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Solar Photovoltaic Energy: The State-of-Art

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ABSTRACT: This paper discusses about basics of solar photovoltaic energy, types of materials used, types of modules and different generations of solar PV technology, along with cost analysis.

I. INTRODUCTION

The sun delivers its energy to us in two main forms: heat and light. There are two main types of solar power systems, namely, solar thermal systems that trap heat to warm up water, and solar PV systems that convert sunlight directly into electricity as shown in Fig. 1.

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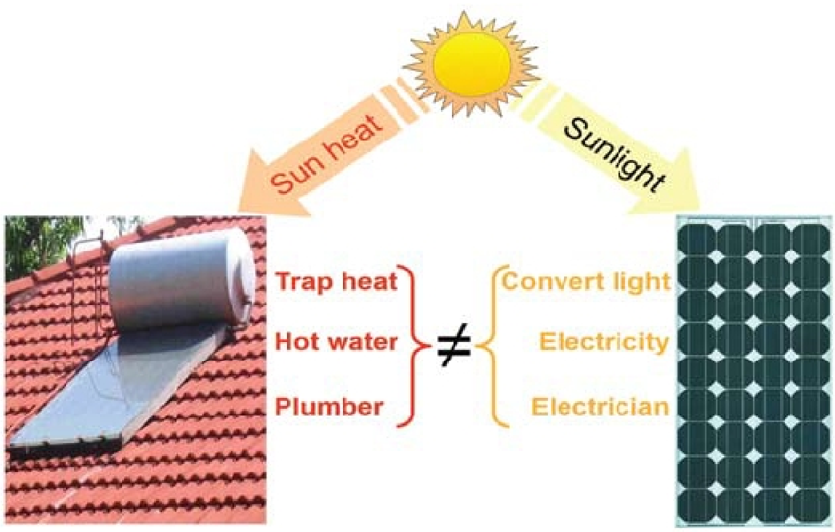

Fig. 1. Conversion of solar heat and light to useful energy.

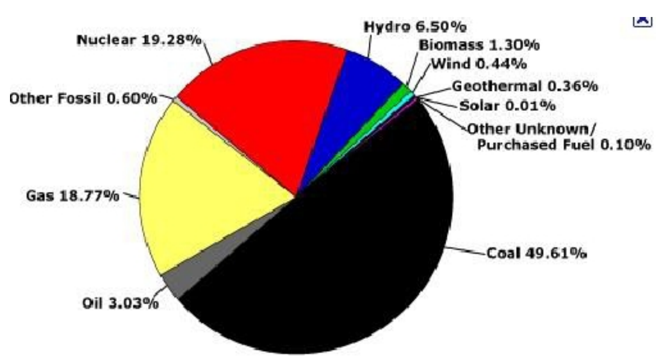

Fig. 2. The Market Share of Global Solar Energy Today: About 0.01%.

II. TYPES OF SOLAR PV SYSTEM

Solar PV systems can be classified based on the end-use application of the technology. There are two main types of solar PV systems: grid-connected (or grid-tied) and off-grid (or stand alone) solar PV systems [1].

A. Grid-connected solar PV systems

The one of the application of solar PV in India is grid-connected. Most solar PV systems installed on buildings or mounted on the ground if land is not a constraint. For buildings, they are either mounted on the roof or integrated into the building. The latter is also known as Building Integrated Photovoltaics ("BIPV"). With BIPV, the PV module usually displaces another building component, e.g. window glass or roof/wall cladding, thereby serving a dual purpose and offsetting some costs.

The configuration of a grid-connected solar PV system is shown in Fig. 3.

