Application Report
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Understanding Photovoltaics and the Market Forces Behind Them

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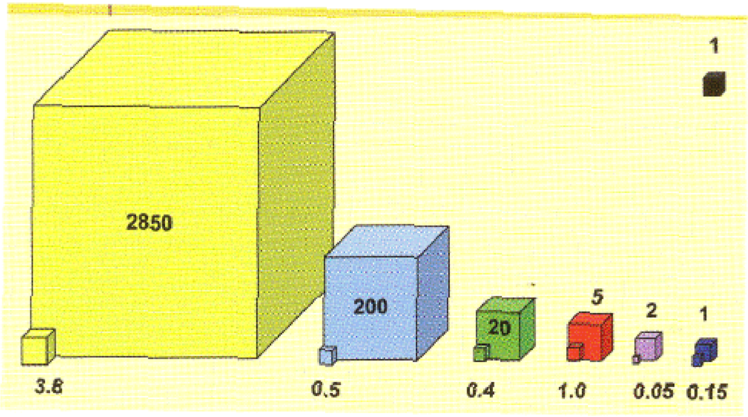
ABSTRACT

Forecasted demand in energy is expected to double through 2030 and could outstrip supply. Furthermore, with increasing energy prices in history, advancements in "clean/green technologies" is creating a wave of opportunity. The last 2 to 3 decades of improvement have made alternative energies more attractive and less expensive. Solar industry is the fastest growing segment in the alternative energy sector where global resources are plentiful. The market and the technology of the solar industry is discussed in this application note.

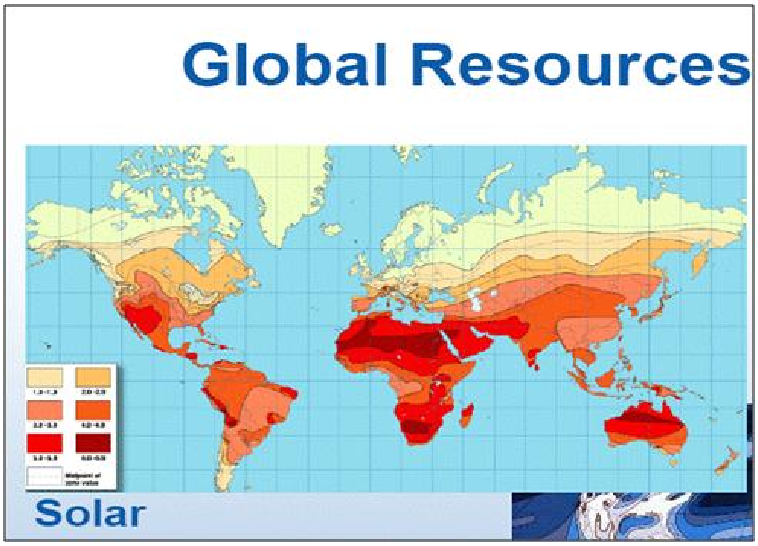
1 Introduction

The solar industry is the fastest growing segment in the alternative energy sector. It is expected to grow from \$11B in 2005 to \$51B in 2015 (Source: Clean Edge). Its global resources are plentiful. Figure 1 and Figure 2 show the relative supply of solar energy in relation to the current world energy consumption and the global resources respectively.



The natural supply of renewable energies in relation to the current world energy consumption (black cube, normalized to 1). Small cubes: The fraction of each energy source that is technically, economically and ecologically exploitable. Yellow: solar radiation onto the continents; blue: wind; green: biomass; red: geothermal heat; dark blue: water power (Source: DLR).

Figure 1. Relative Supply of Solar Energy in Relation to Current World Energy Consumption



(Source: NREL)

Figure 2. Global Resources for Solar Energy Supply

2 Solar Technology

Solar heating is the simplest form of using solar energy. Though similar in concept, solar thermal power generation, also known as concentrated solar power (CSP), is still in the developmental phase. For these systems, parabolic trough or disk collectors focus the sun's rays onto solar towers. The collectors on these towers can reach temperatures of over 1000°C. The liquid in these collectors change phase and can be used to produce electricity using steam or gas turbines.

The most widely used solar technology is photovoltaics where there is direct conversion of sunlight into electrical energy through a device known as a solar cell. Table 1 summarizes the comparison between the two technologies in terms of electricity cost paid by the customer and the market.

