

Abstract

CHRISTY, DANIEL WILLIAM. An Experimental Evaluation of the Performance of the Amorphous Silicon PV Array on the NCSU AFV Garage. (Under the direction of Dr. Herbert M. Eckerlin.)

A comprehensive performance test has been conducted on the 3 kW amorphous silicon photovoltaic (PV) system on the roof of the Alternative Fuel Vehicle Garage of the North Carolina Solar Center. The purpose of this testing program was to measure the performance of the PV system, to determine if any deterioration has occurred over the past three years since installation, and to evaluate the performance of the individual circuits that makeup the PV system.

Test conducted on the individual circuits of the PV system showed significant differences. This is particularly true for the two different solar panel models, which were installed using different techniques. Numerous tests were conducted on these circuits to isolate the problem. The current-voltage curves of the factory-laminated panels were much worse than the self-laminated panels. No cause of the poor performance could be definitively established. Discussions with the PV panel manufacturer are continuing to identify the cause of the variation in PV circuit performance.

Comparisons made to performance data recorded in 2003-2004 show a similar kWh production over 3-month periods, this is encouraging. However, comparisons between global irradiance and AC power production show a 9% reduction in power production.

Continued research is recommended to further evaluate the circuit issues and to study how PV panel temperatures can be reduced so as to improve over PV system efficiencies.

**An Experimental Evaluation of the Performance of the Amorphous Silicon PV Array
on the NCSU AFV Garage**

by
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A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Master of Science

MECHANICAL ENGINEERING

Raleigh, North Carolina

2007

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Biography

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Acknowledgements

I'd like to thank Shawn Fitzpatrick for all of his help building the data logging system and answering all the many questions I had while working on the project and writing the thesis. I'd like to thank Dr. Herbert Eckerlin for all of his constructive feedback during the writing process.

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1. Introduction and Background

The amorphous silicon photovoltaic system investigated in this study is located in Raleigh, North Carolina on the campus of North Carolina State University. The photovoltaic system was installed on the roof of the Alternative Fuels Vehicle (AFV) Garage that is a part of the North Carolina Solar Center. The garage is located next to the NCSU Solar House.

The purpose of this investigation was to determine the performance of the amorphous silicon PV array, to compare its present performance with 2003-2004 performance, to determine if any deterioration had occurred over the past three years, and to evaluate differences in individual circuit performance.

The report begins with a description of the solar array and its components already in place. An overview of how photovoltaic panel work is explained next. A data collection system to monitor parameters of the array was built so that the objectives above could be achieved. This system is described in detail. Many experiments were performed to answer the questions about the system's operational performance and results and conclusions are explained in detail.

1.1. Solar Array

The photovoltaic system includes two types of solar panels in this system. There are sixteen Uni-Solar SSR-128J panels and eight Uni-Solar PVL-128B panels. The main difference between the two types is the PVL-128B panels were field laminated to the roof while the SSR-128J panels were shipped attached to the roofing material. Figure 1 shows

the garage with all 24 panels. The eight PVL-128B panels are on the left or west side of the roof while the sixteen SSR-128J panels are on the right or east side of the garage.



Figure 1. Alternative Fuels Vehicle Garage

The sixteen SSR-128J panels had been in storage for over 3 years before they were placed on the roof. The eight PVL-128B panels were purchased shortly before the entire system was installed on the roof and were glued to the metal roof just prior to roof installation.

The two types of panels have identical electrical specifications. Table 1 shows the specifications given by the manufacturer. One part of this study was to compare the actual performance with the manufacturer's specifications. Each panel has a rated power of 128 watts and with 24 panels the system has about a 3 kW peak power rating. This rating tells how much the DC power the system could provide under optimal conditions.

Table 1. Electrical Specifications

Rated Power (Watts)	128
Operating Voltage (Volts)	33.0
Operating Current (Amps)	3.88
Open Circuit Voltage (Volts)	47.6
Short Circuit Current (Amps)	4.80

The array has pairs of panels (called circuits) in series with one another to raise the output voltage of the system to a level accepted by the inverter. The resulting 12 circuits are then placed in parallel with each other to combine the current output. Figure 2 shows an electrical diagram of the entire system.