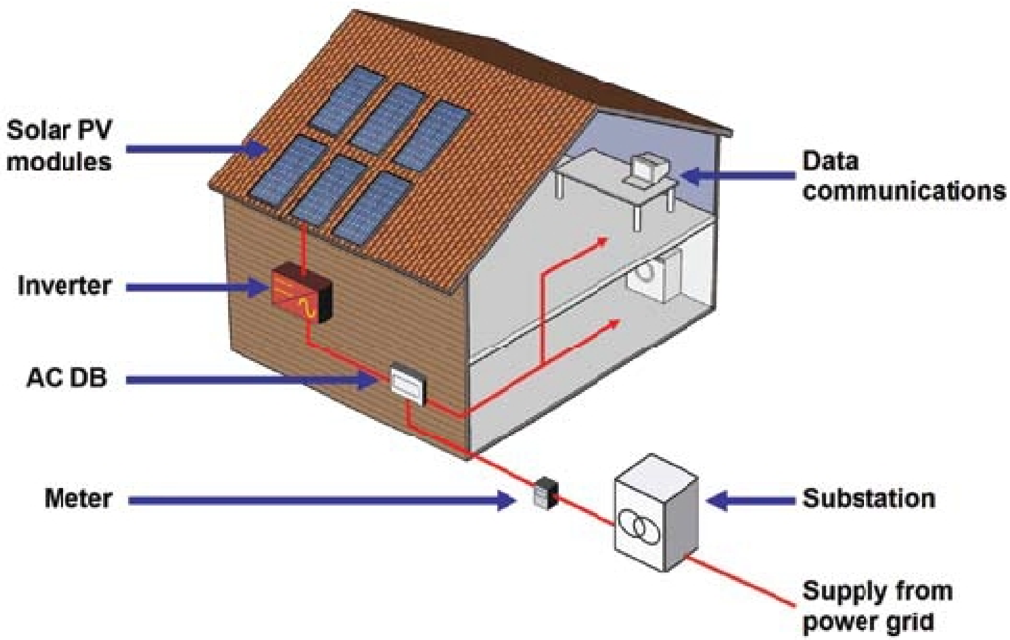

Fig. 3. Grid-connected solar PV system configuration.

A building has two parallel power supplies, one from the solar PV system and the other from the power grid. The combined power supply feeds all the loads connected to the main ACDB.

The ratio of solar PV supply to power grid supply varies, depending on the size of the

solar PV system. Whenever the solar PV supply exceeds the building's demand, excess electricity will be exported into the grid. When there is no sunlight to generate PV electricity at night, the power grid will supply all of the building's demand.

II. OFF-GRID SOLAR PV SYSTEMS

Off-grid solar PV systems are applicable for areas without power grid, as shown in figure 4. Currently, such solar PV systems are usually installed at isolated sites where the power grid is far away, such as rural areas or off-shore islands. But they may also be installed within the city in situations where it is inconvenient or too costly to tap electricity from the power grid.

III. SOLAR PV TECHNOLOGY

This section gives a brief description of the solar PV technology and the common technical terms used.

A solar PV system is powered by many crystalline or thin film PV modules. Individual PV cells are interconnected to form a PV module. This takes the form of a panel for easy installation.

A. Photovoltaic Solar Panels (PV)

Photovoltaics (PV) is a method of generating electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the photovoltaic effect. Photovoltaic power generation employs solar panels composed of a number of solar cells containing a photovoltaic material. Materials presently used for photovoltaics include monocrystalline silicon, polycrystalline silicon, amorphous silicon, cadmium telluride, and copper indium gallium selenide/sulfide. Photovoltaic solar panel is the most commonly used solar technology to generate electricity energy.

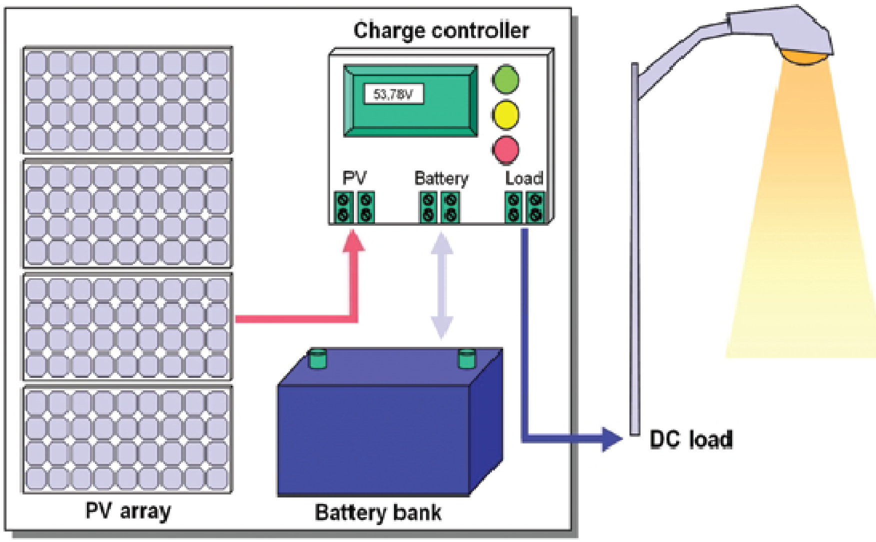

Fig. 4. Off-grid solar PV system configuration.

An advantage of photovoltaic panels is that they are able to collecting both direct and diffuse irradiations, so the technology can work even on cloudy days. Approximately 25 percent of the incident radiation is captured when the sun is high in the sky, depends upon the amount of dust and haze in the atmosphere [2-3].