Table 1. Comparison Between Photovoltaics and CSP Technologies

TECHNOLOGY	COST FOR CUSTOMER TO PAY FOR ELECTRICITY		MARKET
	CURRENT COST	POTENTIAL COST (2015)	
Photovoltaics	18-23 cents/kWh	5-10 cents/kWh	Grid Residential Energy harvest
CSP technologies	12 cents/kWh	6 cents/kWh	Grid

The photovoltaics market segment serves multiple market segments and applications:

- Residential:
  - Home based utility
  - Building Integrated Photovoltaics (BIPV)
- Grid-tied (large scale utility)
- Emerging market:
  - Mobile computing
  - Wireless Mesh Network
  - Disposable electronics
  - Automotive applications
  - Medical applications
  - Environmental applications
  - Construction applications

- Military and aerospace applications

3 Solar Cell Operation

Solar cells are generally made of semiconductor materials. Currently more than 90% of the market is dominated by crystalline silicon solar cells. Silicon has the advantage of being the second most abundant element in the earth's crust. Also, material manufacturing and usage of this material poses no burden to the environment. Figure 3 shows the cross section of a solar cell.

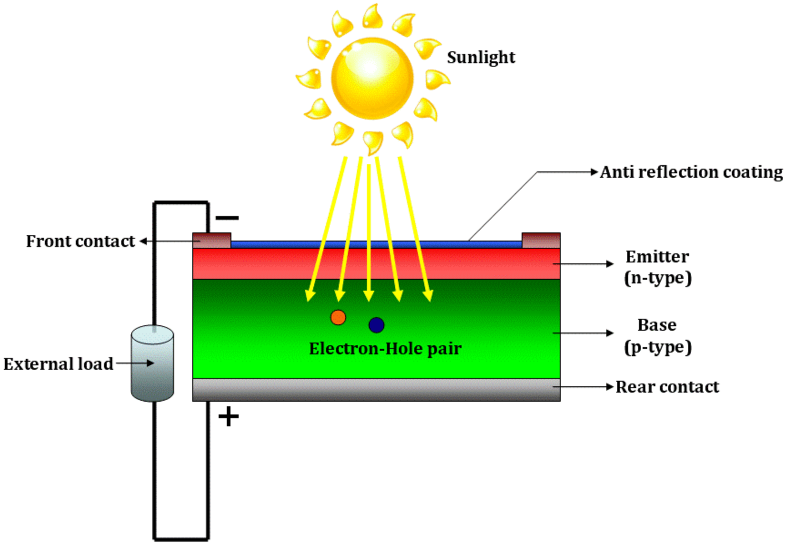


Figure 3. Cross Section of a Solar Cell

A solar cell is a p-n junction diode which has a built-in electric field at the junction. Exposure to light results in separation of the charge carriers or creation of electron-hole pairs. Through conductive contacts, a circuit is created by connecting the solar cell to an external load. The current supplied to the load is proportional to the irradiance of the solar cell.

4 Characteristics of a Solar Cell

Since the solar cell is a diode, the IV characteristic of the cell is similar to that observed in a diode, except that the IV curve is shifted downward due to light illumination. The area under the curve is the power generated by the solar cell. Figure 4 shows the IV characteristics with the various cell parameters and their definitions listed below:

- ***Open circuit voltage (V_{oc}):*** This is the voltage appearing across the solar cell when not connected to a load.
- ***Short circuit current (I_{sc}):*** This is the current flowing through the output terminals of the cell or cells when the terminals are short circuited.
- ***Maximum power (P_{max}):*** This is the maximum power defined by the area A_2. The voltage and current that defines P_{max} are V_{max} and I_{max} respectively. The maximum values change depending on the light intensity of the irradiation and temperature. The condition at which maximum power is achieved is called the maximum power point (MPP) of the IV/PV curve.

  Two other important metrics defined for a cell are efficiency and fill factor. Efficiency is the ratio of power delivered compared to the irradiance. Fill factor defines the squareness of A_2.

  If P_{ein} = Light irradiated power
- ***Fill Factor, FF*** = A_2/A_1
- ***Efficiency,*** $\mu = P_{max}/P_{ein}$
  $= (V_{oc} \times I_{sc} \times FF)/P_{ein}$

