An Evaluation of Solar Photovoltaic Technologies

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Introduction:

Green thinking is the "in" topic these days. Companies are all claiming to be going green. There is a buzz about hybrid vehicles and alternative fuels such as cellulose, ethanol, and hydrogen. Although these alternative fuels will lessen our dependence on oil, they are by no means free. Hybrid vehicles still require an electricity source to charge batteries; cellulose, ethanol, and hydrogen all require significant processing and resultant cost before they can be utilized as energy sources. These alternative fuels and technologies seem to be getting the most media attention recently, but what about renewable energy? Renewable energy, any naturally occurring, theoretically inexhaustible source of energy that is not derived from fossil or nuclear fuel (www.dictionary.com), does not require any upfront refinement to become a viable energy source. These free and nearly limitless energy sources have largely gone untapped. An obvious example is sunlight. The energy in sunlight hitting the earth's surface is approximately 1,000 W/m^2 (apps1.eere.energy.gov/solar/cfm/faqs/), but only a tiny fraction of this energy is collected by using solar technology. This paper will summarize and assess the current solar PV technologies, compare them to other available renewable and non-renewable electricity sources, and discuss the future applications of PV.

Current Photovoltaic Solar Technologies:

Solar energy is harnessed using two approaches: thermal and photovoltaic (PV). Thermal harnessing is the process of absorbing the infrared or heat wavelengths of sunlight whereas PV cells absorb photons from of sunlight and emit electrons which are collected to create an electrical current. Currently, there are four types of commercially produced PV cells: monocrystalline silicon, polycrystalline silicon, thin films, and "group III-V" technologies. (www.masstech.org/cleanenergy/solar/paneltypes.htm) Each has their advantages and disadvantages.

Monocrystalline silicon is produced in large sheets and usually comprises an entire solar panel. Two advantages of monocrystalline silicon are its fairly high efficiency and the ability to be custom cut to a specific shape. Efficiency is the percentage of incident energy that is converted to electric current. (www.masstech.org/cleanenergy/solar/paneltypes.htm) However, it is more expensive to produce than polycrystalline silicon and the silicon itself is rigid and inflexible.

Polycrystalline silicon technology is a combination of silicon cells within a solar panel. Cells are created from slices of a cast block of silicon or from pulled ribbons of molten silicon. Conductive strips connect the silicon slices or ribbons to collect the resultant current. Although this technology is currently the cheapest manufacturing method of PV cells, there is a loss of efficiency relative to monocrystalline cells. (www.masstech.org/cleanenergy/solar/paneltypes.htm)

Thin film technology utilizes amorphous silicon, copper indium diselenide (CIS), or cadmium telluride (CdTe) as the semiconductor material. Since these semiconductors are not crystalline, they can be deposited onto flexible, custom shaped substrates. In addition, they have up to 40% greater absorbency than crystalline silicon so a much thinner layer (~1 micrometer) still absorbs close to 99% of incident light. These thin film cells are coated by highly electrically conductive oxides that serve as current collectors instead of metal strips used in crystalline cells. The greatest advantages of thin film cells are their ease of manufacture, their variability in shape, and their flexibility. Manufacturing a large cell is just a matter of up-scaling the process of manufacturing a small cell. (www1.eere.energy.gov/solar/tf_polycrystalline.html#copper)

Group III-V refers to semiconductor materials constructed from groups III and V on the periodic table. An example of such a semiconductor is gallium arsenide (GaAs). These PV cells are generally only created for aerospace applications due to their extremely high cost. (www.masstech.org/cleanenergy/solar/paneltypes.htm) But with their high cost comes high efficiency.

Comparison of PV Technologies:

Despite the differences in PV technologies described above, the following key parameters can be used to compare them: cost, efficiency, lifecycle, size, and substrate flexibility. Table 1 summarizes these parameters below. Reliable average cost figures for each specific technology could not be found so cost values are relative.