B. Major Types of Photovoltaic Panels

1. Crystalline Silicon: The majority of PV modules (85 percent to 90 percent of the global annual market) are based on wafer-based crystalline-Si. The manufacturing of c-Si modules typically involves growing ingots of silicon, slicing the ingots into wafers to make solar cells, electrically interconnecting the cells, and encapsulating the strings of cells to form a module. Modules currently use silicon in one of two main forms: single- sc-Si or mc-Si. Current commercial single sc-Si modules have higher conversion efficiency about 14 to 20 percent. Their efficiency is expected to increase to 23 percent by 2020 and 25 percent in the longer term [3]

Multi-crystalline silicon modules have a more disordered atomic structure, leading to lower efficiencies. But they are less expensive and more resistant to degradation due to irradiation. The degradation rate is about 2 percent per year for multiple crystalline technologies. Their efficiency is expected to reach 21 percent in the long term. Crystalline silicon PV modules are expected to remain a dominant PV technology until at least 2020, with a forecasted market share of about 50 percent by that time [4]. This is due to their proven and reliable technology, long lifetimes, and abundant primary resources. The main challenge for c-Si modules is to improve the efficiency and effectiveness of resource consumption through materials reduction, improved cell concepts and manufacturing automation [14].

2. Thin Films: Thin films are made by depositing extremely thin layers of photosensitive materials in the micrometre (μm) range on a low-cost backing, such as glass, stainless steel or plastic. The first generation of thin film solar cell produced was a-Si. To reach higher efficiencies, thin amorphous and microcrystalline silicon cells have been combined with thin hybrid silicon cells. With II-VI semiconductor compounds, other thin film technologies have been developed, including cadmium telluride (CdTe) and copper-indium-gallium-diselenide (CIGS) [5].

The main advantages of thin films are their relatively low consumption of raw materials; high automation and production efficiency; ease of building integration and improved appearance; good performance at high ambient temperature; and reduced sensitivity to overheating. The current drawbacks are lower efficiency and the industry's limited experience with lifetime performances. For utility production, thin film technologies will require more land than crystalline silicon technologies in order to reach the same capacity due to their lower efficiency. So, land availability and cost must be taken into consideration when thin film technology is considered.

Thin film technologies are growing rapidly. In recent years, thin film production units have increased from pilot scale to 50 MW lines, with some manufacturing units in the gigawatt (GW) range. As a result, thin films technologies are expected to increase their market share significantly by 2020.

II-VI semiconductor thin films: CdTe cells are a type of II-VI semiconductor thin film that has a relatively simple production process, allowing for lower production costs. CdTe technology has achieved the highest production level of all the thin film technologies. Also, it has an energy payback time of eight months, the shortest time among all existing PV technologies. For CIGS cells, the fabrication process is more demanding and results in higher costs and efficiencies compared to CdTe cells. Today, CdTe cells have achieved a dominant position in the thin film and have a market-leading cost-per watt. However, these materials are toxic and less abundant than silicon. It is difficult to predict which of the thin film technologies will reach higher market shares in the long-term. However, figure 15 forecasts potential efficiency improvements over the next 20 years.

PV systems reached a total global capacity of 40,000 MW at the end of 2010 which is about 3 percent of whole renewable energy capacity – about 16 percent of global final energy consumption comes from renewable [6].

Despite the optimistic prediction of photovoltaic industry, this technology has disadvantages that will need more effort to solve: Solar electricity is still more expensive than most other forms of small-scale alternative energy production. Without governments mandating feed-in tariffs for green solar energy, solar PV is in less affordable to homeowners than solar hot water or solar space heating. Solar electricity is not produced at night and is greatly reduced in cloudy conditions. Therefore, a storage or complementary power system is required. Solar electricity production depends on the limited power density of the location's insolation.

Average daily output of a flat plate collector at latitude tilt in the contiguous area is 3 – 7 kilowatth/m²/day and the performance will be less n high-latitude areas . Solar cells produce direct current (DC) which must be converted to alternating current (AC) using a grid tie inverter in existing distribution grids that use AC. This incurs an energy loss of 4 – 12 percent. However, high voltage DC grid transportation has less energy waste than AC grid; so, there is a trade-off consideration in deciding to construct high voltage DC grids and apply the inverter at the consumers' end. Applying tracking systems to PV is also possible. The cost of a PV tracking system is usually greater than the cost of fixed PV system and its performance is greater than the performance of the fixed PV system – approximately 20 percent more energy produced on a yearly basis. In terms of land occupation, fixed PV field requires about half of the area necessary for a tracker PV system and, as highlighted above, the selection of PV modules may play an important role in determining the area required by the plant. Therefore, it can be concluded that for a large utility scale PV plant, the fixed PV field arrangement should be preferable when land impact is considered [7]

Photovoltaic technologies are the most commonly used solar energy collecting technologies today and will continue to see rapid and steady growth. Each of these photovoltaic technologies have its own advantage and drawbacks and it is not certain which one will dominate the market in the following decades; however it is certain is that the photovoltaic technologies will help countries develop a clean and renewable future.

