders have a preference for higher returns, it is coupled with a preference for lower risks in the projects that they finance.

Policy and regulatory aspects: The Institutional perspective

Government of India and different state governments have been very proactive in promoting solar sector in line with the enabling instruments provided by the Electricity Act 2003, NAPCC and JNNSM. Similarly, regulatory bodies i.e. CERC and SERCs have also supported the solar sector through FiTs and other regulatory provisions. The pragmatic approach on policy front by the respective governments and regulatory front by the respective regulatory bodies has resulted in installation of around 800 MW of solar power projects in the country today, which is higher than envisaged 5 years ago.

The PV sector got a push initially in crystalline PV technology. Recently, thin films have also attracted attention under JNNSM scheme due to allowance of import for thin film while crystalline technology has domestic component and are not allowed to import under the scheme. As a result, large quantities of thin film modules with poor efficiency at the pretext of so called low cost are being dumped in India from all over the world. More than 60% of the approved power projects will be using thin film technology. Ultimately the nation will be the loser.

As stated above, crystalline and thin film technologies are primarily different from each other considering the technical parameters and application methodologies. They need different treatments. However, the policy and regulation in the country does not differentiate between the two technologies. It is again emphasized based on the analysis in preceding sections that the nation will be loser by 9,634,282 units/MW in 25 years life of the project if only thin film PV power project are installed in the country. That translates into 4,817 MUs loss in 25 years for the present scenario in the country with 1000 MW installed capacity having 50% share of thin film. Things will further worsen with yearly capacity addition of solar power projects dominated by thin film technology. This will pose a setback to the energy policy makers who have projected energy security by achieving solar power of 20,000 MW by 2022 assuming 19% CUF.

Both the technologies need entirely different treatment on policy and regulatory front mainly because the government and regulatory bodies are responsible to the society for;

- Efficient utilization of land resource
- Assuring long-term power availability

- Quality assurance and reliability of power
- Avoiding large scale dumping of lower efficiency technologies
- Dissemination of correct information to investors
- Health hazard of the technologies
- Declaration of PV as e-waste and efficient management of waste from power projects after useful life

Use of thin film technology is exempted from domestic content guidelines applicable to crystalline technology. As a result, majority of the projects under JNNSM are expected to prefer thin film technology considering their lower cost and without taking care of other implications. The decisions are purely based on financial considerations and no care is taken for efficient land utilization, environmental concerns and long-term profitability. In fact, many of the promoters are not aware of the technicalities and their implication on their future revenues resulting in large-scale dumping of low quality thin film modules in India which will have a wider ramification in the coming years. The short-term view of investing and exiting as soon as the investment is recovered, is detrimental to the national interest.

It is the government's responsibility to maintain a level playing field in the competing PV technologies. At the same time, it is the responsibility of regulators to vet the technical and financial parameters for thin film and crystalline technologies and to accord differential regulatory treatment, if necessary. Presently, the policies and regulations are both completely silent about the type of PV cells and their future impact on state and national power scenario.

Environmental externalities: The societal perspective

CdTe raises environmental concerns because Cadium is highly toxic. The maximum permissible value for workers (according to German law) is 15 micro gram per litre. No such law exists in India. Once absorbed, Cd is efficiently retained in the human body, in which it accumulates throughout life. Cd is primarily toxic to the kidney, especially to the proximal tubular cells, the main site of accumulation. Cd can also cause bone demineralization, either through direct bone damage or indirectly as a result of renal dysfunction. (A. Bernard, "Cadmium & its adverse effects on human health", Indian J Med Res 128, October 2008, pp 557-564).

Under Indian conditions, it is observed that minimum 1% of modules need to be replaced every year due to breakage of modules caused by thermal stress and micro cracks. These rejected modules can pose severe environmental hazards.

The main manufacturer of CdTe "First Solar" has a policy of EPR (Extended Producer Responsibility) wherein anyone in possession of First Solar module can request collection and recycling at any time at no additional cost. However, responsibility of dismantling and packaging of the modules lies with the owner. This is a dicey situation. First, it is not known whether there is a guarantee that these modules will be taken back by the company. Second, the rejected modules coming out every year from the power plant and their environmental impact if kept in the open as prevalent in India with consequent leakage of Cadmium to the environment through rain water has not been duly considered. Third, the additional cost of dismantling and packing after their useful life is not currently factored in, nor its effect on the economics of the project.