Parameter / PV Cell Technology	Cost	Efficiency (%)	Lifecycle (years)	Thickness (micrometers)	Substrate Flexibility
Group III-V	Extremely High	~25	~20	1-5	Rigid
Monocrystalline silicon	High	15-18	~20	100-300	Rigid
Polycrystalline Silicon	Low	12-14	~20	100-300	Rigid
Amorphous Silicon / Thin Film	Medium	5-6	~20	1-10	Flexible

Table 1: PV Parameter Comparison

(www1.eere.energy.gov/solar/tf_polycrystalline.html#copper, www.masstech.org/cleanenergy/solar/paneltypes.htm)

It is evident from Table 1 that the most obvious trade-off is cost versus efficiency. Group III-V is the clear leader in efficiency at 25%, but its cost is too high for large scale implementation. At the other extreme, thin film PV does not appear to be cost effective because of its relative low efficiency of 5-6%. However, there is another trade-off between thin film’s low efficiency versus its versatility in application, ease of manufacture, thinness, and substrate flexibility. When thin film manufacturing cost decreases and efficiency increases to levels close to polycrystalline silicon, it will most likely become the dominant technology of the four. Manufacturing costs for all PV technologies will decrease with time so the best criterion to assess PV technologies is their rate of efficiency increase over time. To approximate these rates of efficiency, it is necessary to look at historical PV efficiency data.