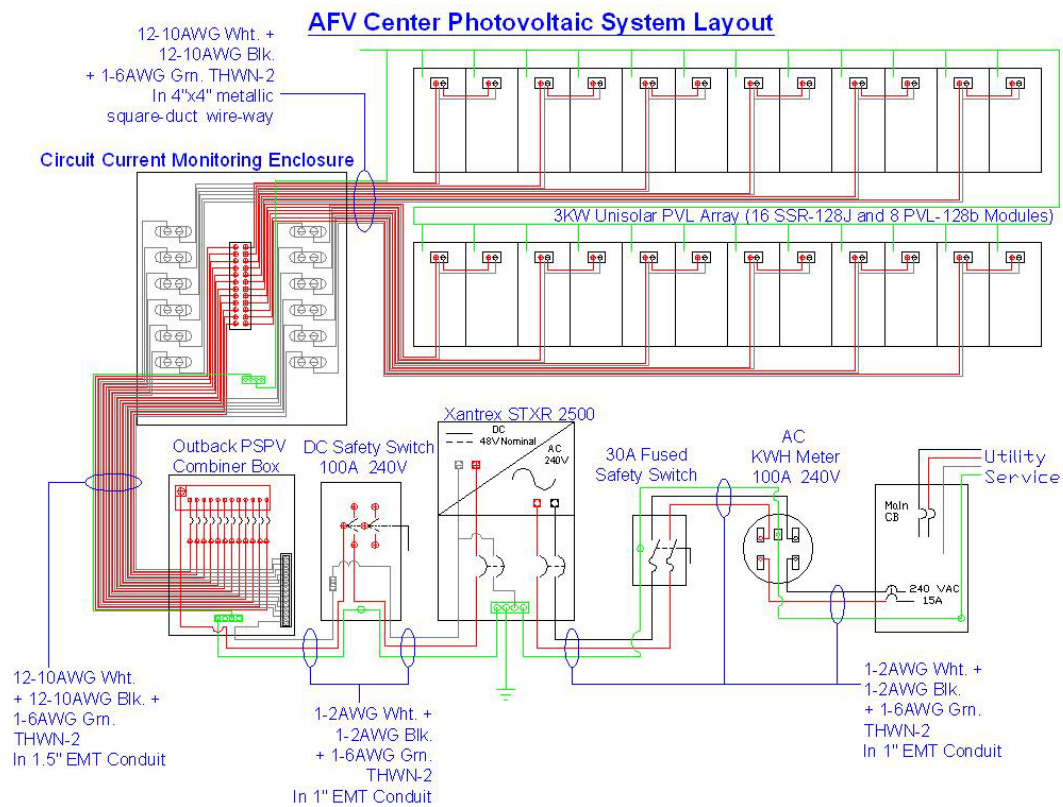


Figure 2. Electrical Diagram of Photovoltaic System Layout (McGuffy 167)

Several components of the system convert DC power produced by the panels into AC power that can be used by the AFV garage or returned to the general power grid. The inverter is the primary piece of equipment for power conditioning and is the device that actually does the DC to AC power conversion. Figure 3 shows some of the power conditioning and energy measurement equipment on the outside wall of the AFV garage. Each of these components is also shown in Figure 2.

