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Solar Efficiency Limits

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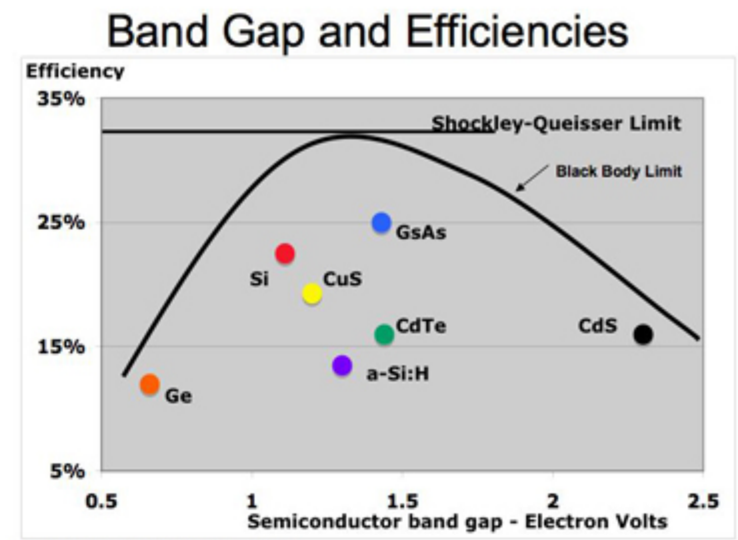
The Shockley Queisser Efficiency Limit



Source: DOE, Lewis Group at Caltech

The **Shockley Queisser (SQ) Limit** refers to the maximum theoretical efficiency of a perfect solar cell using a p/n junction to extract electrical power. It was first calculated by William Shockley and Hans Queisser in 1961. A solar cell's energy conversion efficiency is the percentage of power converted from sunlight to electrical energy under "standard test conditions" (STC). The STC conditions approximate solar noon at the spring and autumn equinoxes in the continental United States with the surface of the solar cell aimed directly at the sun. **The modern SQ Limit calculation is a maximum efficiency of 33% for any type of single junction solar cell.** The original calculation by Shockley and Queisser was 30% for a **silicon** solar cell. Current solar cell production efficiencies vary by the band gap of the semiconductor material as shown on the left. See Junctions & Band Gaps page. The best modern production silicon cell efficiency is 23% at the cell level and 20% at the module level as presented by SunPower in May, 2010. In a laboratory, the record solar cell efficiency is held by the University Of New South Wales in Sydney, Australia at 25%.

There are a number of assumptions associated with the Shockley Queisser Limit that restrict its general applicability to all types of solar cells. But keep in mind that although there are numerous investigations to find ways around the SQ Limit, it is still applicable to 99.9% of the solar cells on the market today. Top

The Critical SQ Limit Assumptions:

- One semiconductor material (excluding doping materials) per solar cell

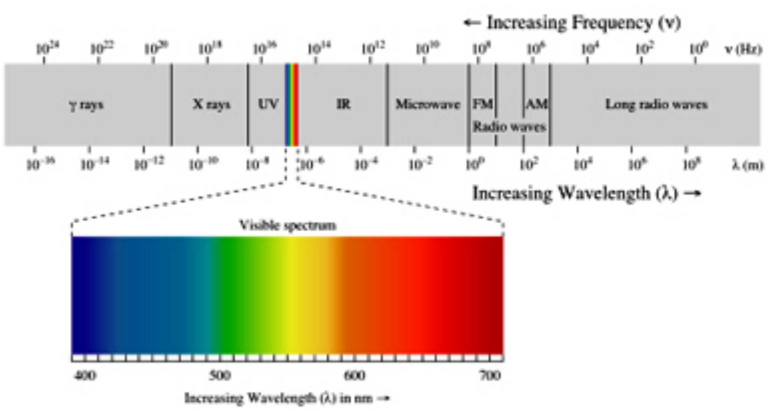
- One P/N junction (see P/N Junction Page) per solar cell
- The sunlight is not concentrated - a "one sun" source
- All energy is converted to heat from photons greater than the band gap

Where Does The 67% Of Energy Loss Go?

