Photovoltaic Cell Efficiency at Elevated Temperatures

by

Katherine Leung Ray

Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements
for the Degree of

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Abstract

In order to determine what type of photovoltaic solar cell could best be used in a thermoelectric photovoltaic hybrid power generator, we tested the change in efficiency due to higher temperatures of three types of solar cells: a polymer cell, an amorphous silicon cell and a CIS cell. Using an AM1.5 G solar simulator at 973 W/m^2 we took the I-V curve of each of the three cells at increasing temperatures. We used the I-V curve to find the maximum power and determine the efficiency of each cell with respect to temperature. We found that the CIS cell had an efficiency of 10% and the performance decreased with respect to temperature in a non-linear manner. The efficiency at 83°C was a peak and the same efficiency as at 40°C. We found that the amorphous silicon cell tested had an efficiency of 4% at 45°C that decreased with respect to temperature in a linear manner such that an 80°C increase in temperature resulted in an efficiency of 3%. We further found that the polymer cell efficiency decreased from 1.1% to 1% with a 60°C increase in temperature, but that the polymer cell is destroyed at temperatures higher than 100°C. We determined that CIS or amorphous silicon could be suitable materials for the photovoltaic portion of the hybrid system.

Thesis Supervisor: Gang Chen
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Acknowledgements

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Introduction

In the past decade concern about the effect of excessive amounts of greenhouse gases in the atmosphere has been rising. Carbon dioxide and methane are two main greenhouse gases, and carbon dioxide is produced whenever gasoline, coal, oil or methane is burned to produce electricity or power transportation. Thus, work has been done to reduce the amount of carbon dioxide going into the atmosphere. Some of the options for reducing the output of carbon dioxide include wind power, geothermal power, fuel cells, carbon sequestration and solar power. Several methods of utilizing solar power have been found. One is solar panels, wherein light strikes a surface, excites an electron, and electricity is produced. Another is thermal power, where the light from the sun is concentrated in one spot and heats water which is then used in a steam turbine. Another possibility involves the Seebeck effect, which results in electricity generation due to a large difference in temperature over a short distance.

Solar power comes to Earth in the form of light, or radiation. Given what we know about the Sun, we can calculate an amount of power hitting the Earth per square meter. The power that comes to the Earth from the Sun, if it can be completely gathered, provides more than enough power for everything humans do now and reasonable growth expectations. Currently there are methods of harvesting solar power into electricity that have an efficiency of 25% at best, but a more efficient power collection mechanism could do quite a bit.

Let's first talk about photovoltaic cells. Most cells are made of silicon, mainly because it works, it is plentiful, and the computer industry also uses it, which means that methods of producing and working with silicon wafers are well understood. Crystalline silicon has a bandgap of 1.1 eV. This means that if a photon of light comes in with an energy of less than 1.1 eV, it fails to create an electron and hole pair across the bandgap, and if it has an energy of more than 1.1 eV it does excite an electron and hole pair, but any extra energy is lost because the electron and hole settle at 1.1 eV quickly. A photon's energy relates to its wavelength by

$$E = \frac{hc}{\lambda}$$

where E is energy, h is Planck's constant, c is the speed of light and λ is the wavelength. Thus photovoltaic cells do not use any of the energy from electromagnetic radiation with longer wavelengths than 1120 nm (which corresponds to 1.1 eV). See Fig. 1. 1120 nm is infrared light. Lower wavelengths of light tend to manifest as heat when it hits an object. Consider that infrared goggles will show warm objects, and microwaves can heat food. Thus, combining a photovoltaic cell and a mechanism to collect the thermal energy could greatly improve the energy collection efficiency of the machine.

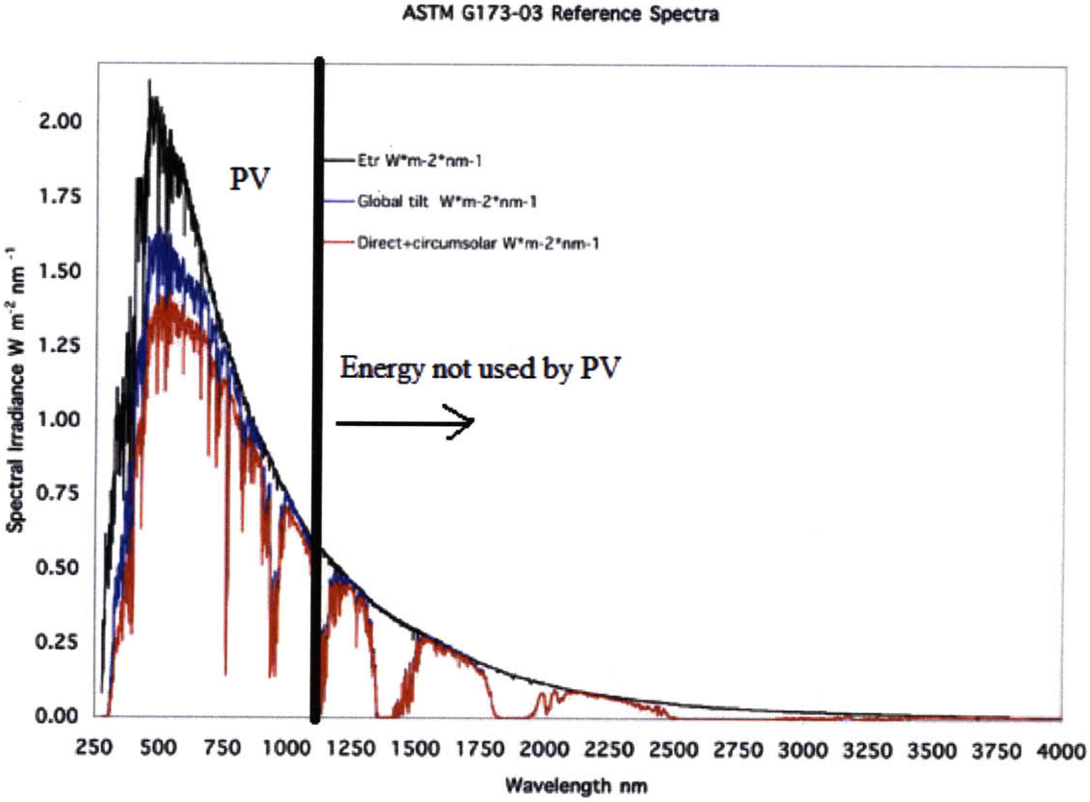

Figure 1: The solar spectrum. 1120 nm is marked. All longer wavelengths of light cannot be used by standard silicon solar cells. The shorter wavelengths create electron-hole pairs of high energy that relax to the bandgap energy. The difference is lost as heat.