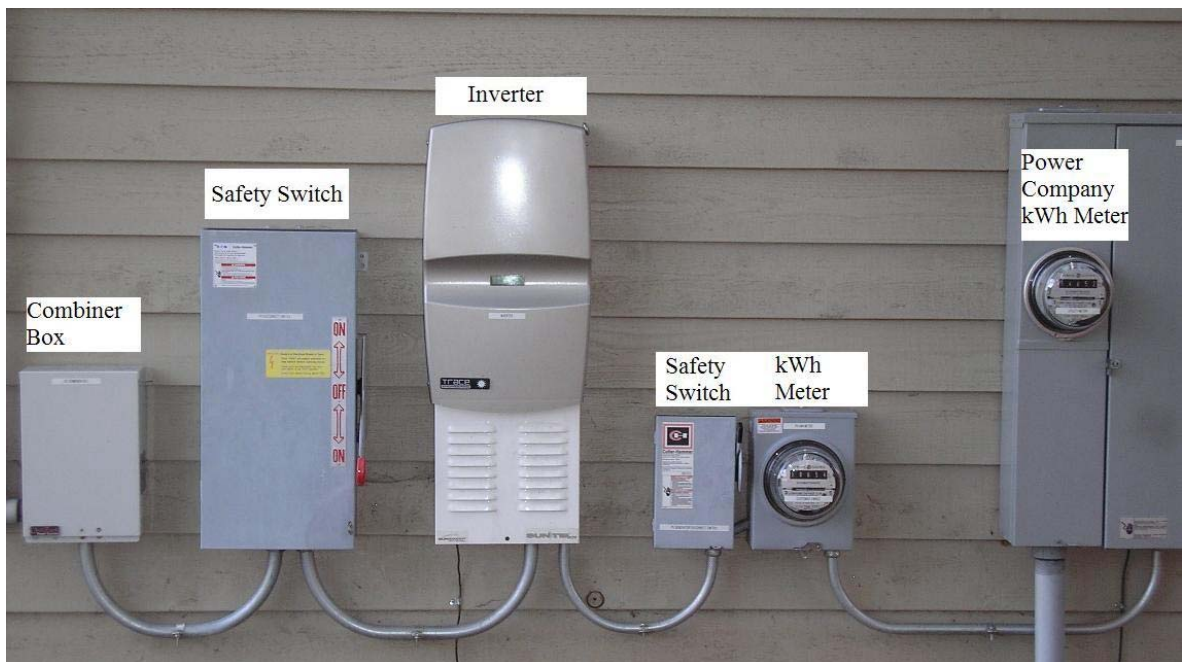


Figure 3. Outdoor Power Conditioning Equipment

The inverter plays an important role in the operation of the PV system in that it holds the entire PV array at a certain DC voltage. This max power voltage is found by sweeping a range of voltages to find the maximum power output. This is called maximum power point tracking or MPPT. The inverter displays the MPPT voltage (i.e. the voltage that provided the maximum power output in the last sweep).

Additional information that is displayed on the inverter includes the operating DC voltage, AC voltage, AC power output, watt-hours produced for the day, time the inverter has been operating for the day and the lifetime kWh produced. These values were recorded several times during the study (see Appendix B for log). The readings were also used during experiments to see how the array was operating under various solar conditions.

Other system components include the combiner box and the service panel. The combiner box is where the wiring from the twelve circuits are combined together to go into the inverter. The service panel is the circuit breaker for the garage and the point where power comes into the garage or out to the grid (depending on the solar resource). Figure 4 shows the inside of the combiner box. The combiner box contains two bus bars where the 12 circuits are combined. The circuit switches are used to turn off individual panels.

