The Basic Economics of Photovoltaics

Greg P. Smestad
Solar Energy Materials and Solar Cells, P.O. Box 5729, San José, California 95150-5729, U.S.A.
e-mail address: inquiries@solideas.com

Abstract: With widespread deployment of PV power imminent, it is useful for researchers to have a basic knowledge of the economic principles that govern PV modules and systems. Several simplified and illustrative equations are presented.

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1. Introduction

Annual production of Photovoltaic (PV) panels was estimated to be 3,800 Megawatts (MW) in 2007 [1, 2]. Cumulative global production stands at approximately 12,400 MW. Annual growth in PV production continues to be 40-50%. According to the Earth Policy Institute, the industry has grown by an average of 48 percent each year since 2002. PV production has been doubling every two years, making it the world's fastest-growing energy source. Module price is currently \$2.5-3.8 per peak watt (\$/Wp), which leads to a Levelized Cost of Electricity (LCOE) of approximately 21 U.S. cents per kWh. When the LCOE for PV is half of this value, widespread economic deployment of PV power will likely be a reality. It is therefore useful for researchers in the field of solar energy to at least have some basic knowledge of the economic principles that govern PV modules and systems. This paper presents a simplified technique for initial steps towards that goal.

John Turner of the U.S. Dept. of Energy's National Renewable Energy Laboratory (NREL) has calculated that a 10% solar-to-electrical system efficiency, well within the efficiency of today's technology, and a square 161 kilometers (km) (100 miles) on a side would produce the energy, during 1 year, equivalent to that used annually in the entire United States. Although 25,921 square kilometers (10,000 square miles) is a large area, it is less than one quarter of the area that the U.S. has covered with roads and streets, and is much less than the area in the U.S. devoted to cropland. This area can be located in one place (e.g. desert areas), or distributed on suitable roof or land areas.

Most commercial PV panels are made from crystalline (c-Si) [3] or multicystalline silicon (mc-Si). Wafer based Si solar cells and are currently produced by growing single crystal ingots or by casting multicrystalline (mc-Si) blocks. The silicon is then sliced into 200-300 micron thick wafers and processed with dopants using methods that are very similar to the technology used for making integrated circuits (ICs). Thin film PV technologies are based on materials such as non-crystalline, amorphous Silicon (a-Si) or on polycrystalline CdTe or $CuInGaSe_2$ [4]. These thin materials can be directly deposited on glass and interconnected using laser or photolithography patterning. Concentrator cells cover only a tiny fraction of a PV system and are typically made from high purity Si and III/V materials. Such cells can reach solar conversion efficiencies of over 40%. Any viable PV production process, be it thin film, wafer-based or for concentrators must be conducive to high throughput production rates (e.g. large areas per unit time) and high yields so that Gigawatt per year capacities are possible.

2. The Basics of PV Economics

The economics of PV devices are related to their efficiency as well as to their optics. The cost of photovoltaic materials is often expressed on a per-unit-area basis, but the modules are often sold based on cost per watt that potentially generated under peak solar illumination conditions. To convert the cost per square meter to this cost per peak watt, the following equation is employed:

$$\$/\mathrm{W_P} = \frac{\$/\mathrm{m}^2}{\eta \bullet 1000\ \mathrm{W_P/m^2}} \quad , \qquad (1)$$

where η is the solar conversion efficiency. A 12% efficient module with a cost of $\$400/m^2$ yields a cost per peak watt of \$3.33. For a PV cell used in concentrator, the cost can be divided by the concentration ratio.

In a simplified economic analysis, it is desirable to estimate the return on the investment made for a particular material used as part of the photovoltaic system. For example, the payback time for the PV module, of cost $\$/m^2$, is related to its efficiency, the location it is installed and the cost at which electricity is sold on the market (in \$/kWh). The payback time is given by

$$\text{Payback time} = \frac{\text{Cost \$/m}^2}{\eta \bullet \dfrac{5\,\text{kWh}}{\text{day}\cdot\text{m}^2} \bullet \dfrac{365\,\text{day}}{\text{y}} \bullet \dfrac{\text{electricity \$}}{\text{kWh}}} \qquad (2)$$

For example, the payback time for a 150 $/m^2 module of 20% efficiency at an electricity selling price of 0.08 $/kWh is approximately 5 years. PV module costs are currently $350-450/m^2 or approximately 3-4 $/Wp.

3. Estimated Solar Module Cost

As an example of the estimated costs of a PV cell, one can consider a hypothetical thin film PV module. One considers the materials and fabrication costs per square meter of PV module produced. We can also assume a single glass monolithic structure (e.g. one piece of glass). The cost of the hypothetical PV module is outlined in the table below and is $250 (2008) dollars per square meter.

	Costs (*\$/m^2*)
Solar Cell Materials and glass	130
Production Overhead:	
Equipment Depreciation, Indirect & Other Direct Materials	20
Labor (Direct and Indirect which includes assembly and testing)	5
Encapsulant or Sealant (e.g. Polymer)	50
Additional moisture barrier and backing (e.g. Tedlar)	10
Frame and electrical interconnects	30
Profit, Interest due on loans	5
Total module cost	*250 \$/m^2*

The direct costs such as tools and labor are related to the actual production of the module, while the indirect costs such as accountants, rent, and computers are volume insensitive. This calculation assumes a 20 MWp/year factory with 100 employees, and a capital cost of equipment of $20,000,000, housed in a 2,000 m^2 facility. For thin film PV, the module costs are determined primarily by the cost of the transparent conductive oxide (TCO) coated glass, and the production overhead. Both thin film and c-Si PV modules require an encapsulant and moisture barrier. Some designs, such as solar shingles, can do away with the expensive metal frame [4-5]. This analysis does not include the costs of securing contracts for materials, or the availability of non-abundant crustal elements such as In, Ga, Ge or Te.