The Nanoengineering Group at MIT has been working on a design of a machine that will combine photovoltaic and thermal solar power. The thermal power in this case will be collected using a thermoelectric device that creates a current from a temperature gradient. There needs to be a temperature difference of at least 50ºC for the thermoelectric device to work efficiently, which means one side will be 25ºC and the other 75ºC, for example. Higher temperature differences tend to be better. A difference of 25ºC to 150ºC would be excellent. However, this means that the photovoltaic cell might be very, very hot. There is not a lot of research into solar cell performance at high temperatures. This paper investigates how different types of solar cells behave at higher temperatures.

Background

Available Solar Energy

The Sun radiates energy based on its temperature (about 5700 K). The amount of power that hits the Earth's upper atmosphere is 1366 W/m^2 (NREL). By the time it penetrates the atmosphere, the power is down to approximately 1000 W/m^2. The Earth has 1.49 x 10^8 km^2 of land (Pidwirny 2006), which means that collecting solar power from all the available land mass gives about 1.4 x 10^5 TW of power, although since weather plays a large part, 3.6 x 10^4 TW may be more realistic (Buonassisi 2009, 3). World power consumption in 2004 was 14 TW (IEA 2006, 6) which is much smaller than 36,000 TW. If there were a 100% efficient solar power collection system, 1/1000th of the Earth's dry surface would provide more than enough power. As it is, with photovoltaic cells averaging 15% efficiency, the U.S. could be powered with 130,000 km^2, or about 50% of Nevada (Buonassisi 2009, 82).

Types of Photovoltaic Solar Cells

Photovoltaic solar cells work by absorbing light, creating electron-hole pairs, separating charges and running them through an external load. The main types of solar cells in use today are crystalline silicon, both single and multi-crystalline, and what are known as thin film solar cells, which include amorphous silicon, cadmium telluride, copper indium gallium diselenide (CIGS), and copper indium diselenide (CIS). There has also been work on organic photovoltaic cells and dye-sensitized cells. The best record efficiencies of the various types of cells is shown in Fig. 2.

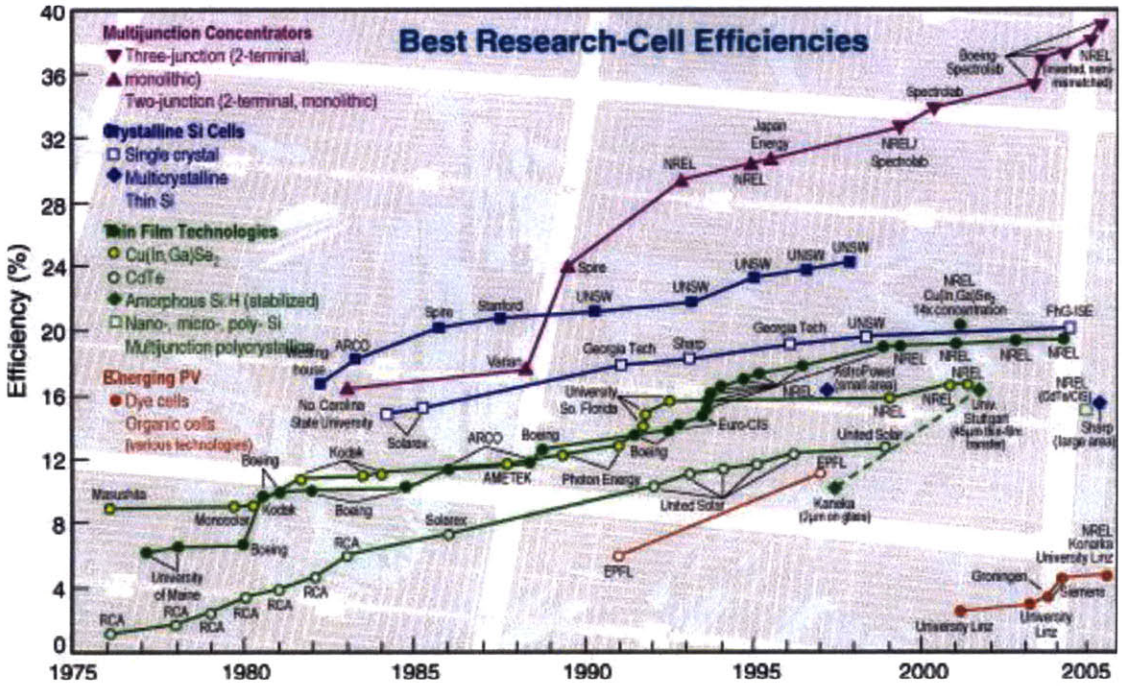

Figure 2: Best recorded efficiency under "standard" conditions, 1000 W/m^2, 25°C. Note that simply putting the cell in the sun generally results in temperatures of about 40°C (from Kazmerski 2006, 106)

Measuring Efficiency of Photovoltaic Cells

Efficiency is the ratio of the amount of energy or power output by a device to the amount of energy or power received. For photovoltaic cells, this is the amount of electric power out (voltage multiplied by current) divided by the amount of power of the incoming sunlight (the standard 1000 W/m^2). The most straight forward way to measure the efficiency of a solar cell is to put it in 1000 W/m^2 light, measure the I-V (current-voltage) curve and find the maximum power point. That power divided by 1000 W/m^2 multiplied by the area of the cell gives the efficiency of the cell. Since sunlight that reaches the ground is different in Alaska than in Singapore (there is more atmosphere to travel through), different in summer than winter, and different on cloudy days than cloudless days, photovoltaic research has come up with a standard against which to test all cells. The standard we used is called AM1.5 G because it is sunlight after going through about 1.5 atmosphere thicknesses with global, G, collection of light. Another standard is the AM1.5 D, (the D is for direct), that is used when the cell tracks the sun. The standard is maintained by having a reference cell measured at a central location and used to compare against the new cell being tested (Green 1986, 99-100). In this case, we used the straight forward method of measuring efficiency by measuring the I-V curve.

When describing I-V curves, three numbers are commonly used: the open-circuit voltage (V_{oc}), the short-circuit current (I_{sc}), and the fill factor (FF). The open-circuit voltage is where the curve crosses the voltage axis and the short-circuit current is where the curve crosses the current axis. The fill factor is defined as

$$FF = \frac{I_{mp} V_{mp}}{I_{sc} V_{oc}}$$

where I_{mp} and V_{mp} are the current and voltage at maximum power and FF, V_{oc}, and I_{sc} are as given above. The closer the fill factor is to 1 the better the solar cell is. Commercial solar modules sold by the company Evergreen Solar have a fill factor of 0.75 (Evergreen Solar).

Thermal Solar

A typical large scale power plant runs on a steam cycle. The fuel is used to boil the water and heat the steam which then runs through a turbine to generate the electricity. Newer power plants might use what is known as a combined cycle, which uses high temperature gas through one turbine and the exhaust gas is used to heat up the steam which then runs through another turbine. Some large scale power plants use solar power, not from photovoltaics, which is expensive, but using mirrors to focus the sunlight onto a fluid in order to heat the fluid. The fluid is then used to provide heat for the standard steam cycle.