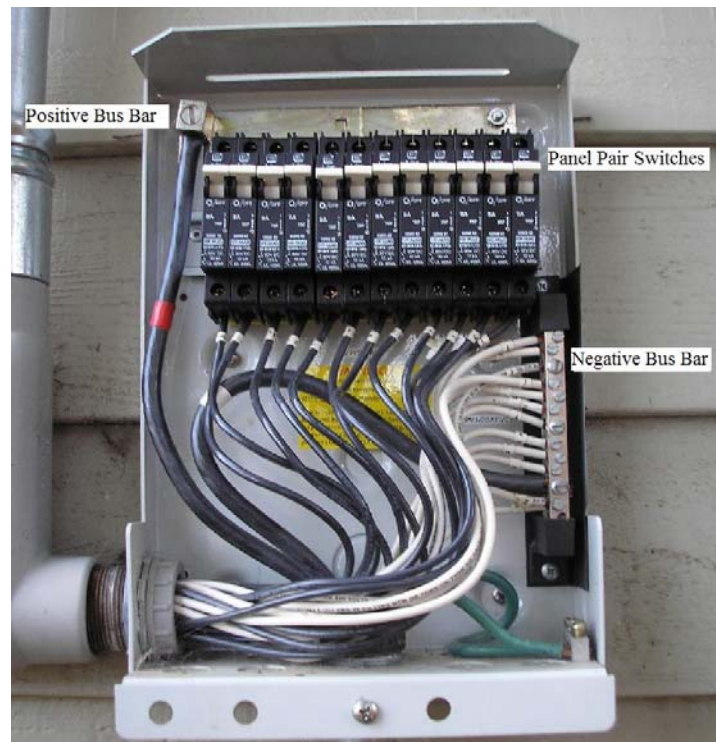


Figure 4. Combiner Box

The existing monitoring components include two kWh meters and a current monitoring box in the attic of the garage. The first kWh meter measures the total energy produced by the solar array. The second kWh meter is the power company meter and measures the net energy used by the garage (i.e., utility power minus PV power provided to the grid). Figure 3 above shows the location of the two kWh meters.

The current monitoring box in the attic has twelve 10 mΩ resistors. The current for each circuit is sent through one of these resistors. A voltage drop can be measured across each 10 mΩ resistor and using Ohm's law, the current can be calculated.

$$V = I \cdot R$$

$$I = \frac{V}{R}$$

Figure 5 shows the current monitoring enclosure.



Figure 5. Current Monitoring Enclosure

1.2. Photovoltaic Effect

Some background into how the photovoltaic effect works can be useful in understanding the basics for some of the experiments conducted in this study. A discussion of semiconductors is necessary in order to explain how a solar cell works. An explanation of how the photovoltaic effect works gives a science-oriented background. The final subsection explains how a solar cell uses the photovoltaic effect to produce power.

1.2.1. Semiconductors

All atoms have an outer layer of electrons called the valence band. These are the electrons that interact with other atoms. Conductors have few electrons in the valence band and insulators have full valence bands. Semiconductors are in between these two. For example, silicon (the most common base material for photovoltaic cells) has four valence electrons with eight electrons needed to fill its particular valence band (Goswami 412).

If electrons in the valence band of an atom are energized they can reach into a higher energy band (called the conduction band). Electrons here need only a small push to be released from the atom entirely. The energy difference between the valence band and the conduction band is called the band gap. Conductors have very low band gap energies and insulators have very high band gaps. Semiconductors are in between the two (Goswami 412).

Semiconductors used in solar cells are doped or extrinsic semiconductors. Doped semiconductors have small amounts of impurities added to them. An n-type semiconductor has an impurity with more electrons in its valence band than the base materials of the semiconductor. With this impurity added, the overall structure of the semiconductor

appears to have an excess of electrons. A p-type semiconductor has fewer electrons in its valence band than the base material and its overall structure seems to have fewer electrons than expected. In other words, the p-type has holes for electrons to fill. By themselves, n-type and p-type semiconductors are electrically neutral (Goswami 412).

If an n-type and a p-type semiconductor are placed next to each other, some of the “excess” electrons from n-type semiconductor go to fill the “holes” in the p-type semiconductor. This causes the n-type side to become electrically positive and the p-type side to become electrically negative. This negative charge assists in directing electrons through an external load. The electrons are freed by the photovoltaic effect (Goswami 414).

1.2.2. Photovoltaic Effect

The photovoltaic effect drives photovoltaic panels in that it causes electrons to move into the conduction band of an atom when the electron absorbs enough solar energy. The amount of energy needed is determined by the band gap of the material the photovoltaic cell is made of. A single photon of light must carry the required energy to push the electron through the band gap. If the photon energy is too small, the energy is converted into heat. Likewise, if the energy of the photon exceeds the band gap energy, the extra energy is converted into heat. One photon cannot energize two electrons. This is the primary reason solar cells are relatively inefficient (Goswami 415).