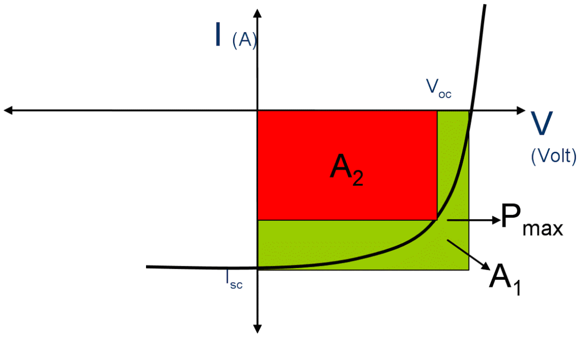
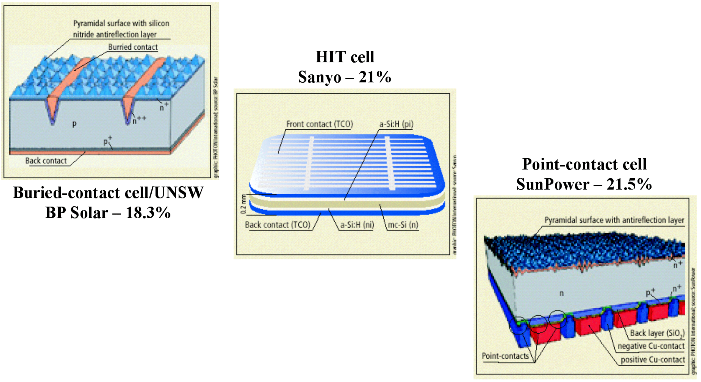


Figure 4. Solar Cell IV Characteristics

Efficiency improvements are dictated by cell design, better light capturing techniques, and choice of material. Figure 5 shows examples of commercially available high efficiency silicon solar cells with advanced cell design and improved light capturing techniques such as surface texturing.



Buried-contact cell/UNSW
BP Solar – 18.3%

HIT cell
Sanyo – 21%

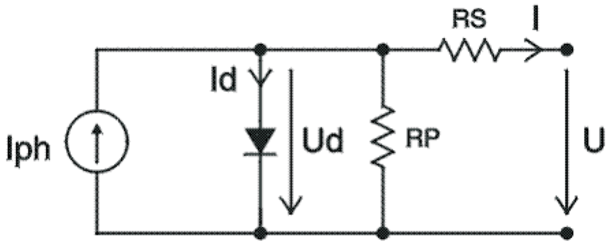
Point-contact cell
SunPower – 21.5%

Thomas Surek, NREL, "Solar Electricity: Progress and Challenges" presentation

Figure 5. Examples of Commercially Available High Efficiency Silicon Solar Cells

5 Modeling Solar Cells

The most commonly used model to study the behaviour of a solar cell and one that can be used in circuits is shown in Figure 6. Every solar cell has a built-in series resistance, Rs (similar to one that exists in an energy source such as a battery) and shunt resistance, Rsh. In general, Rs needs to be very small to avoid any power dissipation. Rs is dependent on the solar cell contacts and light intensity. On the other hand, Rsh needs to be very large and is strongly dependent on the material. A strong deviation from the squareness of the power curve (a low FF) implies a problem with one or both resistances. As a rule of thumb, as Rs increases, cell efficiency decreases. Similarly, as Rsh decreases, cell efficiency decreases.



$$I = I_L - I_0\left[\exp\left[\frac{q(V + IR_S)}{nkT}\right] - 1\right] - \frac{V + IR_S}{R_{SH}}$$

Figure 6. Realistic Model of a Solar Cell

6 Solar Cells to Modules

Solar cells, when connected together in series or parallel, comprise to form a PV module. In a typical residential or grid-tied application, one common way to build a PV system is by connecting modules in series to form a string, called a PV array. Shown in Figure 7 is an example of 72 cells connected in series (front side view) to form a module, sometimes also referred to as a panel. The backside view shows the junction box with a pair of wires for connection of the module to the external load.

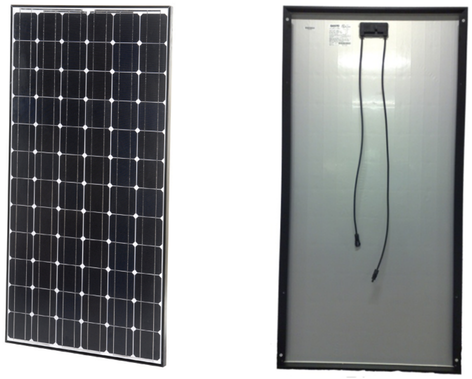


Figure 7. Series of Solar Cells to Form a Module

7 Photovoltaic Materials

Materials are the biggest area that can address lower cost and higher efficiency. Currently, crystalline silicon is the most widely used solar cell material. Current industry efficiencies for crystalline silicon solar cells are close to 20% as shown in Figure 5. However, the race to improving efficiency is limited by silicon's theoretical efficiency of around 28%. Ease of manufacturing also plays a big role in lowering the cost per watt.

