

I.B — A TECHNOLOGY PRIMER ON PHOTOVOLTAICS

I.B.1 — Three Approaches:

Solar energy can be harnessed for socially useful purposes in three principal ways: [1] *direct conversion* of the sunlight to electricity using PV; [2] *concentration of the energy* contained in sunlight through Concentrating Solar Power (CSP) systems, which can focus the sunlight on boilers or solar conversion receptors; and [3] *direct use of sunlight's heat*, without conversion, through Solar Water Heating (SWH) systems, such as in pool, spa and other hot water systems¹. XX's technology and business interest is only on the first of these three mechanisms [PV] for harnessing solar energy ... and it's important to realize that the other two mechanisms generate roughly 50 times more electricity than that generated by solar PV.² This is generally because photovoltaics are still an expensive way of converting solar energy into electricity, while the other two approaches have fewer technical hurdles and can be easily scaled to utility-size installations capable of generating significant power.

I.B.2 — XX's Market Segment, PV Conversion:

All routes for utilizing solar energy exploit the functional steps of *capture, conversion, and storage*. The sun's energy arrives on Earth as radiation distributed across the color spectrum from infrared to ultraviolet; the energy of this radiation must be captured as excited electronhole pairs in a semiconductor, or as heat in a thermal storage medium.³ Photovoltaic cells generally consist of a light absorber that will only absorb solar photons above a certain minimum photon energy level. This minimum threshold energy is called the "energy gap" or "band gap" (E_g); photons with energies below the band gap pass through the absorber, while photons with energies above the band gap are absorbed.⁴

In materials such as Silicon, electrons (e-) have energies that fall within certain energy ranges, called bands; these bands have the energy gaps between them. The band containing electrons with the highest energies is called the *valence band*; the next band of possible electron energies is called the *conduction band*; the valence and conduction bands are separated from each other by the *band gap*.

When all the electrons in the absorber are in their lowest energy state, they fill up the valence band, and the conduction band is empty of electrons. This is the usual situation in the dark. But when light impacts the surface, photons are absorbed, and they transfer their energy to electrons in the filled valence band.

Since the valence band is already full, this new energy promotes electrons across the band gap to the empty conduction band. When photons transfer electrons across the band gap, they create negative charges in the conduction band and leave behind positive charges in the valence band; these positive charges are called *holes* (h+). Thus, absorbed photons in solar cells create *pairs* of negative electrons (e-) and positive holes (h+).

In a PV cell, the electrons and holes formed upon absorption of light separate, and move to opposite sides of the cell structure. There, they are collected and pass through wires connected to the cell to

¹ Jim McVeigh, *Solar Technologies*, October, 2002; p. 1

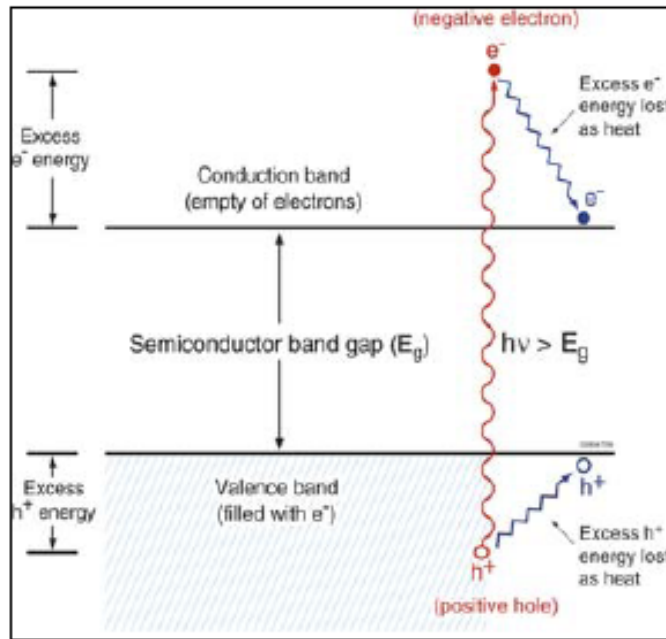
² Office of Integrated Analysis and Forecasting, Energy Information Administration, *Annual Energy Outlook 2007 With Projections to 2030*, USDOE Energy Information Administration, March 19, 2007; p. 162

³ USDOE Office of Science, "Basic Research Needs for Solar Energy Utilization," report of the *Basic Energy Sciences Workshop on Solar Energy Utilization*, April, 2005; p. 3

⁴ *Basic Energy Sciences Workshop*; p. 15

produce a current and a voltage — thus generating electrical power.⁵ When light shines on the solar cell, the electric field across the junction between these two layers causes electricity to flow, generating DC current. The greater the intensity of the light, the greater the flow of electricity.