Once the electron has reached the conduction band, it has potential to generate electricity by being directed across an external resistance. Without anywhere to go, the

electron will simply go back to its original energy state giving up energy as heat. This is where the junction between the n-type and p-type semiconductors becomes important.

1.2.3. Solar Cells

When sunlight strikes the n-type side of the solar cell, it energizes the electrons. When this occurs, the electrons have three choices. They can go through the external load, recombine with the holes in the n-type semiconductor, or move towards the p-type semiconductor side of the solar cell. The goal is to get the electrons to go through the external load. The negative charge of the p-type semiconductor side restricts the movement in that direction. The n-type semiconductor layer is made very thin and this limits the opportunities the electron has to recombine (Goswami 415). Thus, the only option left is the external load, which will generate the electrical power.

Figure 6 shows a simple diagram of the n-type/p-type junction. Right at the interface between the two is the difference in electrical charge. The n-type side gives up electrons to the p-type side. The sunlight will strike the n-type side energizing electrons, which are then directed through the load.

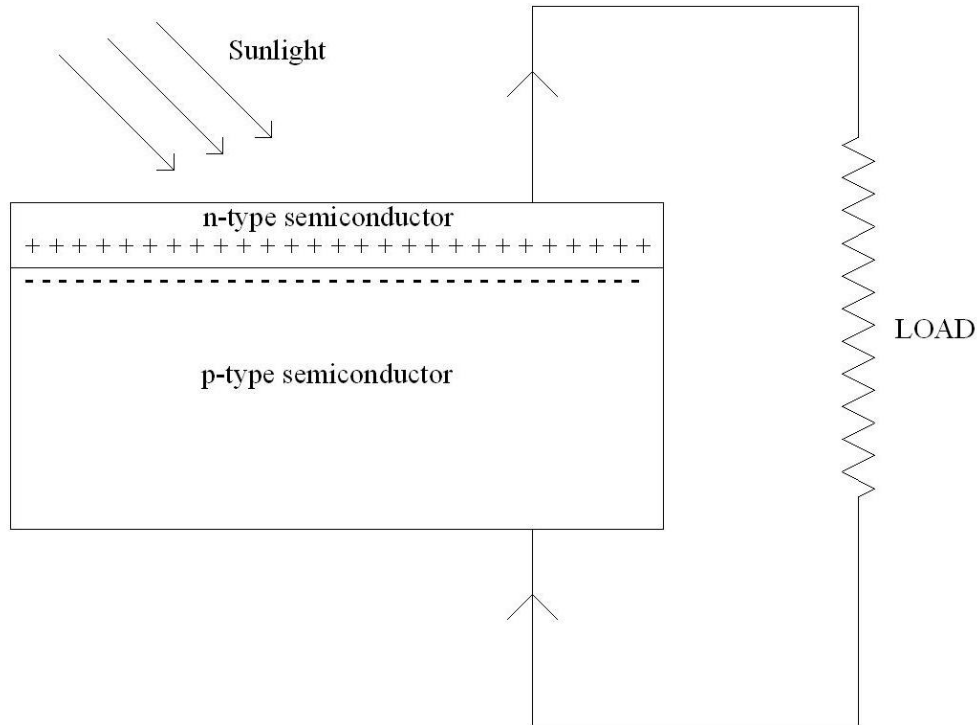


Figure 6. n-type/p-type Junction with Load Shown

1.3. Current-Voltage Curves

The performance of a solar panel can be judged by using a current-voltage or I-V graph. A current-voltage curve shows the current and voltage a solar panel produces over all resistances. The short circuit current and the open circuit voltage make up the ends of the curve. Figure 7 shows an approximation of the rated performance of the panels involved in this study in full sun. Important values from the graph include the short circuit current (the y-intercept), and the open circuit voltage (the x-intercept). These values are easily measurable and give a point of comparison between panels of the same type. These values help in determining the possible degradation of the panels over time and for comparing performance between individual panels.