There is another way to use heat to get electricity, without stopping at mechanical energy first. It is known as a thermoelectric effect. If there is a temperature gradient between two different conductors or semiconductors connected in a loop then a voltage is created by the different response to temperature of the two materials. This is known as the Seebeck effect. Using this effect, one can create a device that, given a current will create a hot side and a cold side, or, given a temperature difference, will create electricity. The greater the temperature difference, the more electricity obtainable.

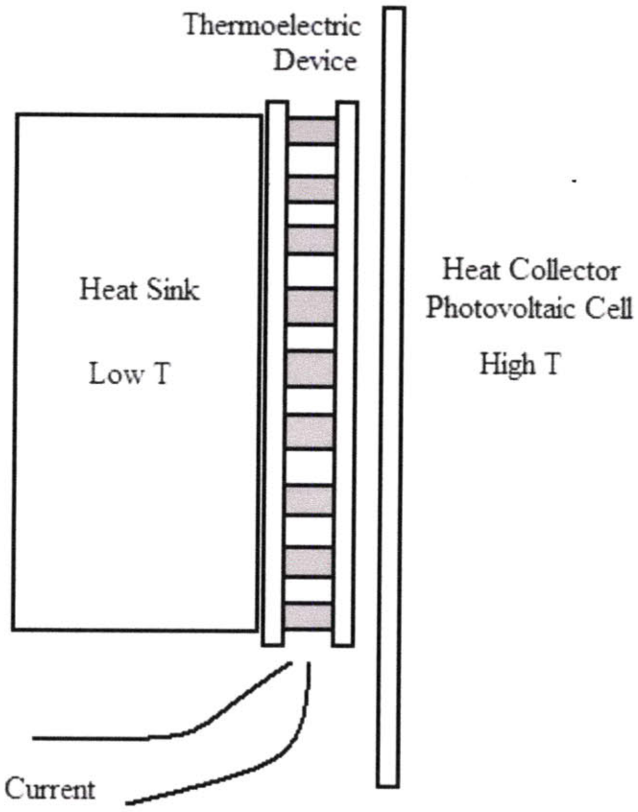

Figure 3: A thermoelectric device situated between a hot side and a cold side produces a current. The temperatures may vary. A larger ΔT is ideal. The heat collector may or may not be a photovoltaic cell.

Thermoelectric devices are evaluated using something called the figure of merit, or ZT. ZT is defined as

$$ZT = \frac{\sigma S^2 T}{k}$$

where σ is the electrical conductivity, S is the Seebeck coefficient, T is the average temperature, and k is the thermal conductivity. In order for a thermoelectric device to be comparable to the standard steam cycles used in power plants, ZT needs to be 3 to 4. Most thermoelectric devices from 1950 to 2000 only achieved a ZT of 1 or less. At the turn of the century, due to engineering at the nanoscale level, some devices achieved a ZT of 2.5, and could conceivably do better (Majumdar 2004, 777). This is the reason that only now thermoelectric devices are being considered for power generation.

One possible set-up for thermoelectric power is to have a photovoltaic cell collect heat for the hot side of the thermoelectric device, and have the ambient temperature be the cold side, as shown in Fig. 3. In this hybrid system, the sunlight is transformed into electricity by both the photovoltaic cell and the thermoelectric device. The photovoltaic portion takes care of the higher wavelength radiation (visible light) and the thermoelectric portion takes care of the lower wavelength radiation (infrared, microwave, "heat") as well as excess energy above the bandgap. The photovoltaic portion would operate at a much higher temperature than has been done before, and thus, we are interested in how much the efficiency degrades as a function of temperature. If the performance degrades too much, it may not be worthwhile to pursue the hybrid concept.

Previous Research

There have been a number of studies into the way that silicon solar cells react at different temperatures. There is one study on the way CIS cells perform at different temperatures. Meneses-Rodríguez et al. (2005) compares one CIS cell to several types of silicon cells over the range of 25°C to 80°C. One of the silicon cells is an amorphous silicon cell tested from 25°C to 80°C. Carlson et al. (2000) examined amorphous silicon cells from 20°C to 100°C and Carlson (1977) has information about amorphous silicon performance from 100 K to 300 K, -173°C to 23°C that includes open circuit voltage and short circuit current, but not fill factor, maximum power or efficiency.

Experimental Set-Up

The objective of this project is to determine whether any of several types of photovoltaic cells are candidates for the hybrid thermoelectric photovoltaic system. Our method of doing so is to measure the efficiency of the various cells at elevated temperatures by measuring their I-V curves.

For these experiments, we used a xenon lamp with an AM1.5 G filter for our solar simulator. The light was not collimated, so there was a spread of intensities. The sample was positioned 3 feet from the exit of the lamp, and the power of the lamp was set at 1600 W. This resulted in a incident power of 973±57 W/m^2. The error is due to the non-uniformity of the light over an area.

We tested three cells. The first was a polymer cell from Konarka. The second was an amorphous silicon cell from Fuji Electronics. The third was a CIS cell. The polymer cell and the amorphous silicon cell were attached to hot plates with a piece of copper in between to spread the heat evenly across the entire plate. Omegabond 300 High Temperature Cement worked well to attach the piece of copper to the hot plate – there was decent thermal contact – however it fell apart a few days after testing, which is either good because it means the hotplate was undamaged or bad because we wanted something firmer. The cement failed to hold the copper to the plastic coating of the amorphous silicon cell. We instead used gasket maker and thermal paste. Since the hot plate only heats and has no cooling functions, the lowest temperature available for these two plates was about 45°C. The CIS cell was attached to a Peltier device, which can either heat or cool depending on the voltage given to it. It was attached with high temperature gasket maker and put Dow Corning 340 silicone heat sink compound in between the cell and the device to ensure good thermal contact.

A K-type thermocouple kept track of the cell temperature. One thermocouple was between the heating element and the cell; another was taped to the front of the cell. We used a Keithley 2430 1 kW Pulse mode SourceMeter to run a particular current through the circuit containing the solar cell and an Agilent 34401A 6 ½ Digit Multimeter to measure the voltage across the cell while that particular current was active. This allowed us to trace an I-V curve for each cell at each temperature. Figure 4 shows a diagram of the set-up.