Key technical markers in materials for solar cell development:

- Band-gap
  - Band-gap engineering: Tailoring materials to create direct band-gap(s) as opposed to in-direct. End result: Improved light carrier generation.
- Optical length or minority carrier lifetime
  - Defect engineering within
  - Light scattering texturing techniques

- Carrier Mobility
  - Reduce lattice disorder
- Absorption co-efficient
  - Tailor materials to improve the spectral response

Based on these criteria, several materials have emerged in the market. Table 2 summarizes the various solar cell materials, their features, their potential applications, and the challenges they face in becoming commercially viable.

Table 2. Materials: One of the Biggest Challenges in Making a Solar Cell Commercially

	MATERIAL	FEATURES	DISADVANTAGE	APPLICATIONS
Bulk	Crystalline Si	Efficiency close to 18–20%	Expensive ($4/Wpeak) material wastage	Residential and military
	III-V / II-VI	Highest efficiencies in the market	Very expensive	Military and space, CSP
	Poly-Si	Cheaper than mono-crystalline SI	Material wastage. Supply is an issue.	Residential and grid
Thin film	Poly-Si	Low cost – Compatible with current IC and MEMS mfg	Efficiency below 15% manufacturing method: direct dep. or anneal?	Portable, medical, automotive (ultra-low power) Integrated with current process technologies grid and residential
	Hydrogenated amorphous Si	Low cost – Compatible with current IC and MEMS mfg	Efficiency ~ 10%	Portable, medical, automotive (ultra-low power) Integrated with current process technologies grid and residential
	CdTe	High efficiency ~ 16%	Te is rare. Process challenge. Cd is toxic: DIsposal issue.	Large area (grid), although still a challenge
	CIS/CIGS	Ideal material for solar cell: Suitable band-gap and high absorption. Hence, lowest thickness. High efficiency ~ 19%	Efficiency degrades. Processing a challenge.	Large area: potentially can incorporate this as a TF in Si IC technologies
Plastic	Organics	Very cheap – Low cost manufacturing	Still an emerging market. No clear choice of material.	Portable, medical, automotive (ultra-low power)
	Dye sensitized materials			

Table 3 lists the manufacturing methods, advantages, and challenges for these solar cells.

Table 3. Solar Cell Manufacturing

MATERIAL	MANUFACTURING METHOD	ADVANTAGES	DISADVANTAGES
Bulk (c-Si, poly-Si, GaAs)	CZ cystal pulling	● Established ● High efficiency	● Very expensive ● Supply issue for large area applications
Thin film (a-Si:H, poly-Si, CIS, CIGS, CdTe, flex-Si)	● PECVD ● Printing ● Vacuum deposition	● Low temperature process ● Compatible with low cost substrates ● Low cost	● Low throughput ● Annealing processes not standardized ● Printing processes not standardized
Organic	● Inkjet printing ● Spin coating	● Very inexpensive	● Manufacturing not dialed-in due to materials being an emerging market

8 Cell Structures

To take maximum advantage of the sun spectrum, cell structures are designed using multi-junctions and dissimilar materials. Multi-junction solar cells are made by stacking individual single junction cells with the band-gap descending from the top to the bottom of the cell. The purpose is to have the highest energy photons absorbed by the top junction and the lower energy photons transmitted to be absorbed by the lower band-gap solar cells. Multi-junctions are usually built using compound semiconductor hetero-structures using III-V and II-V materials.

9 Concentrated Photovoltaics (CPV)

Concentrated photovoltaics, known as CPV, is an emerging solar cell technology that utilizes the benefits of multi-junctions using III-V and II-V materials. The advantages of this technology are two-fold; one is due to the high efficiency that is inherent from the compound semiconductors and secondly, the concentrated intensity that is 10× to 1000× the intensity that is typically used in traditional solar cells. Currently, the cost of these cells is much higher than traditional solar cells. However, this technology has potentially the lowest cost per watt due to the advantage of the higher efficiency it enjoys, a drastic reduction in the material used, and the automatic cost reduction that will be reflected from economy of scale when it reaches large scale production.

10 Moving Forward

Innovation in cell and module design will continue to be the driver for achieving lower cost per watt. This is true for all solar cell markets from silicon to organic solar as well as CPV, which is to reach below $1/W. Although there are several approaches being taken to achieve this goal, some through better technology to improve higher efficiency, which in turn will deliver more wattage for a given cell, whereas others are taking the low cost manufacturing and ease of installation approach. Finally, the concept of smart module is being commercialized where electronics are built into a module to maximize the energy being generated from the module. TI plays into this downstream market of this chain by supplying components to key micro module based electronics customers.

11 References

1. **DLR, Renewable Energy**, Roland Wengenmayr and Thomas Buhrke, Wiley Tech, 2008
2. **NREL, Solar Electricity Progress and Challenges**, Thomas Surek

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