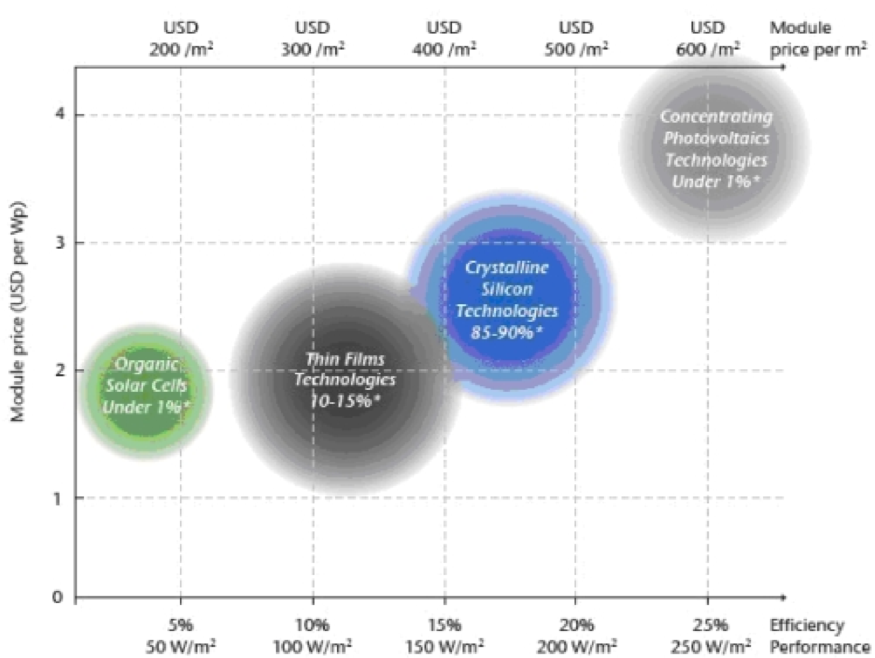

Fig. 5. Performance and price range of different PV technologies.

IV. SCIENCE OF SILICON PV CELLS

● Scientific base for solar PV electric power generation is solid-state physics of semiconductors
● Silicon is a popular candidate material for solar PV cells because:
● It is a semiconductor material.
● Technology is well developed to make silicon to be positive (+ve) or negative (-ve) charge-carriers – essential elements for an electric cell or battery
● Silicon is abundant in supply and relatively inexpensive in production
● Micro- and nano-technologies have enhanced the opto-electricity conversion efficiency of silicon solar PV cells

V. WORKING PRINCIPLE OF SILICON SOLAR PV CELLS

Photovoltaic material of device converts:
Light (photon) Energy ⟹ Electric Energy
Silicon solar photovoltaic cells = a device made of semiconductor materials that produce electricity under light
● A p-n junction is created in silicon by a doping process. SiO2 functions as electric insulators

VI. DOPING OF SEMICONDUCTORS

Doping for common semiconductor, e.g. silicon (Si) involves adding atoms with different number of electrons to create unbalanced number of electrons in the base material (e.g. Si)
● The base material, after doping, with excessive electrons will carry –ve charge.
● The base material, after doping, with deficit in electron will carry +ve charge.
● Doping of silicon can be achieved by "ion implantation" or "diffusion" of Boron (B) atom for +ve charge or of Arsenide (As) or Phosphorus (P) for –ve charge.

A. Doping by Ion Implantation and Diffusion - Doping of Si can be done by either ion implantation at room temperature, or diffusion at high temperature.
● Ion implantation require energy to ionize the dopant. It is a faster doping process.
● Diffusion is a chemical process. It is a slower process but at lower cost and easy to control.
● The profile of the spread of dopant in silicon by diffusion is different from that by ion implantation

B. Silicon Solar PV Product – Silicon Solar PV Panels
Common Solar Cell Materials : Single Crystalline, Polycrystalline,
(Thin films),Silicon (Si), Cadmium telluride (CdTe), Single crystalline Polycrystalline silicon, Copper indium diselenide (CIS),Amorphous silicon (non-crystalline Si for higher light absorption), Gallium arsenide (GaAs)
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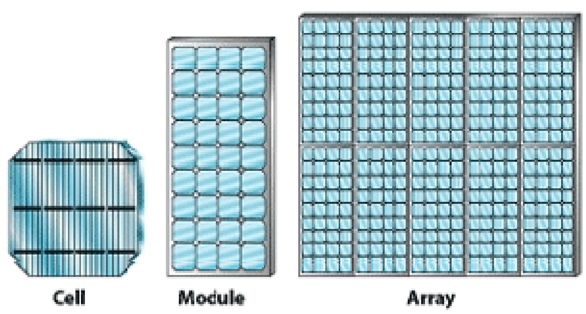
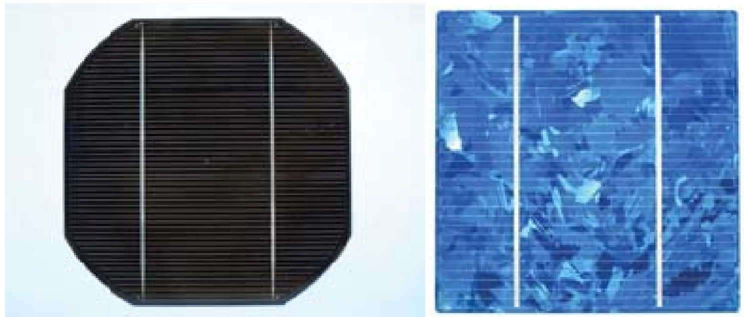


Fig. 6. Cell to module to array.