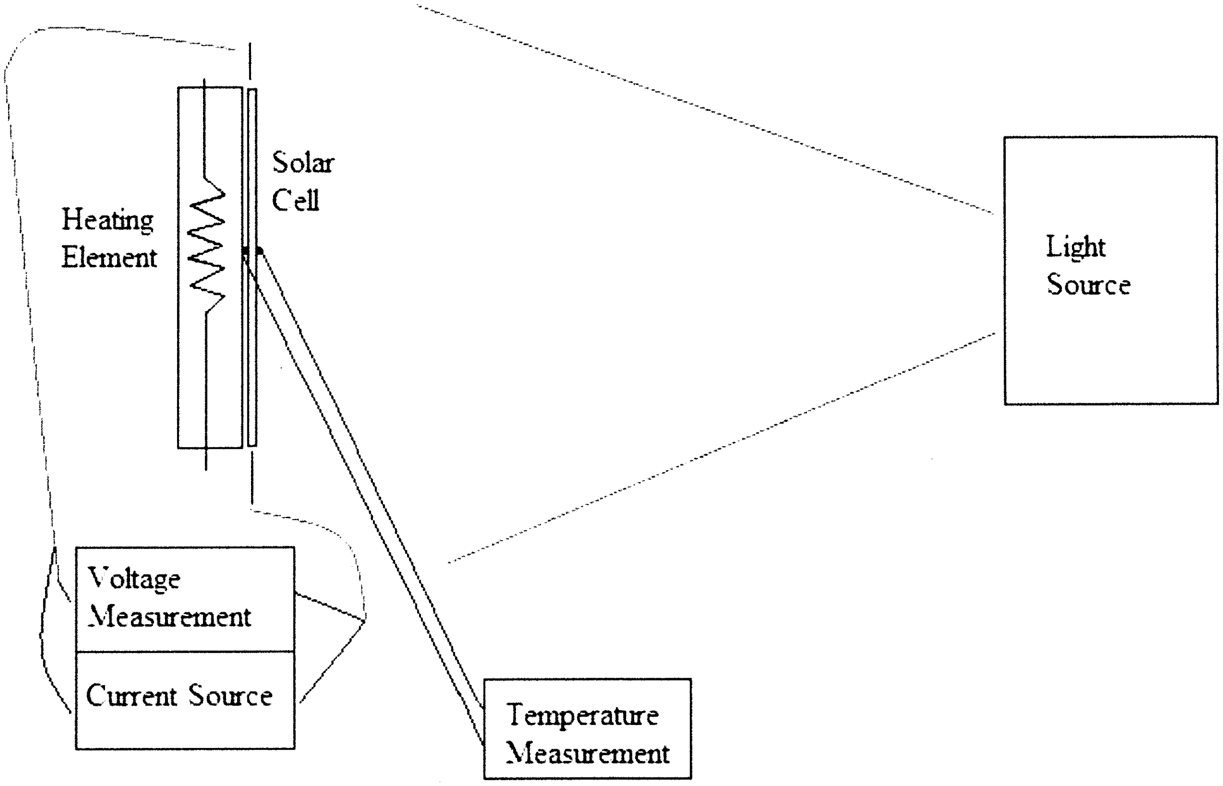

Figure 4: Diagram of the set-up.

Results

A proper characterization of the cells would include the open-circuit voltage, short-circuit current and fill factor. Unfortunately the short-circuit current was not easily measured and cannot be presented here. We only obtained the open-circuit voltage and the maximum power.

Polymer Cell

The polymer cell performance did not change much with temperature, but suffered a total breakdown at temperatures above 102°C. After operating at this very high temperature, the maximum power out of the cell decreased by an order of magnitude. I gathered four sets of data before the cell degraded; however there is another sample that may be used for further testing in the future.

Figure 5 is the I-V curves for the cell from 47°C to 102°C with the measurements from when the cell broke down at 109°C. The short-circuit current is between 80 and 90 mA, which means the fill factor is between 0.53 and 0.57, but cannot be determined with greater accuracy.

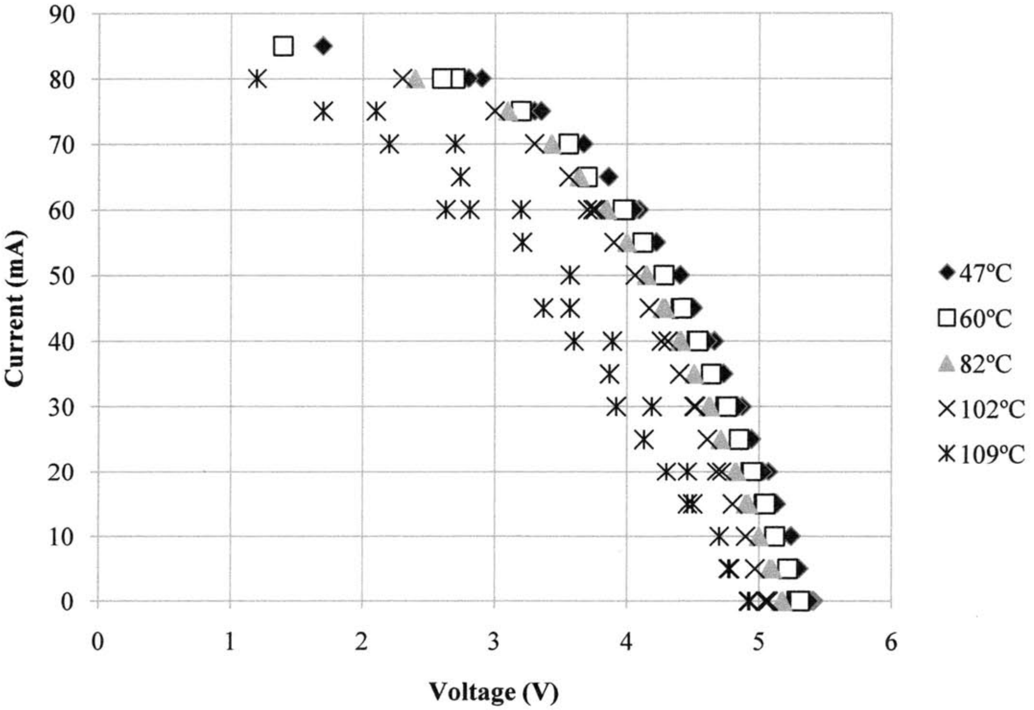

Figure 5: The I-V curve for the polymer cell at 47, 60, 82, 102, and 109°C. Note that the cell begins to break down at 109°C.

Figure 6 shows the maximum power at the four temperatures determined by fitting a polynomial to the I-V curve and finding the maximum power.