- 47% of the solar energy gets converted to heat
- 18% of the photons pass through the solar cell
- 02% of energy is lost from recombination of newly created holes and electrons
- 33% of the sun's energy is theoretically converted to electricity
- 100% total sun's energy

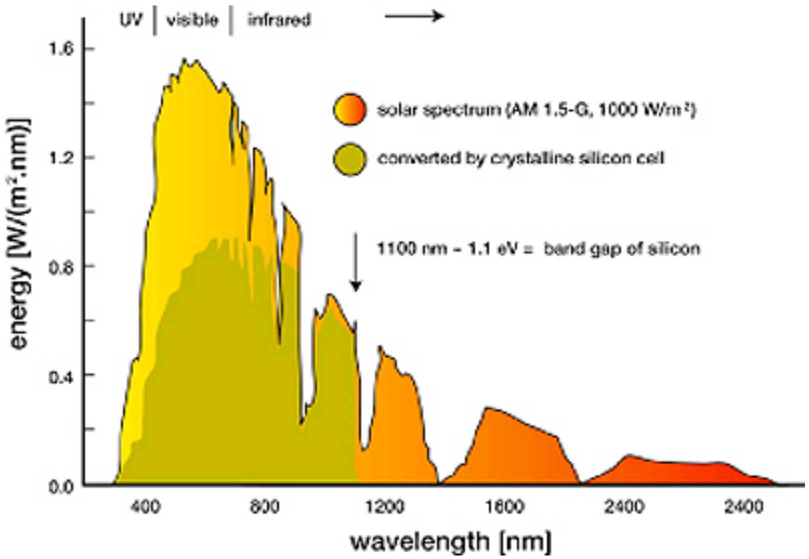
If the theoretical limit for silicon cells is about 30%, what happens to the other 7% that is lost from the best production cell efficiency of 23%? Some sunlight is always reflected off the surface of the cell even though the surface is usually texturized and coated with an anti-reflective coating. In addition there are some losses at the junction of the silicon cell with the electrical contacts that carry the current to the load. Finally, there are some losses due to manufacturing impurities in the silicon. Top

What Electro-Magnetic Waves Are Absorbed By A Solar Cell?



Shown to the left is the complete spectrum of electro-magnetic radiation. The long waves at the right are the weakest. The most powerful rays (gamma rays) are very short and to the left.

For a semiconductor electron to move into an external load circuit, its energy level must be increased from its normal valence level (tightly bound to one atom) to its higher energy conduction level (free to move around). The amount of energy to boost it to the higher level is called the "band gap" energy. See Band Gaps page. Only photons with at least the band gap energy will be able to free electrons to create a



current. Sunlight photons with less than the band gap energy will simply pass through the solar cell. Put in terms of radiation, all the photons in the visible spectrum are strong enough to cause electrons to jump the band gap. Some infrared, all microwave, and all radio waves do not have enough energy and pass right through the solar cell. In the "sunlight energy distribution" chart to the left, only the mustard colored photons can create electricity in a crystalline silicon cell. The red colored ones do not have enough energy and the yellow ones have too much energy. The yellow waves are absorbed and generate electricity, but a lot of their energy is lost.. That is because photons with excess band gap energy generate a free electron and a hole, but the extra energy gets dissipated as heat. X-rays and Gamma rays have just too much energy to be absorbed at all. The mustard area is basically a picture of the SQ Limit applied to silicon as Shockley and Queisser calculated it in 1961. Top

Strategies To Exceed The SQ Limit:

Basically the strategies to obtain better efficiencies than the SQ Limit predicts are to work-around one or more of the critical assumptions listed above (and shown again below).

1) One semiconductor material (excluding doping materials) per solar cell

Use more than one semiconductor material in a cell

2) One P/N junction (see P/N Junction Page) per solar cell

Use more than one junction in a cell - "tandem cells"

3) The sunlight is not concentrated - a "one sun" source

Sunlight can be concentrated about 500 times using inexpensive lenses

4) All energy is converted to heat from photons greater than the band gap

Combine a PV semiconductor with a heat based technology to harvest both forms of energy and/or

Use "quantum dots" to harvest some of the excess photon energy for electricity

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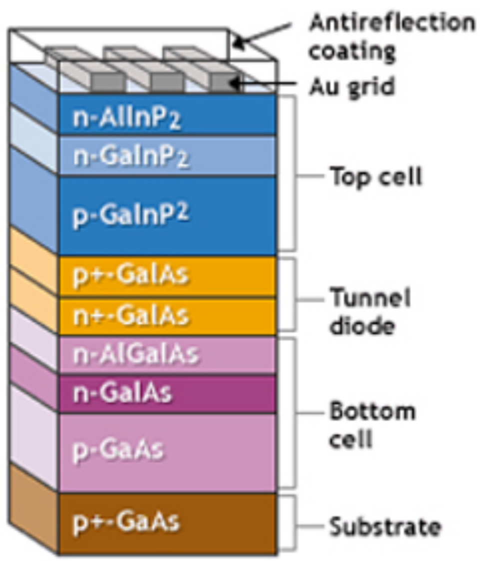
Strategies 1) and 2) Multi-junction Solar Cells - "Tandem Cells"