VII. APPROXIMATE ACHIEVABLE CONVERSION EFFICIENCIES

Single Si 15 – 25%, Poly Si 10 – 15%, GaAs 25 – 30%, CdTe 7%, A-Si 5 – 10%, CIS 10%.
PV cells are made of light-sensitive semiconductor materials that use photons to dislodge electrons to drive an electric current.

There are two broad categories of technology used for PV cells, namely, crystalline silicon, as shown in Figure 7 which accounts for the majority of PV cell production; and thin film, which is newer and growing in popularity. The "family tree" in Fig. 8 gives an overview of these technologies available today.



Mono-Crystalline Silicon PV Cell Poly-Crystalline Silicon PV Cell

Fig. 7. Conducting Grids: Mono-and Poly-Crystalline Silicon PV Cell.

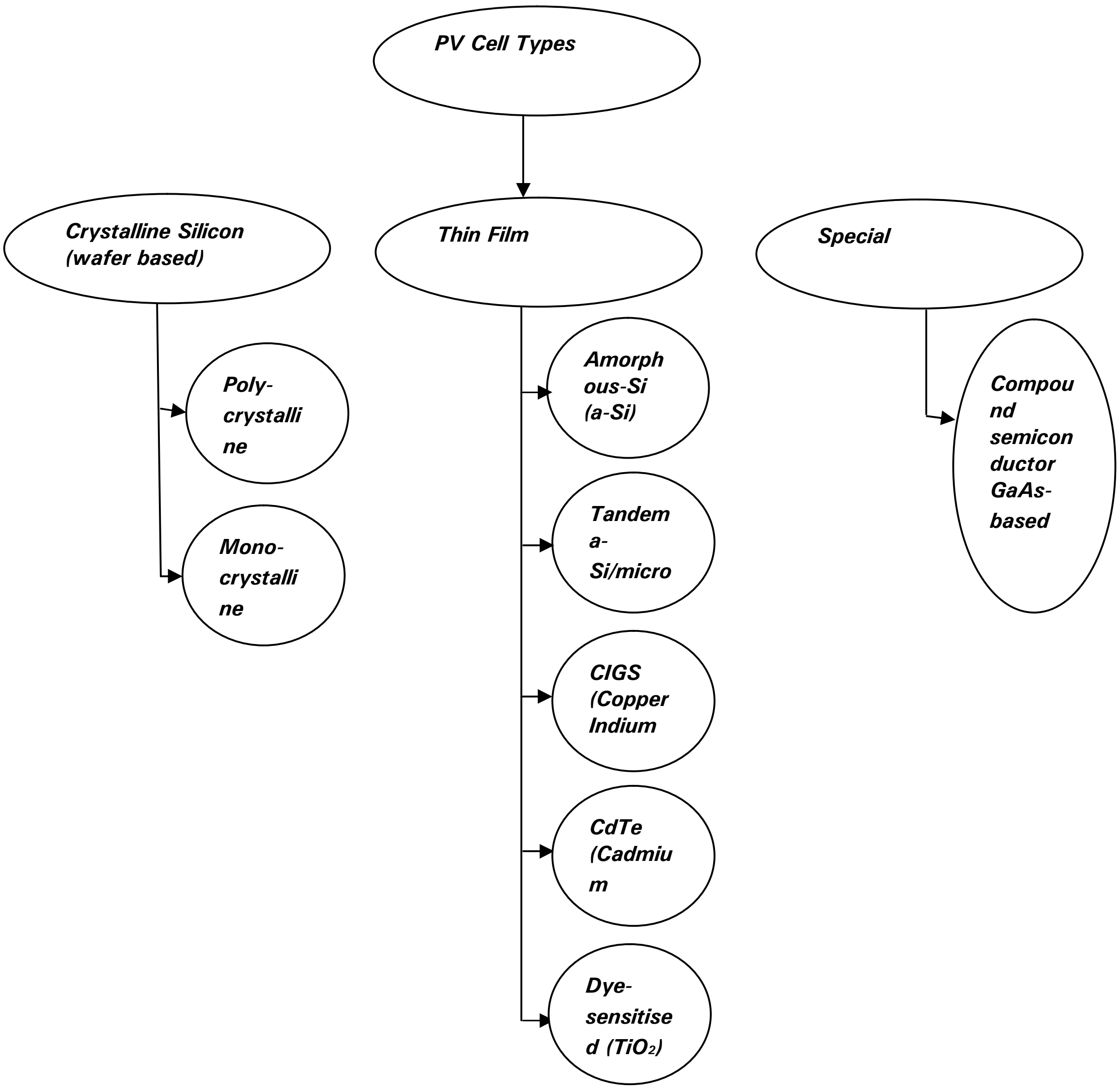


Fig. 8. PV technology family tree.