FIGURE 01
BASIC PHYSICS OF PHOTOVOLTAICS⁶



All PV cells depend upon the absorption of light, the subsequent formation and spatial separation of electrons and holes, and the collection of the electrons and holes at different energies (called electrical potential). The efficiency of electron and hole formation, separation, and collection determines the photocurrent, and the energy difference between the electrons and holes in their final state before leaving the cell determines the photovoltage. The electrical power generated, divided by the power of the incident solar radiation, determines the efficiency of the cell in converting solar power to electrical power. The output power rating of a solar cell is expressed as the **peak power (Wp)** generated at high noon on a cloudless day.⁷

The key to the success of this process is the use of a semiconductor material which can be adapted to release electrons, the negatively charged particles which form the basis of electricity. The most common semi-conductor material used in PV cells is Silicon, an element most commonly found in sand.⁸ To make a solar cell, Silicon is melted and shaped into ingots, which are literally chopped (or extruded) into thin slices called wafers. The wafers are doped with phosphorous and boron and then collector wires are attached, forming a solar cell, which is about the size of a compact disk. Cells are then connected and wired together in a frame with a transparent cover to form panels (also called modules).

FIGURE 02
BASIC SOLAR CELL STRUCTURE⁹

⁵ *Ibid.*

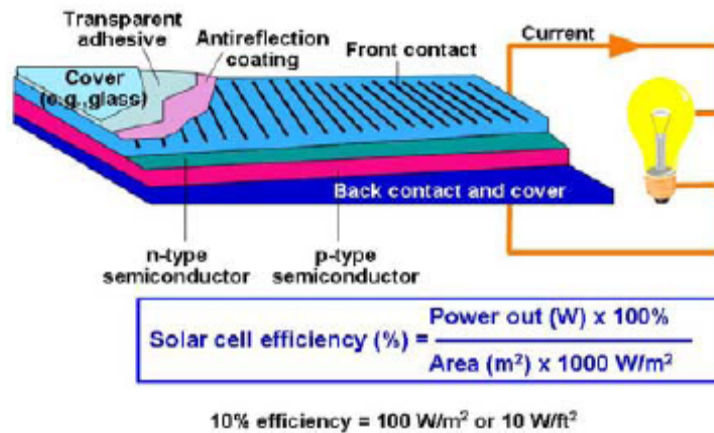
⁶ *Basic Energy Sciences Workshop*; p.24

⁷ *Ibid.*

⁸ *Basic Energy Sciences Workshop*; p. 10

⁹ *Basic Energy Sciences Workshop*; p. 16

A Solar Cell Structure



Although Silicon is one of the most abundant minerals on the planet, second only to Oxygen,¹⁰ the third-most abundant mineral on Earth, naturally-occurring Silicon is full of impurities; semiconductor-grade Silicon requires purification steps which can make it quite expensive. Silicon can be made in Mono-crystalline, Poly-crystalline or amorphous forms; in either case, the preferred end-result is a thin wafer of Silicon. Typically, a solar array for a residential rooftop consists of 25 modules, which produces 3-4 kW of electricity, at a cost of US\$20-25,000.¹¹

I.C — CURRENTLY-DOMINANT PV TECHNOLOGY — CRYSTALLINE SILICON

I.C.1 — Use and Cost of Crystalline Silicon:

Silicon is by far the most widely-used material for solar PV cells, and it comes in three basic forms — Mono-crystalline Silicon, Poly-crystalline Silicon, and in a non-crystalline form called amorphous Silicon [a-Si]. Amorphous Silicon is not normally a good converter of sunlight into electricity, though thin layers of a-Si have recently been successfully used as thin-films on non-Silicon substrates. Though amorphous Silicon is increasing its share of the solar PV market, the great bulk of the market is for the crystalline forms, either Mono-crystalline Silicon or Poly-crystalline Silicon. These will be discussed in detail.