Further, solar modules are officially regarded as e-waste and are going to be considered by the European Union to be regulated under WEEE. This will impose further restrictions.

Scrap generation

Solar power projects based on crystalline modules will generate scrap of 100 tonnes per MW, after their useful life. Since the mounting structures for thin film are almost double that of crystalline PV, the scrap generation will also be double in the case of thin film. Moreover, thin films are expected to have shorter life and hence earlier scrap generation. None of these life-cycle related costs are internalized into the current cost calculus.

Considering the projected target as given in section on "National Status" in chapter-2, the comparative projected scrap generation by the two technologies after expiry of the project i.e. 25 years are presented in **figure 4.6** below.

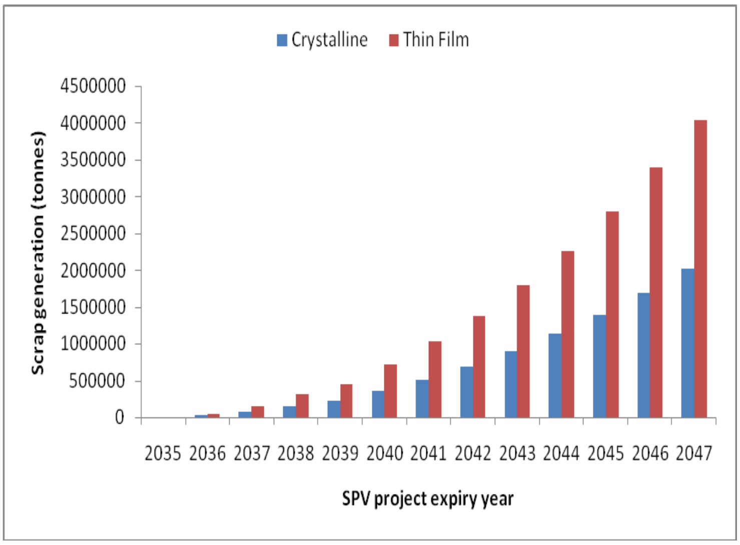

Fig. 4.6 Comparative projected scrap generation by the two technologies after expiry of the project i.e. 25 years

Thin film business risk: Sample case

An interesting sample case of the business leader in thin film solar cells is of First Solar, USA. The annual report 2011 of the company has declared following risk factors relevant to the present study (Reproduce as it is) which are self explanatory.

- Environmental obligations and liabilities could have a substantial negative impact on our financial condition, cash flows, and profitability.

- Thin-film technology has a short history, and our thin-film technology and solar modules and systems may perform below expectations; problems with product quality or performance may cause us to incur significant and/or unexpected warranty and related expenses, damage our market reputation, and prevent us from maintaining or increasing our market share.
- If our estimates regarding the future cost of collecting and recycling our solar modules are incorrect, we could be required to accrue additional expenses at and from the time we realize our estimates are incorrect and face a significant unplanned cash burden.

Conclusions

- Thin films do not have the cost advantage in terms of initial investment costs over the crystalline solar cells – important from both equity and debt perspectives.
- The return on equity is higher for crystalline PV as compared to thin film technology - important from both equity and debt perspectives.
- The Debt Service Coverage Ratio (DSCR) is higher for crystalline PV as compared to thin film technology. Projects based on crystalline technology will have lower technology risk as compared to thin film technology. Both these are important from debt perspectives.
- Evaluated over the entire project lifetime of 25 years, i.e. in longer term, crystalline technology scores significantly higher than thin film technology. Moreover, projects based on crystalline technologies can probably continue generating beyond 25 years, making them more attractive.
- Apart from other factors, crystalline technologies require less land per MW compared to thin film technologies. This is important from policy perspective of both central and state governments.
- At the project / technology level, thin film technology has higher environmental externalities due to presence of heavy metals as compared to crystalline PV technologies. This is important from the societal perspective.

Based on the above considerations, it is concluded that crystalline PV technologies perform significantly better than thin film technologies in our assessment. This conclusion derives from the due diligence approach adopted in this study.

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