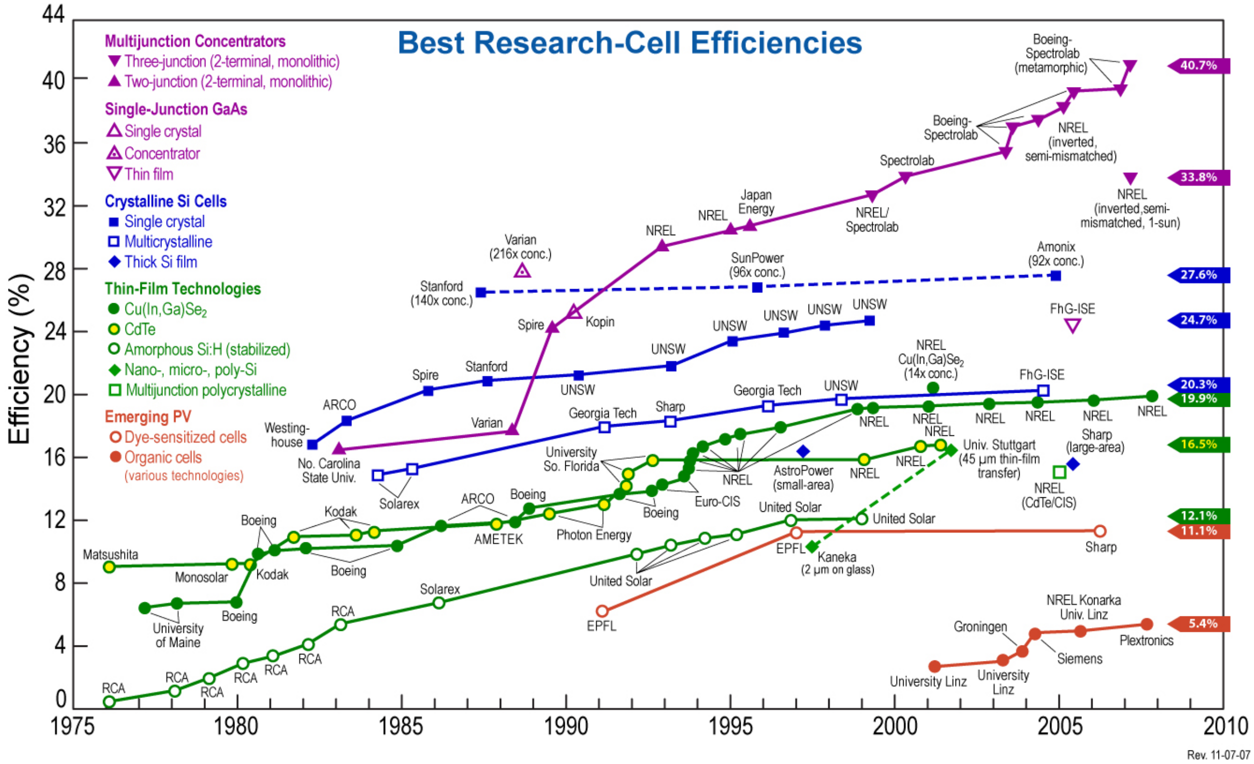


Figure 1: PV Research Efficiency over Time (Lawrence Kazmerski, Don Gwinner, Al Hicks, 11/11/07, NREL courtesy of US Department of Energy)

Above is a graph of efficiency trends of several PV technologies over the span of 32 years (1975 to 2007). Purple color-coded, single-Junction GaAs data represents Group III-V, blue color-coded data represents both mono and polycrystalline silicon, and green color-coded data represents thin film. One aspect to note is that the research efficiencies of all four technologies is much higher than their current respective manufactured efficiencies. This is most likely due to manufacturing processes' inability to exactly replicate the laboratory environment. Since manufacturers are concerned with producing high quantities of cells, they may not be able to reproduce the quality of one-of-kind cells that researchers can produce. Despite the discrepancy between research and manufactured efficiencies, three important points can be gleaned from Figure 1.

The first point is that the research data quantifies the performance envelope of efficiency for each specific PV technology. In other words, the research efficiencies are a measure of the maximum achievable efficiencies for a given material. For example, thin film may currently be manufactured with 5-6% efficiency, but it is capable of nearly 12-20% depending on the specific material.

The second point is that the efficiency increases per year can be approximated for each of the four technologies shown in Figure 1. The following approximation was used to calculate the efficiency slope of the PV technologies:

Efficiency Slope = (Maximum Efficiency – Minimum Efficiency) / Development Years

The results are recorded in the third data column in Table 2. Please note that the values are approximate since the calculation method assumed a linear fit, but it still represents a fairly accurate measure of efficiency slope.

Research Data / PV Cell Technology	Total Efficiency Increase (%)	Development Time (yrs)	Approximate Slope (% efficiency / yr)	Maximum Efficiency (%)	Year of Last Data Point
Group III-V (Single-Junction GaAs)	N/A (too little data)	N/A (too little	N/A (too little data)	25.0	1990
Crystalline Silicon					
Monocrystalline	11	23	0.48	27.6	2004
Polycrystalline	5	21	0.24	20.3	2005
Thin Film					
CIS	14	30	0.47	19.9	2008
CdTe	8	25	0.30	16.5	2002
Amorphous Silicon	12	23	0.52	12.1	1999
Multijunction Concentrators	25	24	1.04	40.7	2008