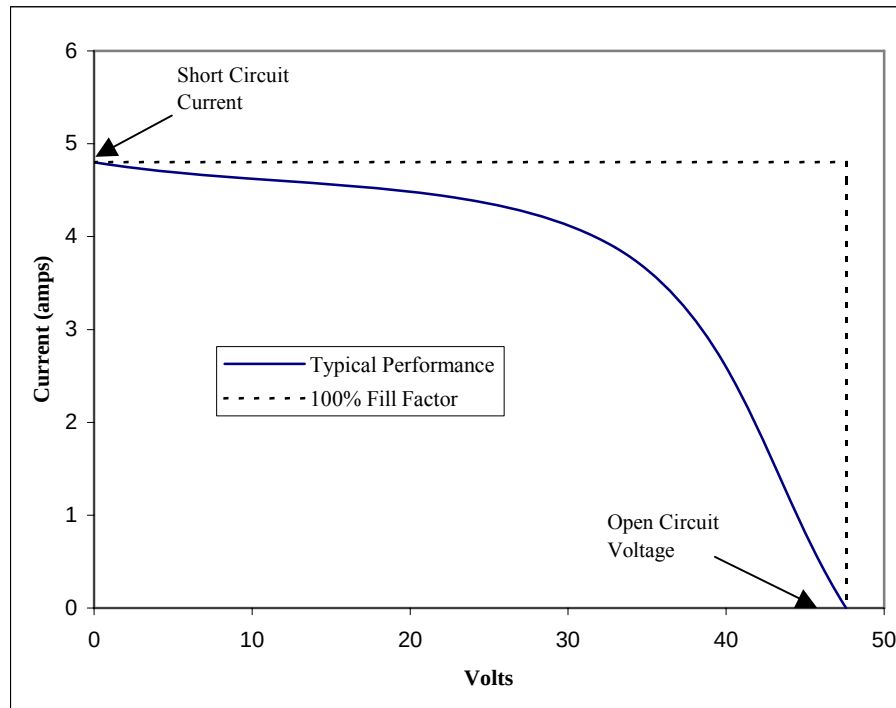


Figure 7. Current-Voltage Curve

Figure 7 shows a second plot with the open circuit voltage and the short circuit current forming a rectangle. This is called 100% fill factor. The fill factor of a panel is defined as the percentage of the box that is filled by the actual current-voltage curve. A higher fill factor indicates a better performing panel.

Figure 8 shows the voltage-power graph corresponding to Figure 7. The curve shows how the power varies with voltage by simply multiplying the voltage and current at each point on the I-V plot. This graph is used to determine the max power point, which in this case occurs at 33 volts with a power output of 128 watts.