VIII. SOLAR PHOTOVOLTAIC TECHNOLOGIES

Photovoltaics, also called solar cells, are electronic devices that convert sunlight directly into electricity. The modern form of the solar cell was invented in 1954 at Bell Telephone Laboratories. Today, PV is one of the fastest growing renewable energy technologies and it is expected that it will play a major role in the future global electricity generation mix.

Solar PV systems are also one of the most "democratic" renewable technologies, in that their modular size means that they are within the reach of individuals, co-operatives and small-businesses who want to access their own generation and lock-in electricity prices.

PV technology offers a number of significant benefits, including:

»»Solar power is a renewable resource that is available everywhere in the world.

»»Solar PV technologies are small and highly modular and can be used virtually anywhere, unlike many other electricity generation technologies.

»»Unlike conventional power plants using coal, nuclear, oil and gas; solar PV has no fuel costs and relatively low operation and maintenance (O&M) costs. PV can therefore offer a price hedge against volatile fossil fuel prices.

»»PV, although variable, has a high coincidence with peak electricity demand driven by cooling in summer and year round in hot countries. A PV system consists of PV cells that are grouped together to form a PV module, and the auxiliary components (i.e. balance of system - BOS), including the inverter, controls, etc. There are a wide range of PV cell technologies on the market today, using different types of materials, and an even larger number will be available in the future. PV cell technologies are usually classified into three generations, depending on the basic material used and the level of commercial maturity:

»»First-generation PV systems (fully commercial) use the wafer-based crystalline silicon (c-Si) technology, either single crystalline (sc-Si) or multi-crystalline (mc-Si). »»Second-generation PV systems (early market deployment) are based on thin-film

PV technologies and generally include three main families: 1) amorphous (a-Si) and micromorph silicon (a-Si/μc-Si); 2) Cadmium-Telluride (CdTe); and 3) Copper- Indium-Selenide (CIS) and Copper-Indium-Gallium-Diselenide (CIGS).

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

A. First-Generation PV Technologies

Crystalline Silicon CELLS :Silicon is one of the most abundant elements in the earth's crust. It is a semiconductor material suitable for PV applications, with energy band gap of 1.1eV.

Crystalline silicon is the material most commonly used in the PV industry, and wafer-based c-Si PV cells and modules dominate the current market.

The Photovoltaic effect is when two different (or differently doped) semiconducting materials (e.g. silicon, germanium), in close contact with each other generate an electrical current when exposed to sunlight. The sunlight provides the electrons with the energy needed to leave their bounds and cross the junction between the two materials. This occurs more easily in one direction than in the other and gives one side of the junction a negative charge with respect to the other side (p-n junction), thus generating a voltage and a direct current (DC). PV cells work with direct and diffused light and generate electricity even during cloudy days, though with reduced production and conversion efficiency. Electricity production is roughly proportional to the solar irradiance, while efficiency is reduced only slowly as solar irradiance declines.

The energy needed to produce electron excitation and to activate the PV process.

And the technology that utilises the accumulated knowledge base developed within the electronic industry. This type of solar cell is in mass production and individual companies will soon be producing it at the rate of several hundred MW a year and even at the GW-scale. The manufacturing process of wafer-based silicon PV modules comprises four steps:

1. Polysilicon production;
2. Ingot/wafer production;
3. Cell production; and
4. Module assembly.

Crystalline silicon cells are classified into three main types depending on how the Si wafers are made. They are:

Monocrystalline (Mono c-Si) sometimes also called single crystalline (sc-Si); »»Polycrystalline (Poly c-Si), sometimes referred to as multi-crystalline (mc-Si); and »» EFG ribbon silicon and silicon sheet-defined film growth (EFG ribbon-sheet c-Si).

Commercial production of c-Si modules began in 1963 when Sharp Corporation of Japan started producing commercial PV modules and installed a 242 Watt (W) PV module on a lighthouse, the world's largest commercial PV installation at the time[8]. Crystalline silicon technologies accounted for about 87% of global PV sales in 2010[9]. The efficiency of crystalline silicon modules ranges from 14% to 19% . While a mature technology, continued cost reductions are possible through improvements in materials and manufacturing processes, and from economies of scale if the market continues to grow, enabling a number of high-volume manufacturers to emerge.