Table 2: Efficiency Slope Approximations from Figure 1

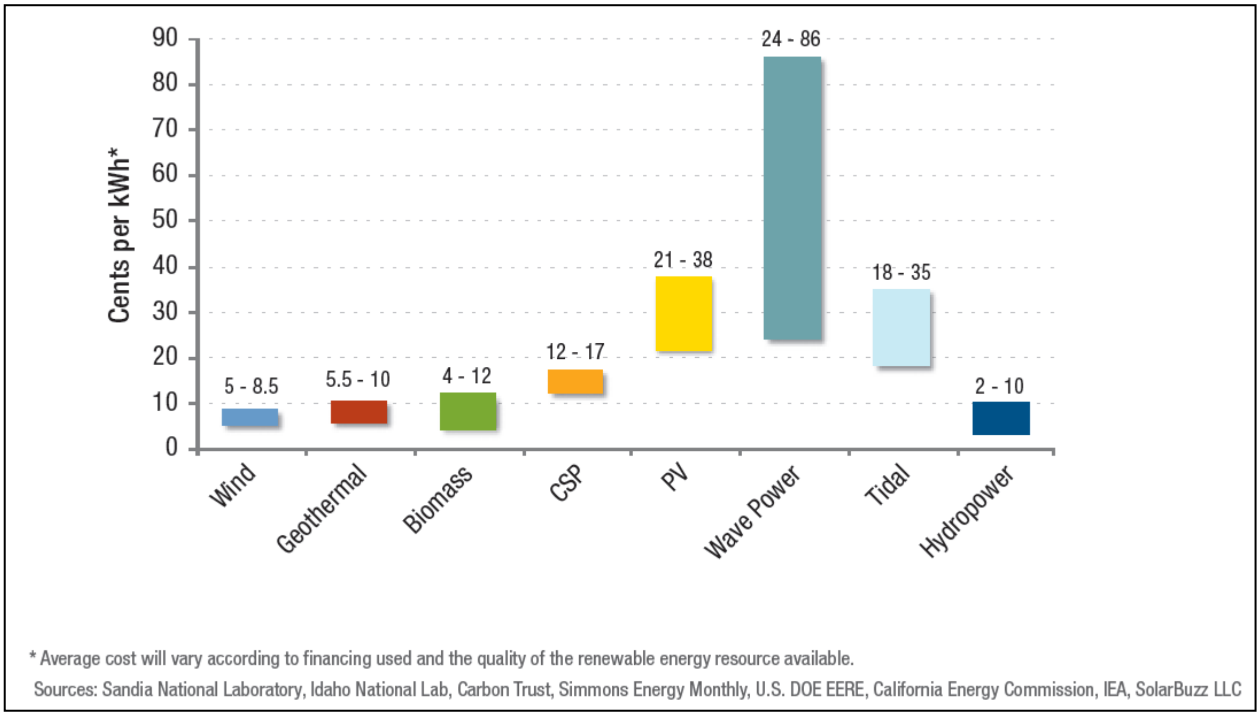
Overall, the maximum efficiency slopes between crystalline silicon and thin film are similar at ~0.5% efficiency increase per year. Multijunction concentrators are the clear winners with the greatest rate of efficiency increase of any PV technology. The rate is about 1% increase a year with a maximum efficiency of over 40%. However, multijunction concentrators are strictly in the research and development stage and have not been commercially manufactured to date. (http://www.masstech.org/cleanenergy/solar/paneltypes.htm) This leaves the competition between crystalline silicon and thin film technologies.

The third point gleaned from Figure 1 is identification of which PV technologies researchers are currently developing. This helps further determine the "winner" between crystalline silicon and thin film. From the furthest right column of Table 2, it appears the PV research community is currently focusing on CIS thin film and multijunction concentrator technology. The last significant efficiency increase for crystalline silicon was in 2005 and no further advancement has occurred since then. This implies that crystalline silicon may have reached its natural technological limit in 2005 influencing researchers to focus mainly on thin films and multijunction concentrators. These two technologies have resulted in consistently greater achievable efficiencies in recent years.

From the combined data of Table 1, Figure 1, and Table 2, CIS thin film and multijunction concentrator technology appear to be the future of PV technology. Because CIS has the longest history of continued efficiency advancement and has the most versatile applications, it will be most likely dominate the near term future of PV technology. Multijunction concentrators, on the other hand, will most likely dominate once they become cost effective enough to manufacture because of their high efficiencies.