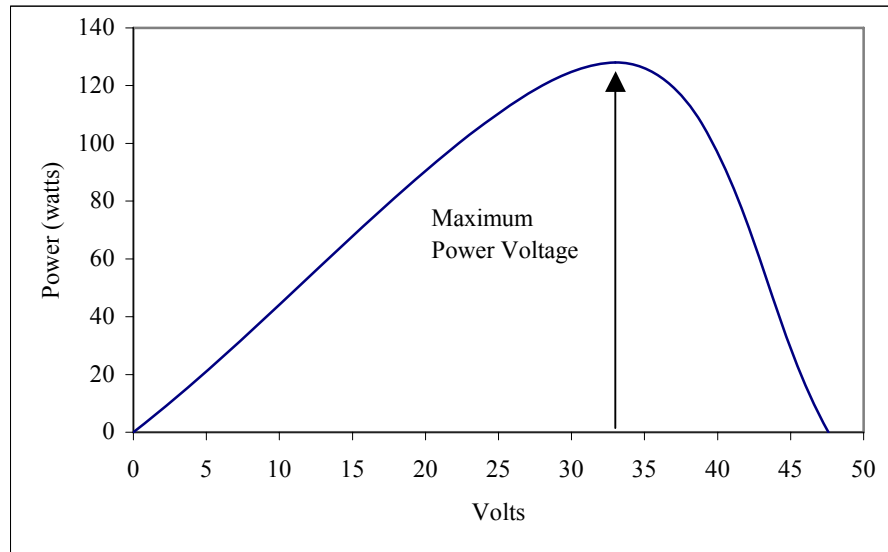


Figure 8. Voltage vs. Power

1.4. Previous Work

The solar array was installed and made operational on November 13, 2003. A performance study had been performed on the array from November 13, 2003 through April 9, 2004. The focus of the study was to analyze the relationship between the panel short circuit current and the global irradiance. The study concluded that the ratio between short circuit current and solar irradiance was 0.004184 amps per watt per square meter. Thus, for a solar irradiance of 1000 watts per square meter, each circuit would yield a short circuit current of 4.184 amps (Stanley). Additional data was collected at that time. Some of this data was used in the present study to determine if the performance of the PV system had degraded over the past three years.

2. Data Collection System

The heart of the data collection system is a Campbell Scientific CR10X data logger. All of the data collection and initial storage takes place in this device. Data collected includes solar intensity, AC power, DC voltage, current through circuits, ambient temperature, and panel temperature (Appendix A shows example data output and the data logger program. Figure 9 shows the schematic of the data logging system.

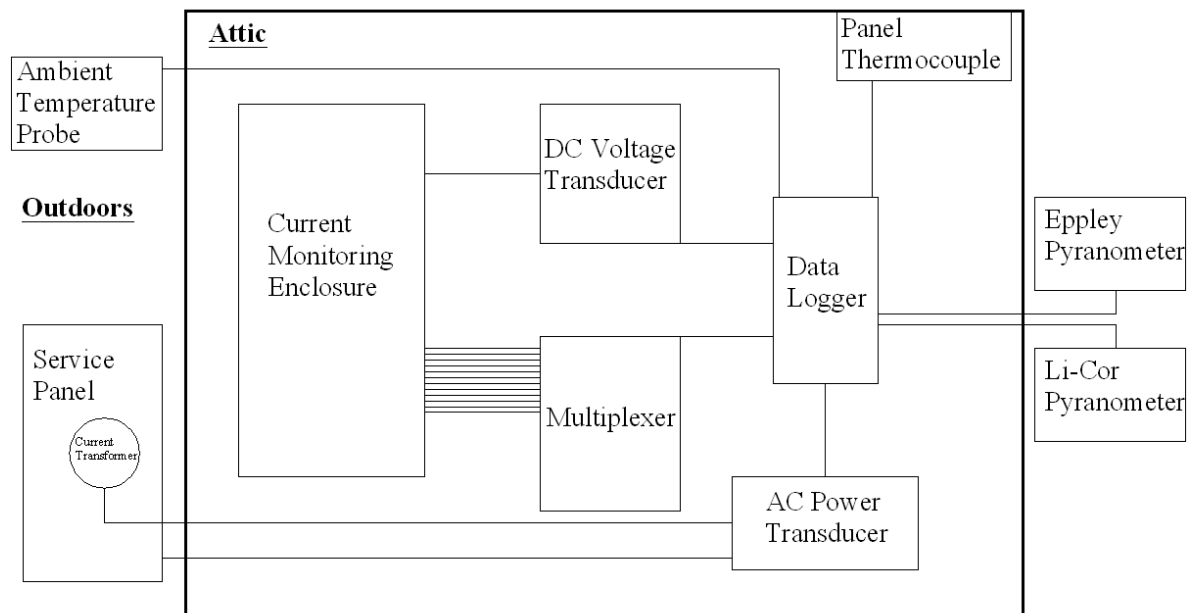


Figure 9. Data Logging System Schematic

Figure 10 shows a photograph of a portion of data logging system in place in the attic of the AFV garage. Included are the Ohio Semitronics DC voltage and AC power measurement devices. Inputs not shown in the figure include the two pyranometers, the thermocouple measuring panel temperature and the 107 temperature probe measuring ambient temperature. All these devices feed into the data logger.