B. Second-Generation PV

Technologies: Thin-Film Solar Cells

After more than 20 years of R&D, thin-film solar cells are beginning to be deployed in significant quantities. Thin-film solar cells could potentially provide lower cost electricity than c-Si wafer-based solar cells. However, this isn't certain, as lower capital costs, due to lower production and materials costs, are offset to some extent by lower efficiencies and very low c-Si module costs make the economics even more challenging. Thin-film solar cells are comprised of successive thin layers, just 1 to 4 μm thick, of solar cells deposited onto a large, inexpensive substrate such as glass, polymer, or metal. As a consequence, they require a lot less semiconductor material to manufacture in order to absorb the same amount of sunlight (up to 99% less material than crystalline solar cells). In addition, thin films can be packaged into flexible and lightweight structures, which can be easily integrated into building components (building-integrated PV, BIPV). The three primary types of thin-film solar cells that have been commercially developed are:

»»Amorphous silicon (a-Si and a-Si/μc-Si);
»»Cadmium Telluride (Cd-Te); and
»»Copper-Indium-Selenide (CIS) and Copper-Indium-Gallium-Diselenide (CIGS).

Amorphous silicon solar cells, along with CdTe PV cells, are the most developed and widely known thin-film solar cells. Amorphous silicon can be deposited on cheap and

very large substrates (up to 5.7 m² of glass) based on continuous deposition techniques, thus considerably reducing manufacturing costs. A number of companies are also developing light, flexible a-Si modules perfectly suitable for flat and curved surfaces, such as roofs and facades. Currently, amorphous silicon PV module efficiencies are in the range 4% to 8%. Very small cells at laboratory level may reach efficiencies of 12.2% [10]. The main disadvantage of amorphous silicon It is important to be aware of the hierarchy of efficiency in PV, as a number of efficiencies can be quoted. The highest efficiency for a PV material is usually the "laboratory" efficiency, where optimum designs are tested. PV cell efficiencies are less than this, because compromises are often required to make affordable cells. Module efficiency is somewhat lower than cell efficiency, given the losses involved in the PV module system.

C. Third-Generation PV Technologies

Third-generation PV technologies are at the precommercial stage and vary from technologies under demonstration (e.g. multi-junction concentrating PV) to novel concepts still in need of basic R&D (e.g. quantum-structured PV cells). Some third-generation PV technologies are beginning to be commercialised, but it remains to be seen how successful they will be in taking market share from existing technologies. There are four types of third-generation PV technologies:

»»Concentrating PV (CPV);
»»Dye-sensitized solar cells (DSSC);
»»Organic solar cells; and
»»Novel and emerging solar cell concepts.

Concentrating photovoltaic technology: Concentrating PV (CPV) systems utilise optical devices, such as lenses or mirrors, to concentrate direct solar radiation onto very small, highly efficient multi-junction solar cells made of a semiconductor material. The sunlight concentration factor ranges from 2 to 100 suns (low- to medium-concentration) up to 1000 suns (high concentration). To be effective, the lenses need to be permanently oriented towards the sun, using a single- or double-axis tracking system for low and high concentrations, respectively. Cooling systems (active or passive) are needed for some concentrating PV designs, while other novel approaches can get round this need.

Low- to medium-concentration systems (up to 100 suns) can be combined with silicon solar cells, but higher temperatures will reduce their efficiency, while high concentration systems (beyond 500 suns) are usually associated with multi-junction solar cells made by semiconductor compounds from groups III and V of the periodic table (e.g. gallium arsenide), which offer the highest PV conversion efficiency. Multi-junction (either 'tandem' or 'triple' junction) solar cells consist of a stack of layered p–n junctions, each made from a distinct set of semiconductors, with different band gap and spectral absorption to absorb as much of the solar spectrum as possible. Most commonly employed materials are solar cells is that they suffer from a significant reduction in power output over time (15% to 35%), as the sun degrades their performance. Even thinner layers could increase the electric field strength across the material and provide better stability and less reduction in power output, but this reduces light absorption and hence cell efficiency. A notable variant of amorphous silicon solar cells is the multi-junction thin-film silicon (a-Si/μc-Si) which consists of a-Si cell with additional layers of a-Si and micro-crystalline silicon (μc-Si) applied onto the substrate. The advantage of the μc-Si layer is that it absorbs more light from the red and near infrared part of the light spectrum, thus increasing the efficiency by up to 10%. The thickness of the μc-Si layer is in the order of 3 μm and makes the cells thicker and more stable. The current deposition techniques enable the production of multi-junction thin-films up to 1.4 m². Cadmium Telluride thin-film PV solar cells have lower production costs and higher cell efficiencies (up to 16.7% [8]) than other thin-film technologies.

This combination makes CdTe thin-films the most economical thin-film technology currently available, with manufacturing costs of under USD 0.75/W achieved by at least one producer [11]. The two main raw materials are cadmium and tellurium. Cadmium is a by-product of zinc mining and tellurium is a by product of copper processing.