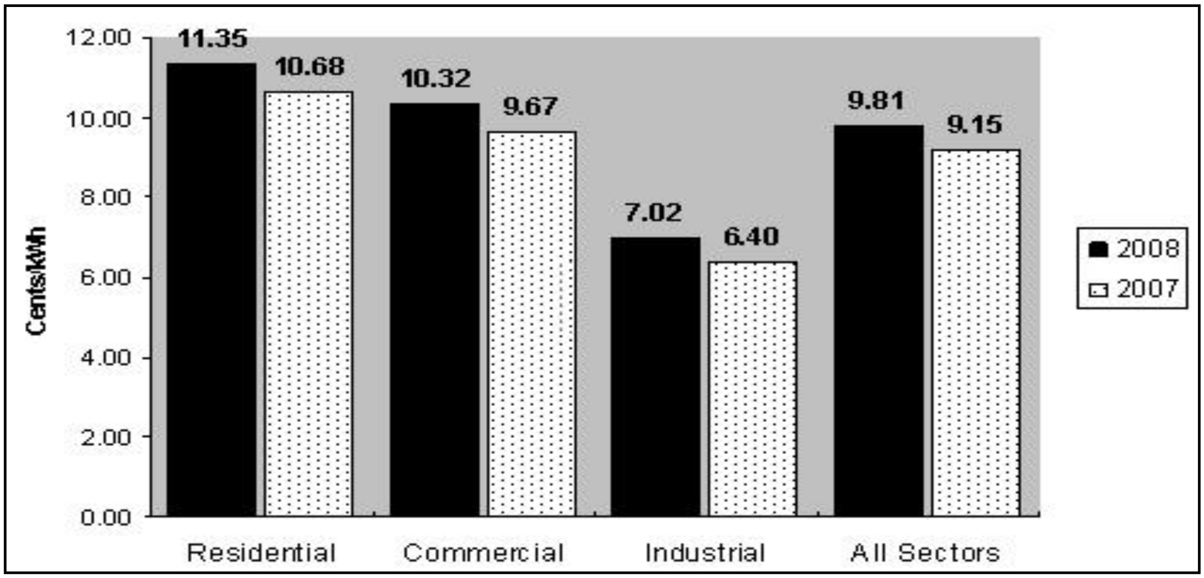
PV Technologies versus Other Electricity Sources:

It is difficult to evaluate multiple sources of electrical energy because of the inherent differences in their technologies, but there is one common parameter that can be used. This parameter is cost. The cost in cents per kWh of renewable energy produced in the United States is shown in Figure 2. When cost is analyzed, it is clear why PV electricity is the least prevalent renewable source of electricity in the US. (*Renewable Energy Data Book - Energy Efficiency& Renewable Energy* by the US Department of Energy, September 12, 2008, page 7) PV is the second most expensive at 21–38 cents per kWh. Concentrated Solar Power (CSP), which harnesses thermal solar energy, is considerably cheaper at 12–17 cents per kWh, but even the cost of CSP is still considerably higher than wind, geothermal, biomass, and hydropower. Currently, PV solar power is simply too expensive to be implemented on a scale large enough to compete with other renewable, fossil fuel, or nuclear generated electricity.