To estimate the cost per peak watt, one relates the cost per unit area with the power produced, which depends on the solar conversion efficiency and the peak solar illumination as described in the previous section. For a PV module operating at a solar conversion efficiency of 16%, power could be produced at 2.5 $/Wp if the module cost is 400 $/m^2. For a 10% efficient module, the $/Wp cost would be the same for 250 $/m^2. One should point out that the cost of PV modules is often different (e.g. by as much as 1 $/Wp) than their price and that this depends on market factors and the availability of supply.

4. Economics of Photovoltaic Systems

To produce useful power in a commercial application, one must consider the average illumination, instead of the peak, as well as the additional costs of land, batteries, support structures *and* the lifetime of the PV panel. There is more to a PV system than just the module. Balance of Systems (BOS) costs such as the mounting, wiring, and power conditioning must also be considered, as well as the operating and maintenance costs. When these factors are taken into consideration, a rough cost per generated kilowatt hour can be estimated. The cost of electricity generated by solar cells can be estimated from equation

$$\frac{\text{Cost}}{\text{kWh}} = \frac{\left(\text{Cost of system \$/m}^2\right) \bullet \text{amortization}}{\text{kWh produced each year}} + \text{O\&M} \qquad (3a)$$

Inserting the relevant terms, Eqn. 3a becomes

$$\frac{\$}{\text{kWh}}=\frac{\text{Module }\$/\text{m}^2+\text{Mount }\$/\text{m}^2+\left(\text{Inverter }\$/\text{kW}\right)\bullet\eta}{\eta\bullet\dfrac{5\,\text{kWh}}{\text{day}\cdot\text{m}^2}\bullet\dfrac{365\text{day}}{\text{y}}}\bullet\text{amortization}\left(1+\text{Indirect}\right)+\text{O\&M} \tag{3b}$$

The per-unit-area cost of solar cells seems to be the largest and most variable cost item in a photovoltaic system. For concentrator PV systems, the area related module cost is reduced, because optics can be much less expensive than semiconductors (e.g. in the above equation, it is split into two $\$/\text{m}^2$ costs) [4, 5]. The amortization rate is calculated from the real discount rate of *i*, and a PV lifetime, N, as

$$\text{amortization}=\frac{i}{\left[1-\left(1+i\right)^{-\text{N}}\right]} \tag{4}$$

This rate, of course, depends on current interest rates and the availability of capital. For a solar insolation of 4.4 - 5 kWh/day/m^2 (1600 - 1800 kWh/year/ m^2), and an O&M Operating and Maintenance cost of $0.005/kWh, the electricity costs can thus be estimated. The cost of conventional electricity is between 0.06 and 0.13 $/kWh and depends on location and time of day. For a relative comparison, one can use the following numbers that are believed to be reasonable for near term PV technologies: module cost of 250 $\$/\text{m}^2$, mount costs of 50-75 $\$/\text{m}^2$, inverter costs of $170 per peak kW (e.g. power conditioning), and an indirect cost of 30% of direct cost for architect and engineer fees, along with interest during construction.

If Balance of Systems (BOS) costs are considered, the cost of power produced with PV could be 0.08-0.13 $/kWh, assuming a 15% efficient module which lasts at least 15 years under the irradiance levels found in the sunnier regions of the western United States. This gives a reasonable estimate for the LCOE. Note that this cost falls in the range of electricity costs for conventional fossil fuel based systems, and thus the above analysis outlines under what conditions solar cells could represent a viable energy option. The results of this kind of simplified economic analysis also indicates that, although solar cells of 15% efficiency, which last for 15 years, can be competitive with fossil fuels, solar cells of less than 8% efficiency with lifetimes of 15 years will probably not be economical or competitive.

This analysis did not include the total cost of capital (e.g. loans), nor does it include the social and environmental benefits of solar power generation compared to conventional power sources such as fossil fuels or nuclear power. One important economic issue that is often neglected when formulating energy policy is subsidies to energy production. The definition of a subsidy is any government action designed to influence energy market outcomes, whether through financial incentives, regulation, research and development (R&D) or public enterprise. Consideration of subsidies, in general, is becoming increasingly more important. The removal of energy subsidies can actually protect the environment and provide benefits to the consumer in many cases. Subsides can favor certain energy industries and skew the economics so that one energy source looks unfavorable when it actually may not be. Of the billions of dollars spent on energy subsidies, most currently go to fossil fuels and nuclear energy and 5-10% percent go to renewable and non-polluting sources of energy and energy conservation and energy efficiency.

The analysis presented herein, however simplified, outlines the basic factors involved in the costs of both PV cells and PV systems and thus can be used to illustrate the areas for further research and discussion. It updates the presentation previously published [5].

5. References

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