

## Solar Energy. Brighter Future Ahead?

When I was in elementary school, we were told that solar energy was going to solve the energy needs of the future. By now, according to the story those many years ago, virtually all the energy used in the world would come from a few solar power plants in sunny parts of the world, such as the Sonoran, Sahara, and Gobi Deserts. That hasn't come to pass, at least not yet (although Pres. Obama *is* spending \$2 billion on new solar energy in Colorado and Arizona).

The main difficulty is the low efficiency of solar energy conversion. Today, you can buy a solar energy system with efficiency up to 19% in direct sunlight, or 12% average over the daylight hours -- and the standard model is six hours of sunlight per day. This means that, averaged over the entire day, a photovoltaic solar cell (one that directly converts sunlight into electricity -- *photo* for light, *voltaic* for electricity) can produce 30 W per square meter, or 2.8 W per square foot. (Since we buy electricity in kWh, we can say that it takes about a day and a half for a photovoltaic panel one square meter in size to generate one kWh, and over two weeks for a square foot panel to generate one kWh.)

### What is the Limitation, and What Can Be Done to Improve the Situation?

*(We're going to have to get a little technical here.)*

There are, of course, limitations on how efficiently power can be converted from one type to another. If, for example, I had a device that was 110% efficient in converting heat to electricity, I could hook it up to a resistor to provide heat, then take out the extra 10% of electricity for free. Whether, like science-fiction author Robert Heinlein, we phrase this as "There ain't no such thing as a free lunch," or we refer to the First and Second Laws of Thermodynamics, or even go as far as to consider the Law of Conservation of Energy, we generally have to admit that this kind of perpetual motion machine cannot exist in the real universe. Scientifically, we need to consider thermodynamics—the science of energy conversion—since turning light into electricity is a form of energy conversion.

In the 1820's, Nicolas Léonard Sadi Carnot came up with a general theorem that, once you describe energy conversion as energy transfer between two objects at different temperatures, conversion efficiency can never exceed  $1 - T_c/T_h$ , where  $T_c$  and  $T_h$  are the temperatures (in absolute units, such as Kelvin) of the cold and hot objects, respectively. (The Second Law of Thermodynamics requires that the energy converted has to transfer from the higher temperature to the lower temperature.)

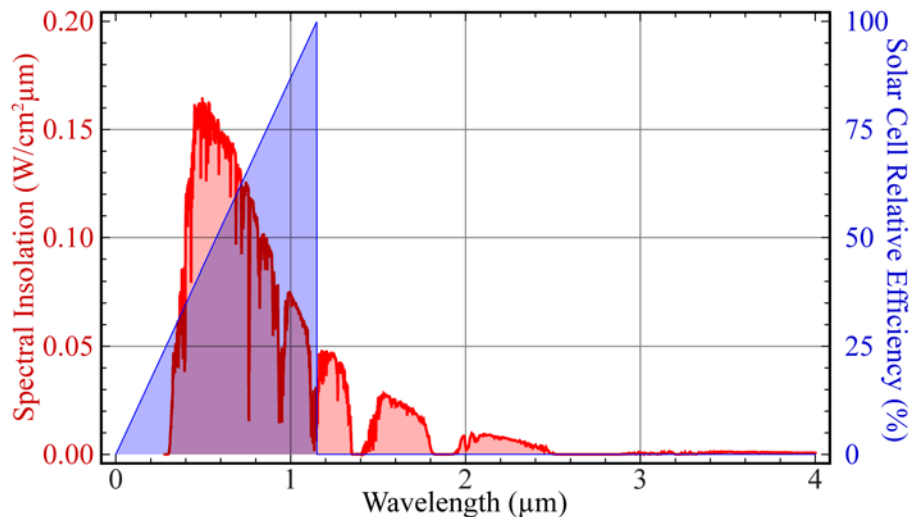
The solar cell can be modeled in this way. The sun can be modeled as an object whose temperature is 5770 K (9930°F, 5500°C). By comparison, the average temperature of the earth one foot below the surface is 288 K (60°F, 15°C). If the solar cell is attached to some kind of heat conductor, and the other end is buried at least a foot into the ground, the temperature of the solar cell can be stabilized at about 288 K (this temperature stability defined the earth as a "heat reservoir" in thermodynamics; the sun is another, since its temperature doesn't change if we set up a solar cell). Thus, the absolute maximum efficiency that can be achieved by a solar

cell under perfect conditions (more on this later) is  $1-288/5770$ , or 95.0%. There are, clearly, no such solar cells at present; indeed, there are other effects that limit the efficiency, and we'll discuss those in the next paragraphs.