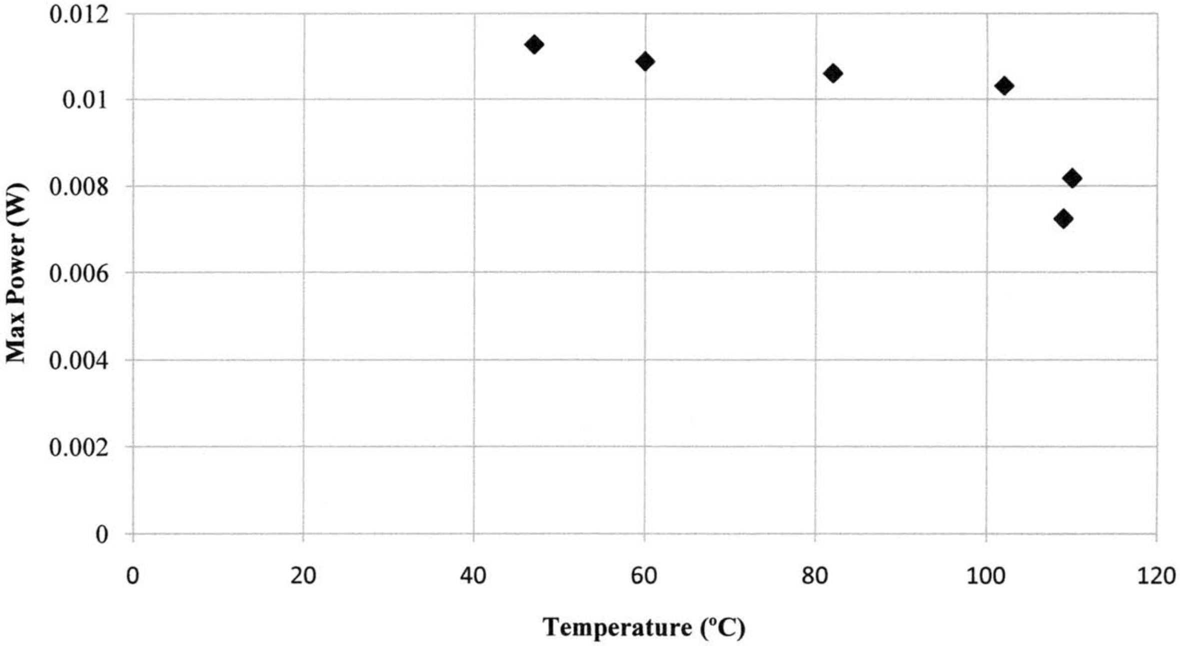

Figure 6: Graph of the maximum power vs. temperature for the polymer cell.

Figure 7 is the I-V curve of the degraded polymer cell. The short-circuit current is 10 times less than before, and the behavior differs based on whether one moves from 2 mA to 3 mA or 3 mA to 2 mA. It is interesting that there is a hysteresis effect, but as this is the degraded behavior it does not pertain to the investigation at hand.

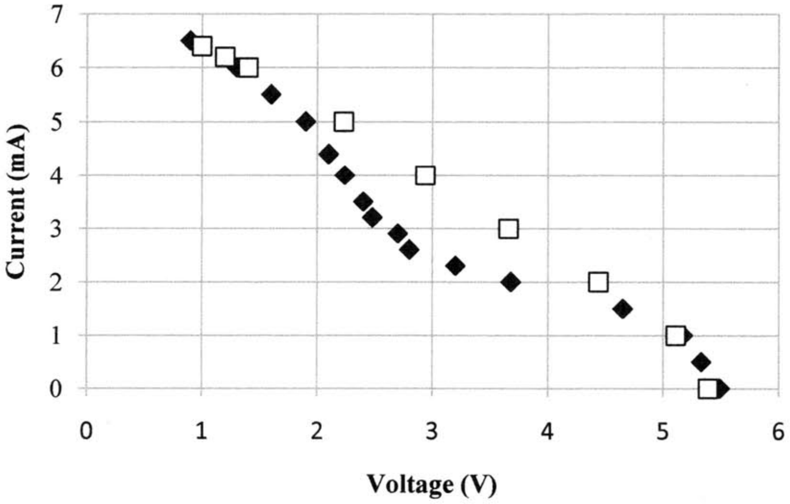

Figure 7: This is a graph of the I-V curve of the polymer cell at 65°C after it operated at high temperature. The curve changed based on whether the current was increased or decreased. The maximum power was also 10 times less.

Amorphous Silicon Cell

There are 19 I-V curves for the amorphous silicon cell taken on three separate days ranging from 45°C to 122°C. On the first day of testing, the cell had a higher short-circuit current and a correspondingly higher maximum power than on the next two days of testing, as can be seen in Fig. 8. The short circuit current is on the order of 120 mA, which results in a fill factor between 0.56 and 0.64.

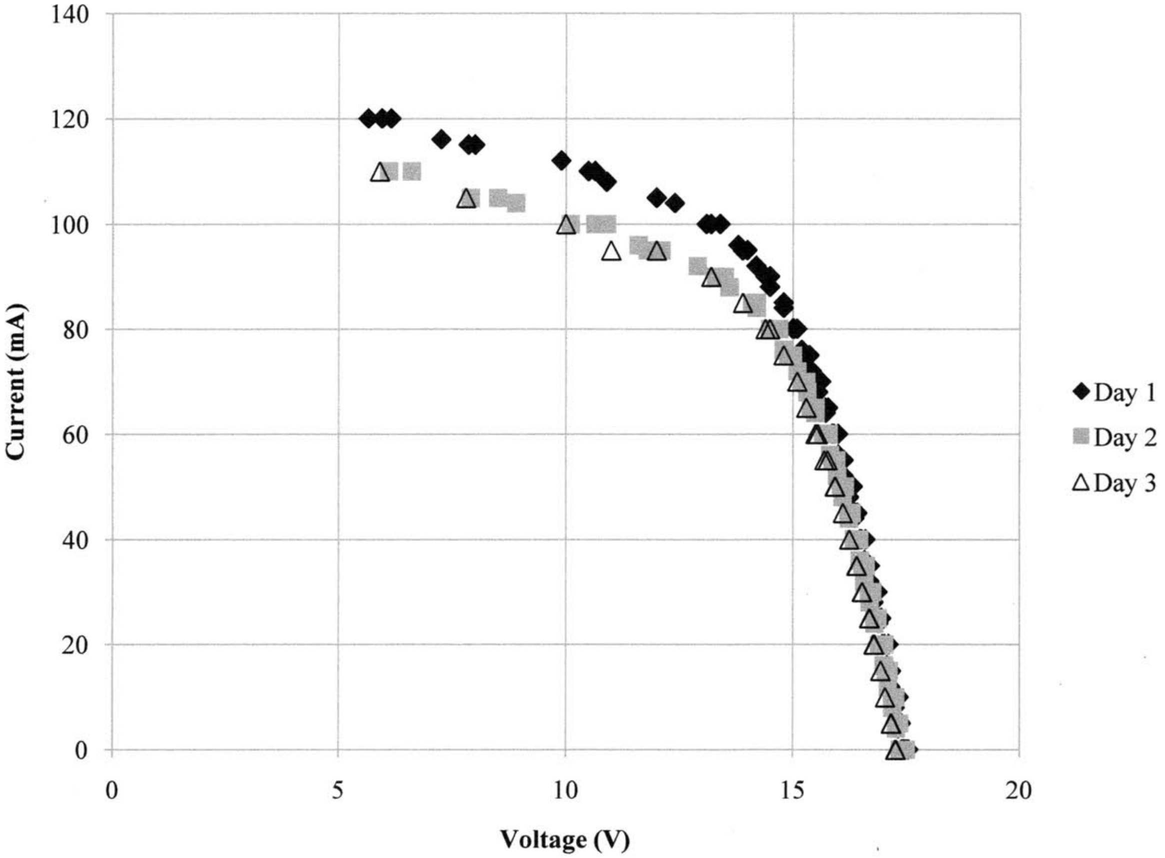

Figure 8: I-V curve at 44°C for the three days of testing. Day 1 the cell went to higher currents for the same voltage.