The earliest and most frequent work around to the SQ Limit has been the use of multiple p/n junctions, each one tuned to a different frequency of the solar spectrum. Since sunlight will only react strongly with band gaps roughly the same width as their wavelength, the top layers are made very thin so they are almost transparent to longer wavelengths. This allows the junctions to be stacked, with the layers capturing the shortest wavelengths on top, and the longer wavelength photons passing through them to the lower layers.

The example of a multi-junction cell on the left has a top cell of gallium indium phosphide, then a "tunnel junction", and a bottom cell of gallium arsenide. The tunnel junction allows the electrons to flow between the cells and keeps the electric fields of the two cells separate. Most of today's research in multi-junction cells focuses on gallium arsenide as one of the component cells as it has a very desirable band gap. Performing a calculation using the Shockley Queisser methodology; a two-layer cell can reach a maximum efficiency of 42% and three-layer cells 49%. The record for a multi-junction cell is held by the University Of New South Wales (UNSW) in Sydney, Australia at 43% using a five cell tandem approach. However, the UNSW tandem cell is very expensive. In addition to the cost issue, there are other constraints that make the tandem cells complex. For example, all the layers must be lattice compatible with one another in their crystalline structure and the currents from each individual cell must match the other cells. Multi-junction cells are commercially used in only special applications because their expense outweighs any efficiency improvement. At the moment they are used in space where weight is most important and in concentrated PV systems where the sunlight is focused on a very small cell area. See the Amonix discussion.

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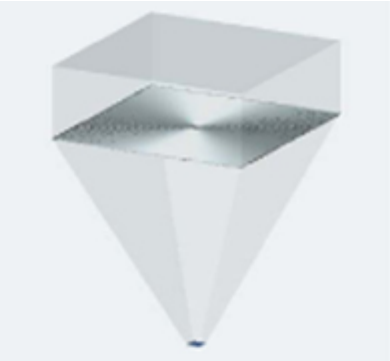
Strategy 3) Concentrate The Sunlight

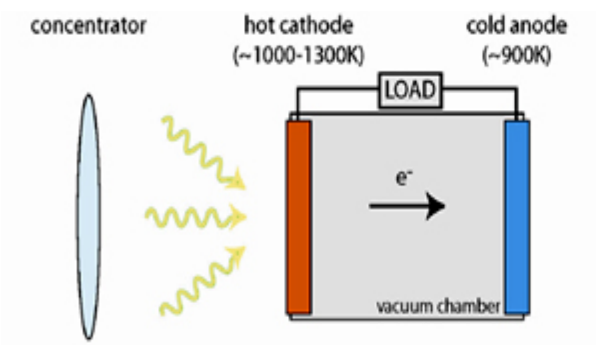


Concentrated PhotoVoltaics (CPV), in which sunlight is focused onto a small solar cell by lenses to generate more power per unit of surface area, was an early favorite to increase solar efficiency. CPV’s main attraction is that it can leverage modest "one sun" cell electricity production to a much larger scale production using relatively simple and inexpensive optical concentration.

Instead of a typical 6 inch by 6 inch solar cell, a 7 inch by 7 inch square plastic Fresnel (pronounced Fray-NELL) lens incorporating circular facets, is used to focus the sunlight as shown on the left. A tiny, **39% efficient multi-junction solar cell** is mounted at the focal point which converts the sun's energy into electricity. Future cell efficiencies are expected to approach 50%. The Fresnel lens concentrates the sun's energy about 500 times its normal intensity. A number of Fresnel lenses are manufactured as a single plastic piece. The tiny solar cells are mounted on a supporting plate at locations corresponding to the focus point of each Fresnel lens. Hundreds of lenses make up a solar array mounted on a sun tracking heliostat. With a high **"module efficiency" of 31%**, CPV systems take up less land than traditional PV systems, use no water, and are ideal for desert type areas. See the Amonix discussion.