The first limitation is the field of view (FOV) of the solar cell. A typical flat solar cell, pointed directly at the sun, has a FOV from one horizon to the other. Using solid angles, the cell FOV is  $2\pi$  sr (steradians). The sun, on the other hand, fills only 0.000068 sr, or  $1.08 \times 10^{-5}$  of the sky. The rest of the sky has a temperature less than that of the earth, so the effective temperature seen by the flat solar cell is 524 K. Thus, a flat solar cell can never exceed  $1-288/524$ , or 45.0%, efficiency. Even this is making several simplifying assumptions, such as that the sun is a perfect radiator (a blackbody) and that the solar cell, despite being attached to the earth as a heat reservoir, is outside the atmosphere.

In reality, we need to look at the actual amount of light reaching the ground. The amount of solar radiation reaching the surface of the earth, averaged and adjusted to the angle of the sun to the earth in the mid-latitudes (such as the southern US), is tabulated in the "Air Mass 1.5" specification. It turns out that this total insolation (yes, that's what it's called – it comes from "in" and "sol," input from the sun) is  $100.5 \text{ mW/cm}^2$ . That corresponds to an object at a temperature of 434 K covering the entire sky. In other words, in real life, a solar cell is limited to  $1-288/434 = 33.6\%$  efficiency.

Let's step away from thermodynamics for a moment and look at spectroscopy. (It really is necessary to be this technical.) The Air Mass 1.5 spectrum, the actual spectral insolation as a function of wavelength, does not necessarily match the solar cell's response. This is shown in the following figure:



For the solar cell shown in the figure, the maximum efficiency is at  $1.15 \mu\text{m}$ ; any light coming in at a long wavelength doesn't convert to electricity. In addition, below  $1.15 \mu\text{m}$ , even though light is converted to electricity, the efficiency is less than perfect. These two effects reduce the efficiency of a typical solar cell to significantly less than the anticipated 33.6%. To make matters worse, the light that is not turned into electricity is converted to heat, which increases the

effective temperature of the solar cell and further reduces its efficiency. For this kind of solar cell, the actual efficiency is generally agreed to be no greater than 25%.

## Solving the Spectral Problem – Multijunction Cells

The first improvement is to improve the solar cell's efficiency. The figure above shows a solar cell made from a single material. Typical photovoltaic solar cells (the normal ones you can buy, made from semiconductors such as silicon) are called "photon detectors." In other words, one photon creates one set of charges. In these systems, any wavelength of light (that is shorter than the cutoff wavelength, which is shown as  $1.15\ \mu\text{m}$  in the figure but depends on the material) creates just one equal amount of charge for each photon. Quantum mechanics, however, tells us that the energy of each photon is proportional to the inverse of its wavelength; that is why the efficiency of the solar cell is lower at shorter wavelengths. But what if we could find a way to adjust the solar cell so that its maximum response was at the wavelength of each incoming photon? Then each photon would generate charge that matched the photon energy, and the relative efficiency of the solar cell would be 100%.