The maximum power of the cell is linear with respect to temperature, ignoring the higher power on the first day of testing (see Fig. 9). Amorphous silicon solar cells are well known for being more efficient the first time they are exposed to light than the second time, so the data from the second and third day of testing are more to be trusted.

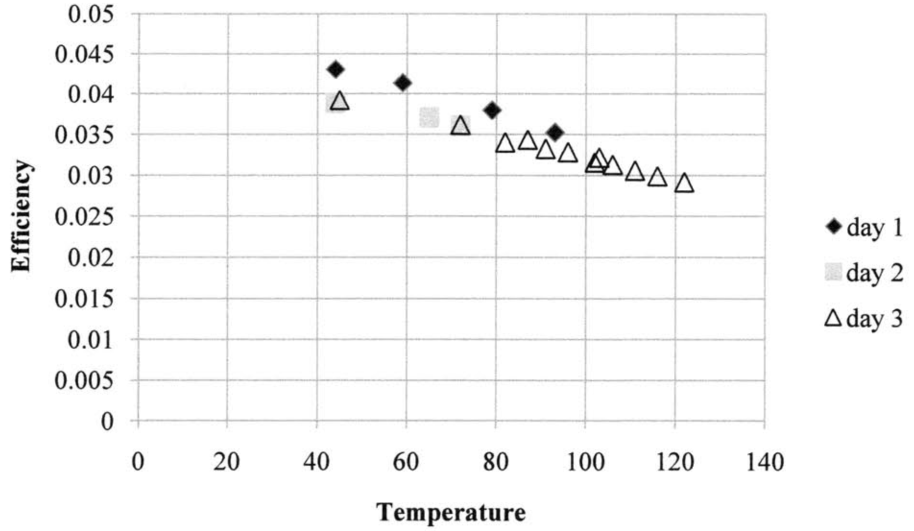

Figure 9: Maximum power vs. temperature for the amorphous silicon cell. The cell behaved differently between successive testings.

CIS Cell

The CIS cell had 24 I-V curves taken on three separate days ranging from 7°C to 104°C. The short circuit current is somewhere around 68-70 mA, which gives a fill factor of 0.29 to 0.34 at lower temperatures (7-60°C) and 0.37 to 0.41 at higher temperatures (80-104°C).

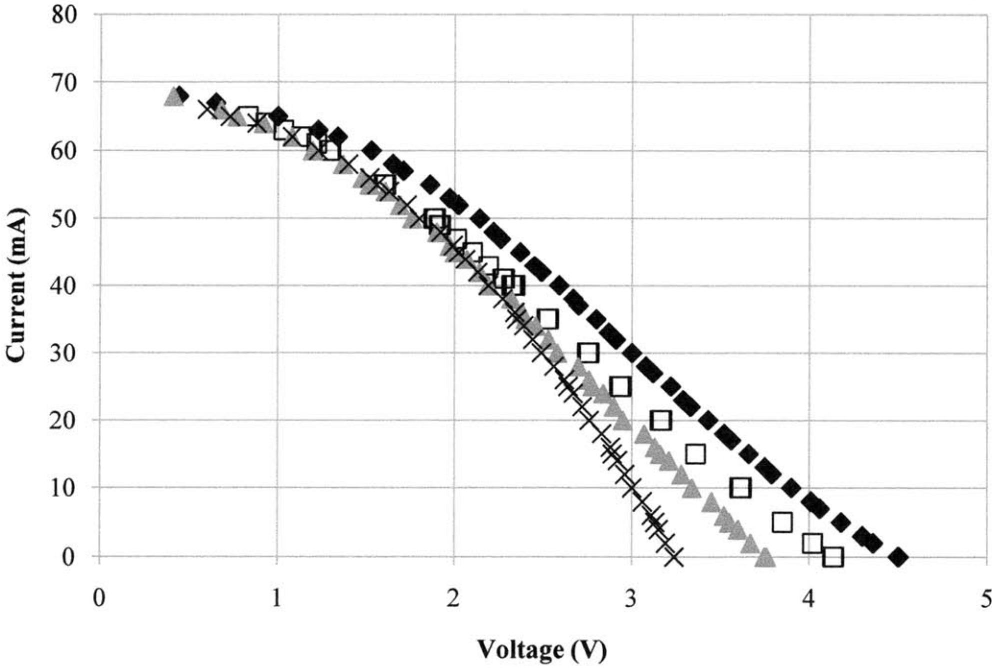

Figure 10: I-V curves for the CIS cell.

The maximum power of the CIS cell with respect to temperature does not fit a straight line (see Fig. 11). The power on the first day was worse than the power on the two later days. There was a slight bump at 83°C. This may have to do with the improvement in fill factor even though the open-circuit voltage is decreasing. Further study may be warranted.

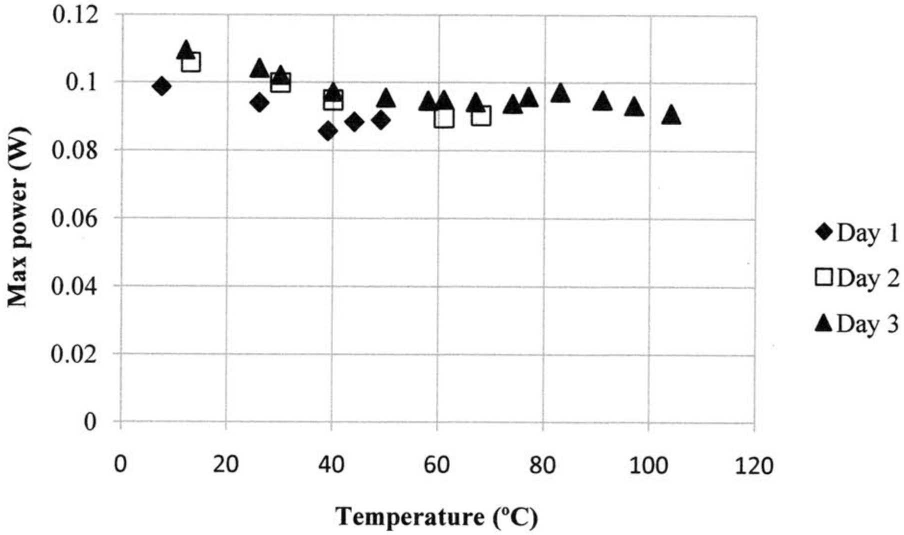

Figure 11: Maximum power for the CIS cell.

All Three Cells

Each solar cell was a different size, so when we want to compare the cells, it is necessary to use efficiency. Figure 12 shows the efficiency based on an input power of 973 W/m^2. The CIS cell is the most efficient of the three. The amorphous silicon cell is next best and the polymer cell has the lowest efficiency. The polymer cell performance has the least amount of temperature dependence. The amorphous silicon cell output vs. temperature behaves in a predictable and linear manner. The CIS cell behaves in a non-linear manner.