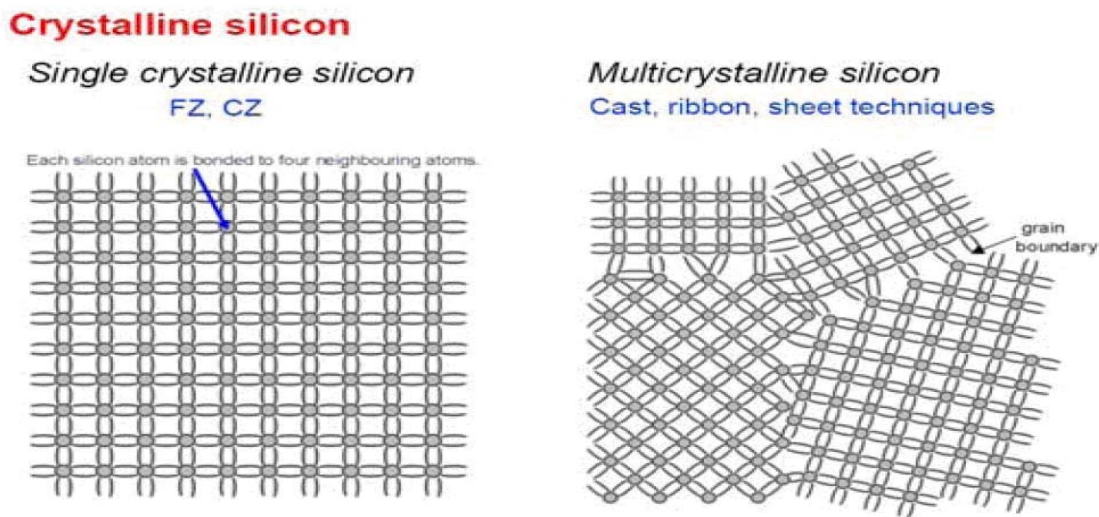
With Mono-crystalline Silicon, as the name implies, the entire wafer is comprised of one single crystal of Silicon; with Poly-crystalline Silicon, multiple crystals are formed in the wafer. Mono-crystalline Silicon is more efficient than Poly-crystalline Silicon in converting sunlight to electricity for two key reasons — [1] grain boundaries of multiple, overlapping crystals interfere with the efficiency of electron migration in the Poly-crystalline form, and [2] Poly-crystalline Silicon has many more impurities, which also degrade electron movement and efficiency. In addition, Poly-crystalline Silicon is highly reflective, which means that some solar energy is reflected back and therefore lost. Though the fundamental physical properties such as bandgap and absorption are similar in both Mono- and

¹⁰ <http://Mono-crystalline Siliconwww.pbs.org/transistor/glossary.html>

¹¹ The Progressive Investor, *Special Report: The Solar Investment Landscape* JAN/FEB, 2005 [downloaded from SustainableBusiness.com]; p. 4

Poly-, the primary differences are the density of defects and impurities — “and cost, cost, cost.”¹² Figure 03 shows these differences graphically:

FIGURE 03
SINGLE- VS. POLY-CRYSTALLINE SILICON¹³



The high cost of Mono-crystalline Silicon is due to the difficulty of creating single-crystal wafers of Silicon with few impurities. There is a shortage of Silicon for solar panels that is driving up the cost of solar and slowing solar growth. What is little understood is that there is not precisely a shortage of Silicon as such, rather, the computer chip industry is giving solar companies heavy competition for all available Silicon, and chip companies are paying more for Silicon than the solar industry can afford to pay, buying up the available Silicon and leaving a shortage of Silicon for solar manufacturing. Bloomberg reports that Silicon prices have gone from \$20-25/kilogram in 2004 to \$100-200/kilogram in 2006.¹⁴

As indicated above, the first manufacturing step is creating an ingot of Mono-crystalline Silicon. This ingot is typically a cylinder, which must then be sawed into wafers, much like a salami. But since only the surface of a Silicon wafer reacts to the light, manufacturers try to make the Silicon slices as thin as possible. This means that the kerf — the portion turned into “sawdust” by the slicing blade or other mechanism — is a high percentage of the finished wafer. The sawing action also scratches the Silicon wafer, requiring further cost and material loss to polish the wafer surfaces. It is estimated that up to 50% to 60% of the Mono-crystalline Silicon ingot is lost in the process of manufacturing solar cells.¹⁵

¹² David Danielson, *et al.*, “PV in 2012,” *MIT Energy Resources Class PowerPoint Presentation*; 1/13/07 [downloaded from web.mit.edu/mit_energy/resources/classes.html]; p. 12; emphasis in original

¹³ *Ibid.*

¹⁴ Russell Hassan, *A Research Report on Solar Power Investment: The Dawn of Solar Power*; *Alternative Energy News Source* 7/26/06 [downloaded from Altenews.com]; p. 7

¹⁵ *Basic Energy Sciences Workshop*; p. 20