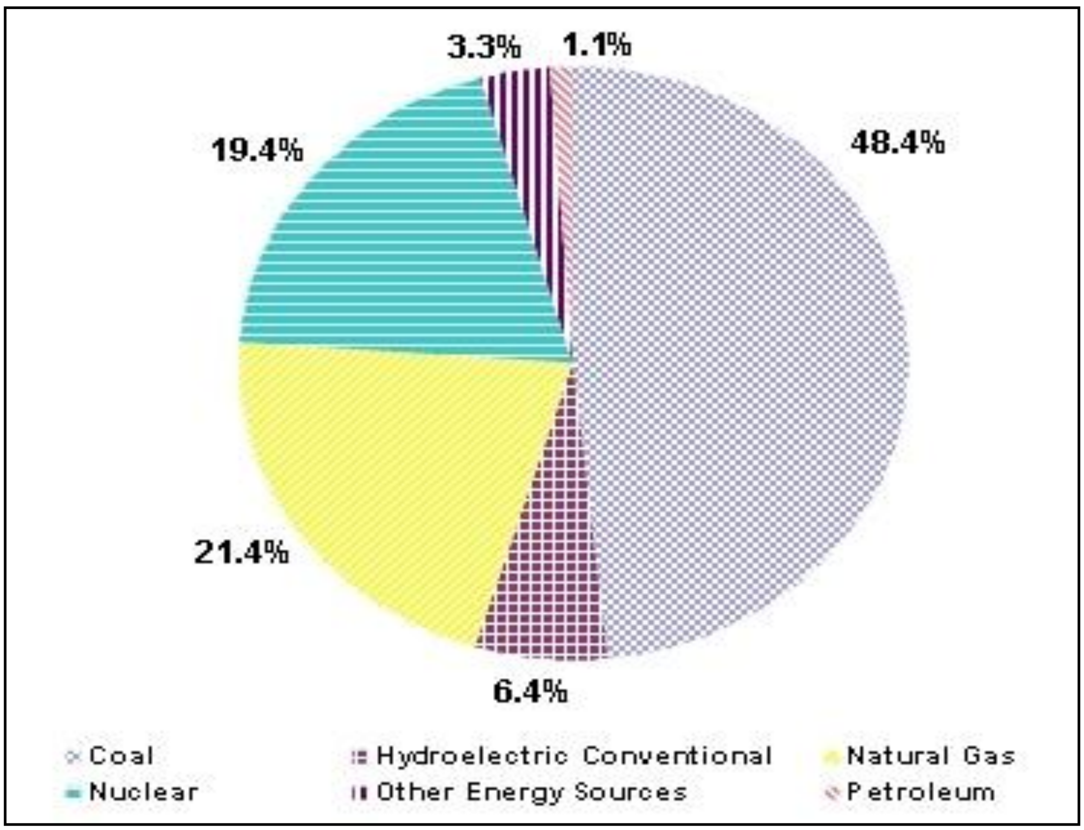


<u>Figure 2: Cents per kWh for Renewable Energy Sources in the US in 2007</u> (*Renewable Energy Data Book - Energy Efficiency& Renewable Energy* by the US Department of Energy, September 12, 2008, page 13)

However, Figure 3 shows that the average price of electricity in the US in 2008 was 9.81 cents/kWh for all sectors and 11.35 cents per kWh for the residential sector. Since 90% of the electrical production source was coal, petroleum, natural gas, or nuclear, (shown in Figure 4) these average costs of electricity is an approximate cost of all non-renewable sources.



<u>Figure 3: Average Price of Electricity in the US in 2007 and 2008</u> (*Electric Power Monthly* by the Energy Information Administration, February 13, 2009)



<u>Figure 4: US Electrical Production by Source in 2008</u> (*Electric Power Monthly* by the Energy Information Administration, February 13, 2009)

The cost of PV electricity is still over double the current price of non-renewable electricity, but as advancements in manufacturing and efficiency are made, PV electricity will become competitive with other renewable and non-renewable electricity.

The Future of PV Technology:

PV technology has had a compounded growth rate of 29.5% in the US from 2000 to 2007 and 31.5% globally from 2000 to 2006. (*Renewable Energy Data Book - Energy Efficiency& Renewable Energy* by the US Department of Energy, September 12, 2008, pages 25 and 49) As solar technology becomes more efficient and less costly, there will be a dramatic global increase in solar electricity production by utility companies, commercial companies, and individual consumers. Unlike other renewable energy sources, PV technology is accessible to anyone who desires to reduce their electricity costs and it will work in any environment that receives sunlight. Because PV thin film technology is so versatile, there will be a myriad of products and systems for the individual consumer in the near future. Thin films are already being produced as housing shingles and other building materials. (http://www1.eere.energy.gov/solar/want_pv.html) Massachusetts startup Konarka has even successfully used inkjet printing to generate PV cells. (*Startup Makes Cheap Solar Film Cells ... With an Inkjet Printer*, By Emily Masamitsu, Popular Mechanics, March 6, 2008) The possibility of solar ink and printable PV cells would add a whole new dimension of applications. The future is bright for PV technology.

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