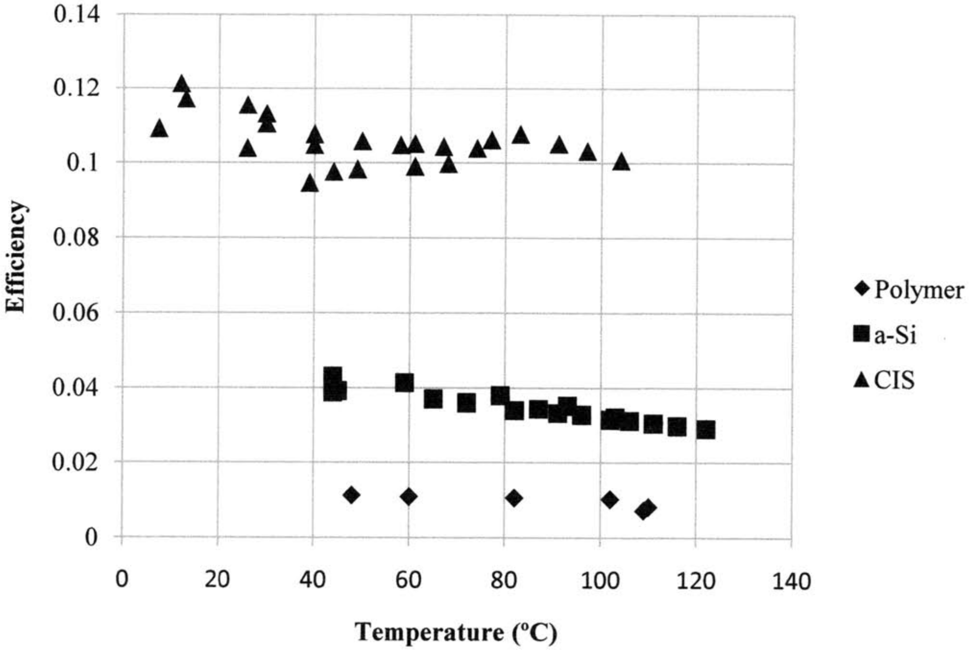

Figure 12: Efficiency comparisons of the three cells.

Figure 13 shows the I-V curves at 45°C and 82°C for the three cells. The CIS cell's I-V curve changes shape, the polymer cell's I-V curve shifts to the left, and the amorphous silicon cell's' I-V curve changes the most.

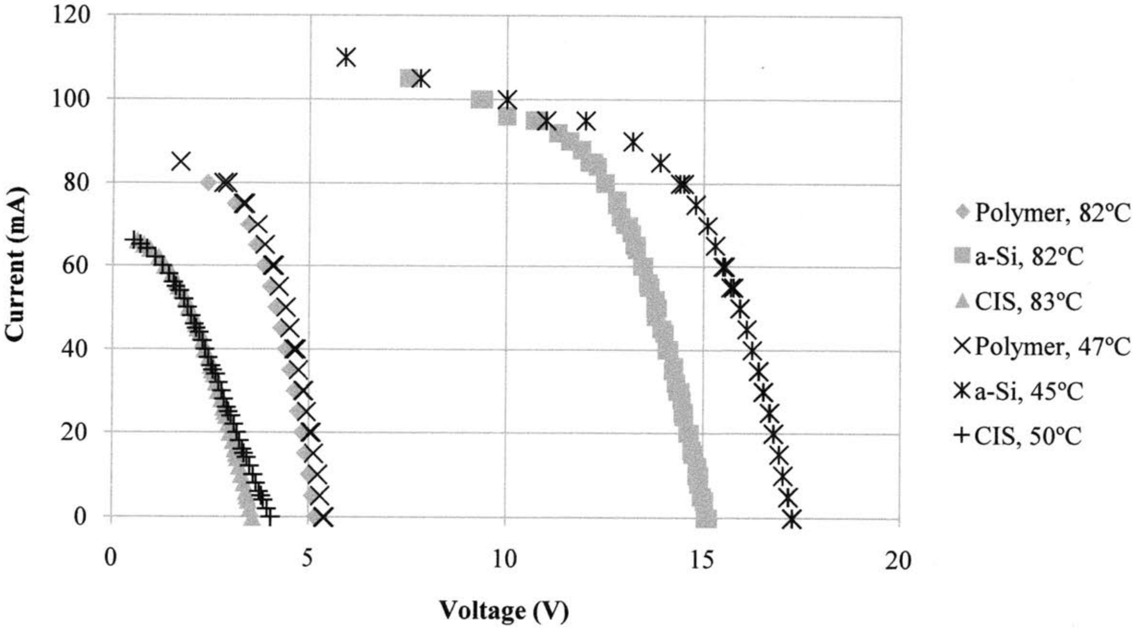

Figure 13: I-V curves at 82 and 47°C.

Figure 14 shows the open circuit voltage vs. temperature.

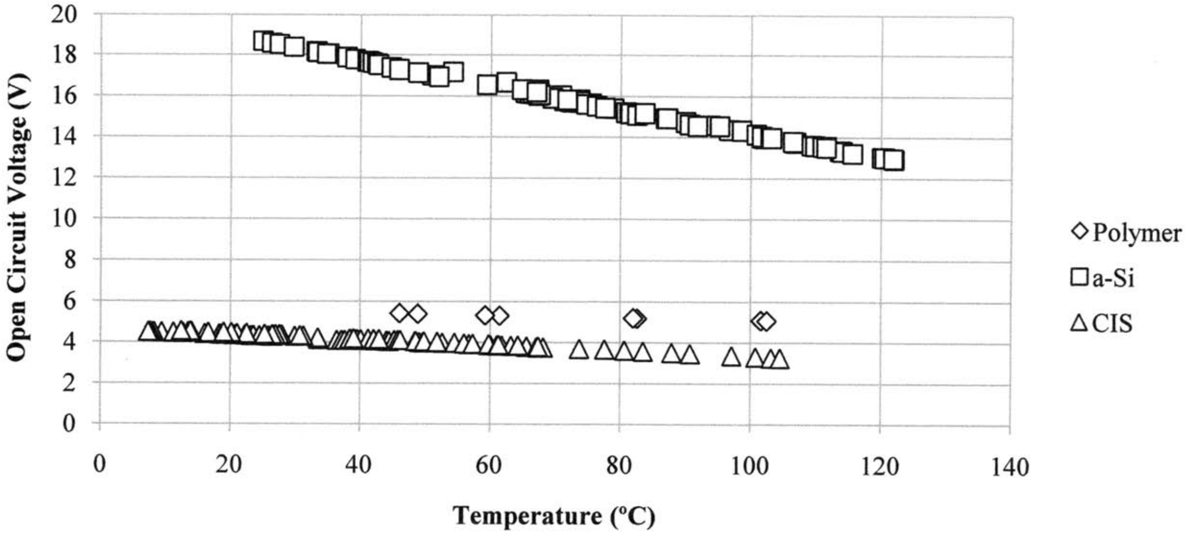

Figure 14: V_{oc} for the three cells. The polymer cell has a slope of -0.0061 V/°C, the amorphous silicon cell has a slope of -0.059 V/°C, and the CIS cell has a slope of -0.013 V/°C.