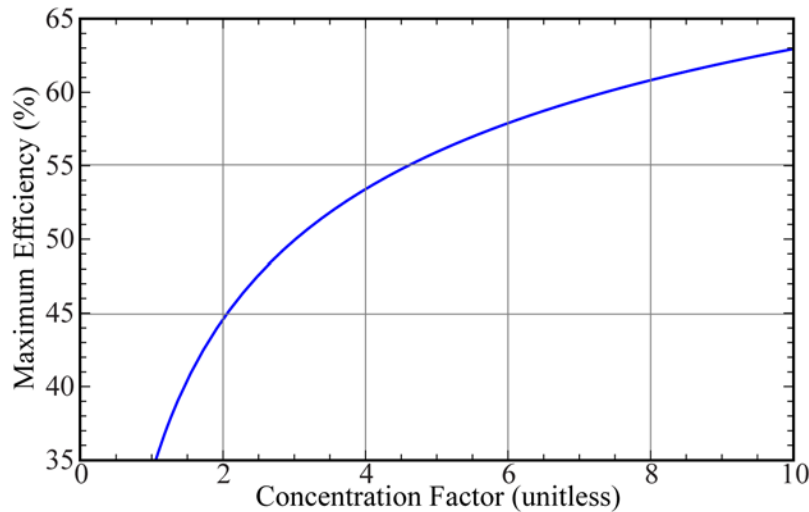
Well, we can't quite do that. The best we can do is find photovoltaic materials with different cutoff wavelengths, and that are transparent at wavelengths longer than the cutoff. We could then build a stack, where the bottom had a cutoff wavelength of (for example)  $2\ \mu\text{m}$ , the next layer  $1.75\ \mu\text{m}$ , then  $1.5\ \mu\text{m}$ ,  $1.25\ \mu\text{m}$ ,  $1.0\ \mu\text{m}$ ,  $0.75\ \mu\text{m}$ , and  $0.5\ \mu\text{m}$ . Then all the photons whose wavelength was shorter than  $0.5\ \mu\text{m}$  would be collected by the top layer, those whose wavelengths were  $0.5\text{-}0.75\ \mu\text{m}$  by the second layer, etc. Each layer would have a much higher efficiency at its wavelength range than the layer below it.

Instead of multilayer solar cells, the industry has decided to call these multijunction cells. The solar cell layers are attached through a "tunnel junction," and several such junctions make a multijunction cell. Of course, stacking a number of photovoltaic layers causes its own efficiency reductions, so there is a limit to how much improvement can be achieved with such a solar cell; the best estimates are that the efficiency could be nearly double that of a single-junction cell (depending on the material). Use of multijunction solar cells significantly reduces the losses caused by the mismatch of the spectral insolation to the solar cell—the difference between the efficiency of the cell and the amount of light at the same wavelength—and also reduces the amount of heat generated by capturing the light.

## Solar Concentrators

I said above that we would get to the efficiency improvements brought about by concentrating the insolation – or, in other words, by reducing the solar cell FOV. This can be done by something as simple as a magnifying glass or similar lens. When I was in elementary school, we would take a magnifying glass out when it was sunny and focus the sun's light onto a piece of paper. If the magnifying glass' lens was good enough, we could get the paper to burn; we increased the effective temperature of the sky from  $434\ \text{K}$  (calculated above) to at least  $750\ \text{K}$  (well above the temperature at which paper burns, which is sometimes quoted to be as low as

506 K – 233°C, or 451°F). In theory, a perfect concentrator could make the effective temperature of the sky 5340 K – the temperature that results in the 100.5 mW/cm<sup>2</sup> insolation calculated from Air Mass 1.5 data, if the FOV of the solar cell is restricted to only see the sun. That would allow a perfect multijunction solar cell to reach an energy conversion efficiency of  $1 - 288/5340 = 94.6\%$ . There are many reasons why this value cannot be achieved; the generally accepted maximum theoretical efficiency of a solar cell is about 85%. As the following figure shows, the possible efficiency of a perfect solar cell on the surface of the earth increases from 33.6% when it is used flat, without any concentrator, to 62.9% with 10× concentration.



So the possible efficiency can be increased, but not by a lot. In fact, a perfect solar cell using a perfect solar concentrator only increases its efficiency by 2.8× compared to the same cell without a concentrator. Since concentrators can be difficult and expensive, why use them?

It really comes down to costs. For a commercial solar panel, the silicon—the photovoltaic material—costs between 75% and 90% of the total cost of the panel. The advantage, then, of the concentrator is that it reduces the amount of photovoltaic material needed. If, for example, the concentrator is 10×, only 10% as much of the expensive material is required. By reducing the amount needed, more expensive material—or multijunction solar cells—can become economically feasible. Somewhat higher efficiency due to the use of multijunction cells, and somewhat higher efficiency due to the use of a solar concentrator, contribute only a small amount to the cost savings when compared to the significant reduction in the amount of photovoltaic material needed.