Despite the concentration advantages, CPV has been slow to gain market share. While the tiny solar cells use less of the expensive semiconductor materials, cost was a factor as a two-axis sun tracking heliostat is necessary to accurately keep the focus point on the solar cell as the sun travels east to west each day and north and south each season. CPV does not do well in cloudy climates as diffuse sunlight does not concentrate well. In addition, the large heliostats were not well suited for the small installations that have been the mainstream of the recent PV market. Today, CPV costs are very competitive and CPV is benefiting from growing demand for large utility size solar plants, especially in the desert areas of California, Arizona, Spain, and Australia. Top

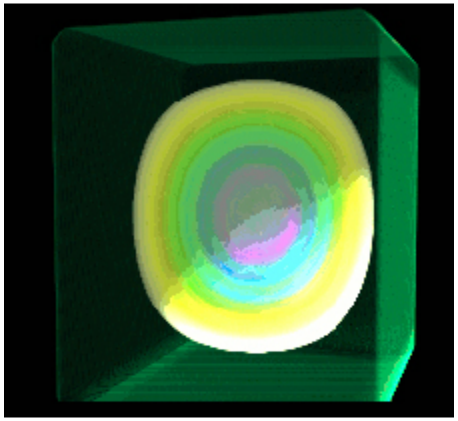
Strategy 4a) Combine a PV semiconductor with a heat based technology



The Stanford University Photon Enhanced Thermionic Emission (PETE) prototype uses concentrated sunlight as its source of energy and in a two step process uses both the sun's photon energy and its heat. A thermionic converter consists of two electrodes separated by a vacuum, see the figure to the left. When the cathode is heated to a high temperature, electrons become excited, jump across the thin vacuum to the relatively cold anode, and drive a current through an external circuit back to the cathode. In the Stanford prototype, the cathode emitter is a semiconductor material rather than a metal electrode. First, the highly concentrated sunlight photons partially excite the electrons in the cathode semiconductor so that in step two, the remaining heat energy necessary for emission is lower than that for a standard thermionic converter (see the thermionic/PETE discussion on the Solar In-depth page). The surface of the cathode on the vacuum side is texturized to increase emissions. PETE converts about 25% of the sunlight's energy into electricity.at 200°C and higher efficiencies at higher temperatures, i.e. 45% at 1000°C. Because of the high temperatures this type of solar system would probably only be used by utilities to generate grid electricity. A lot of work needs to be done to get from today's laboratory set up to a production product in the field. A competitive product is probably 8 to 10 years away. Top

Strategy 4b) Quantum Dots Absorb Some of the Excess Photon Energy

In a regular solar cell, each photon collision generates a particle pair consisting of one free hole and one free electron. **Quantum Dots** are extremely small **"nanocrystals"** (the names are used somewhat interchangeably) interspersed in a larger semiconducting material. Quantum Dots (QDs) range between **2 and 8 nanometers in size**. (A nanometer is one billionth of a meter.) Semiconductors at this size have different physical properties than their big brothers. When photons with energy greater than the band gap energy collide with a Quantum Dot several "hot" hole/electron pairs can be created as opposed to one pair and heat. Although silicon can be used as a nanocrystal, lead selenide, also a semiconductor, is being used more frequently as the material of choice. Another characteristic of a Quantum Dot is that different sizes capture different wavelengths of light. Small Dots capture small wavelengths and larger dots bigger wavelengths. Some researchers have figured out how to stack the dots from small to large to capture more photon energy similar to how tandem cells do (see strategy one/two above).



Once a hot electron is created inside a Quantum Dot, it stretches its lifetime as much as a 1000 times before it cools. The electrons like to stay inside the QD. One of the challenges was to figure out how to extract the hot electrons from the QDs. It turns out that titanium dioxide is a compound that very much likes to absorb electrons and can be arranged in the form of nanotubes to usher the electrons out. Shown at the left is an electron wave function (i.e. the probability of an electron being in any specific location at any given time - purple is low probability, white is high probability) in a Quantum Dot.

Today (Q4 2010) the practical upper limit for "thin film" solar cells is thought to be about 20%. The upper limit using Quantum Dots is thought to be about 30%. It should be emphasized that the research into Quantum Dots is at the very basic stage of establishing and demonstrating scientific principles. No one at this time has actually made a working prototype Quantum Dot solar cell. Production solar cells using Quantum Dots are thought to be 10 to 20 years into the future.

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