Discussion

We can compare the cell performance tested in this paper to cells from literature. Meneses-Rodríguez et al. (2005) used a measurement called K_T to report the behavior of the tested cells. K_T is defined as

$$K_T = \frac{dP_{max}}{dT} * \frac{1}{P_{max}} * 1000$$

or the change in maximum power based on temperature normalized by the maximum power, reported by the authors in parts per thousand and Kelvin. Meneses-Rodríguez reported a K_T of -2.5 for their CIS cell testing from 25°C -80°C, and further stated that other literature reported a K_T of -5.9 to -2.4. There is more than one dP_{max}/dT for the CIS cell in this report. Using the slope between 13°C and 61°C and the minimum and maximum power over that range as shown in Fig. 11, we have a K_T of -2.7 to -3.3, or -3.0 using average power. That is comparable to the K_T found by Meneses-Rodríguez. Referring to the same Figure, using the slope between 61°C and 104°C and the minimum and maximum power for that range, we have K_T is -0.82 to -0.88, which is much flatter.

Meneses-Rodríguez et al. (2005) also reported a K_T of amorphous silicon testing from 25°C to 80°C of -2.1 and literature values of -2.2. This amorphous silicon cell had a K_T of -3.1

using the projected maximum power at 25°C, -3.4 from the maximum power at 44°C and -4.5 from the maximum power at 122°C as shown in Fig. 9. These numbers are high. Carlson et al. 2000 found that the efficiency of a single junction amorphous silicon cell at 100°C was 87% of what it was at 25°C, and that the efficiency at 25°C was the same within 1% as the efficiency at 45°C. They also used tandem cells for which the efficiency at 100°C was 75% of the efficiency at 25°C so long as the cell had sat in light for 642 hours (~4 weeks) first. At 103°C this project's amorphous silicon cell was at 83% of the efficiency at 44°C and 76% of the projected efficiency at 25°C. Carlson (1977) measures from -173°C to 25°C. His data show that current falls abruptly at temperatures lower than 150 K (-123°C). The slope of open circuit voltage per degree Kelvin is -2.3×10^{-3} V/K in Carlson's report, compared to -5.9×10^{-2} V/K for the cell in this study at higher temperatures.

The polymer cell performance at high temperatures has no comparison in literature. Its efficiency was measured at 1% (see Fig. 12). The best recorded polymer cell in 2006 had an efficiency of 4% (see Fig. 2). Liang et al. (2009) reported a new polymer cell with an efficiency of 7.4%. The commercially available polymer cells are a non-ideal choice due to their low efficiency and maximum temperature of 100°C. The polymer cell in this project has a K_T of -1.5, which is less temperature dependence than either the CIS cell or the amorphous silicon cell.

The amorphous silicon had a measured efficiency of 2.9 to 3.8%. The best recorded amorphous silicon cell has an efficiency of 12% (see Fig. 2). Carlson et al. (2000) tested amorphous silicon cells that had 4% and 8% efficiencies. The CIS cell had a measured efficiency of 10.0% to 10.7%. The best recorded CIS cell efficiency was 16% (Fig. 2). This means the CIS cell had relatively high efficiency for its type while the amorphous silicon cell used in this project had worse performance than amorphous silicon cells potentially could have. Before picking a candidate for the hybrid system it may be advisable to run another set of tests on the CIS cell (or a second CIS cell) in order to pin down the temperature dependant behavior, and a set of tests on a higher efficiency amorphous silicon cell.

Conclusion

In order to build a good hybrid thermoelectric photovoltaic device, the photovoltaic part needs to have a good efficiency at high temperatures. The CIS cell had a higher efficiency and operated at temperatures up to 102°C without degrading. The amorphous silicon cell had a lower efficiency, but other amorphous silicon cells that have been tested have had efficiencies comparable to the CIS cell's efficiency. The polymer cell cannot be operated over 100°C without degradation, and this should be factored into any design that requires the polymer cell to operate at high temperatures. The polymer cell's efficiency was very low. It does not seem a suitable candidate for the photovoltaic part of the hybrid system.

Both CIS and amorphous silicon are suitable materials for the photovoltaic part of the solar cell. Further testing could be done to ensure that the maximum operable temperature of both types of cells is not under the desired operating temperature of the hybrid system. More testing could be done on a higher efficiency amorphous silicon cell, and more testing could be done on the CIS cells to pin down the CIS cell's non-linear temperature dependant behavior.

References

Buonassisi, T. “The Solar Resource.” Lecture Notes, 2.627: Fundamentals of Photovoltaics, Fall 2009.

Carlson, D.E. “The Effects of Impurities and Temperature on Amorphous Silicon Solar Cells.” *IEEE* (1977) 214-217.

Carlson, D.E., G. Lin, G. Ganguly “Temperature Dependence of Amorphous Silicon Solar Cell PV Parameters.” *IEEE* (2000) 707-712.

Evergreen Solar, Inc. ES-A Series Photovoltaic Solar Panels. Datasheet. http://www.evergreensolar.com/app/en/products/item/739/. Accessed May 7, 2010.

Green, M. *Solar Cells: Operating Principles, Technology and System Applications*, Sydney: University of New South Wales, 1986.

International Energy Agency (IEA). “1973 and 2004 Fuel Shares of Total Primary Energy Supply.” *Key World Energy Statistics*, 2006. Available from http://www.iea.org/Textbase/publications/free_new_Desc.asp?PUBS_ID=1199/.

Kazmerski, L.L. “Solar photovoltaics R&D at the tipping point: A 2005 technology overview” *Journal of Electron Spectroscopy and Related Phenomena* 150 (2006): 105–135.

Liang, Y., Z. Xu, J. Xia, S.T. Tsai, Y. Wu, G. Li, C. Ray, L. Yu. “For the Bright Future – Bulk Heterojunction Polymer Solar Cells with Power Conversion Efficiency of 7.4%” *Advanced Materials* 22 (2010): 1-4.

Majumdar, A. “Thermoelectricity in Semiconductor Nanostructures.” *Science* 303, (2004): 777-778.

Meneses-Rodriguez, D. et al. “Photovoltaic solar cells performance at elevated temperatures” *Solar Energy* 78 (2005) 243-250.

National Renewable Energy Laboratory (NREL). “Solar Spectra: Standard Air Mass Zero.” http://rredc.nrel.gov/solar/spectra/am0/ASTM2000.html/. (accessed April 26, 2010)

Pidwirny, M. "Introduction to the Oceans." in *Fundamentals of Physical Geography, 2nd Edition*. 2006. http://www.physicalgeography.net/fundamentals/8o.html/.