A potential problem is that tellurium is produced in far lower quantities than cadmium and availability in the long-term may depend on whether the copper industry can optimise extraction, refining and recycling yields. Cadmium also has issues around its toxicity that may limit its use. Copper-Indium-Selenide (CIS) and Copper-Indium- Gallium-Diselenide (CIGS) PV cells offer the highest efficiencies of all thin-film PV technologies. CIS solar cell production has been successfully commercialised by many firms in conjunction with universities (e.g. Wurth Solar, Solibro, Miasole, Nanosolar, Avancis, SolarFrontier and Honda Soltec). Current module efficiencies are in the range of 7% to 16%, but efficiencies of up to 20.3% have been achieved in the laboratory, close to that of c-Si cells [8]. The race is now on to increase the efficiency of commercial modules. By 2010, CIGS producer Solar Frontier has reached an annual production capacity of 1 GW [12].

D. Dye-sensitized solar cells

Dye-sensitized solar cells use photo-electrochemical solar cells, which are based on semiconductor structures formed between a photo-sensitised anode and an electrolyte. In a typical DSSC, the semiconductor nanocrystals serve as antennae that harvest the sunlight (photons) and the dye molecule is responsible for the charge separation (photocurrent). It is unique in that it mimics natural photosynthesis [13]. These cells are attractive because they use low-cost materials and are simple to manufacture. They release electrons from, for example, titanium dioxide covered by a light absorbing pigment. However, their performance can degrade over time with exposure to UV light and the use of a liquid electrolyte can be problematic when there is a risk of freezing. Laboratory efficiencies of around 12% have been achieved due to the development of new broadband dyes and electrolytes[14], however, commercial efficiencies are low - typically under 4% to 5%. The main reason why efficiencies of DSSC are low is because there are very few dyes that can absorb a broad spectral range. An interesting area of research is the use of nanocrystalline semiconductors that can allow DSSCs to have a broad spectral coverage. Thousands of organic dyes have been studied and tested in order to design, synthesise and assemble nano structured materials that will allow higher power conversion efficiencies for DSSCs.

E. Organic Solar Cells

Organic solar cells are composed of organic or polymer materials (such as organic polymers or small organic molecules). They are inexpensive, but not very efficient.They are emerging as a niche technology, but their future development is not clear. Their success in recent years has been due to many significant improvements that have led to higher efficiencies. Organic PV module efficiencies are now in the range 4% to 5% for commercial systems and 6% to 8% in the laboratory [15].

In addition to the low efficiency, a major challenge for organic solar cells is their instability over time. Suppliers of organic solar cells are moving towards full commercialisation and have announced plans to increase production to more than 1 GW by 2012 [16]. Organic cell production uses high-speed and low temperature roll-to-roll manufacturing processes and standard printing technologies. As a result, organic solar cells may be able to compete with other PV technologies in some applications, because manufacturing costs are continuing to decline and are expected to reach USD 0.50/W by 2020 [16]. Organic cells can be applied to plastic sheets in a manner similar to the printing and coating industries, meaning that organic solar cells are lightweight and flexible, making them ideal for mobile applications and for fitting to a variety of uneven surfaces. This makes them particularly useful for portable applications, a first target market for this technology. Potential uses include battery chargers for mobile phones, laptops, radios, flashlights, toys and almost any hand-held device that uses a battery. The Solar Junctions (U.S.) reported that USDOE NREL has confirmed that the III-V multi-junction CPV cell developed by Solar Junctions has achieved a record 43.5% efficiency at greater than 400 suns and preserved an efficiency as high as 43% out to 1000 suns. This type solar cell is also known as the Grätzel cell, after its inventor Michael Grätzel.

IX. COST ANALYSIS OF SOLAR PHOTOVOLTAICS

Modules can be fixed almost anywhere to anything, or they can be incorporated into the housing of a device.

They can also be rolled up or folded for storage when not in use. These properties will make organic PV modules attractive for building-integrated applications as it will expand the range of shapes and forms where PV systems can be applied. Another advantage is that the technology uses abundant, non-toxic materials and is based on a very scalable production process with high productivity.

Novel and emerging solar cell concepts :In addition to the above mentioned third-generation technologies, there are a number of novel solar cell technologies under development that rely on using quantum dots/wires, quantum wells, or super lattice technologies [17]. These technologies are likely to be used in concentrating PV technologies where they could achieve very high efficiencies by overcoming the thermodynamic limitations of conventional (crystalline) cells. However, these high efficiency approaches are in the fundamental materials research phase. Furthest from the market are the novel concepts, often incorporating enabling technologies such as nanotechnology, which aim to modify the active layer to better match the solar spectrum [18].

X.THE SOLAR PV RESOURCE

Solar PV systems operate in the presence of direct or diffuse solar irradiation. The higher the level of solar resource, the lower the LCOE will be. Siting solar PV systems in areas with high solar resources, usually expressed as annual mean figures in kWh/m^2/year or as kWh/m^2/day, will therefore minimise the cost of electricity from solar PV. The global solar resource is massive. Around 885 million TWh worth of solar radiation reaches the Earth's surface each year [19].

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