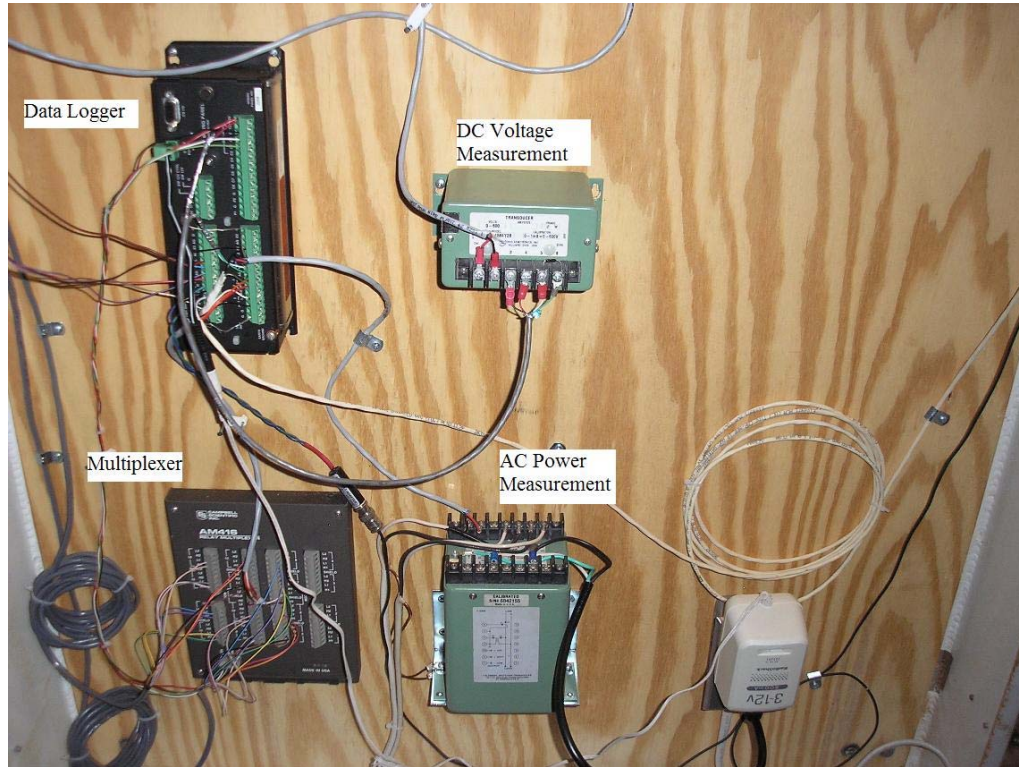


Figure 10. Data Logging System

Table 2 shows manufacturers and model numbers for the equipment used in the data logging system.

Table 2. Data Logger Equipment List

Equipment	Manufacturer	Model No.
Data Logger	Campbell Scientific	CR10X
Multiplexer	Campbell Scientific	AM416
Voltage Transducer	Ohio Semitronics	VT7
Power Transducer	Ohio Semitronics	GWV5
Pyranometer 1	Eppeley	PSP
Pyranometer 2	Li-Cor	PYRANOMETER
Panel Thermocouple	Omega	Type T

2.1. Data Logger

The Campbell Scientific CR10X data logger has twelve voltage inputs that can be used for twelve single ended measurements or six differential voltage measurements. The setup used a mixture of measurement types. A multiplexer was used to expand the available channels. A multiplexer combines several channels of data down to one.

Figure 11 shows the setup of the channel inputs to the data logger. The DC Voltage (3H), AC Power (3L), and the two pyranometers (4L, 5H) are all single-ended voltage measurements. They are all also connected to the analog ground. The thermocouple reference (4H) and the 107-temperature probe (5L) are single ended voltage measurements, but they also are connected to an excitation voltage and analog ground. The single thermocouple (6H, 6L) is used to measure the temperature on the back of a solar panel and requires two of the twelve channels.

The multiplexer takes up four channels (1H, 1L, 2H, 2L) and has additional connections to the data logger for power and controls. These include a 12V line, a ground, and two control voltages. The multiplexer takes 12 differential voltages and outputs them one at a time to the data logger. The control voltages change the differential voltage that is the output from the multiplexer.

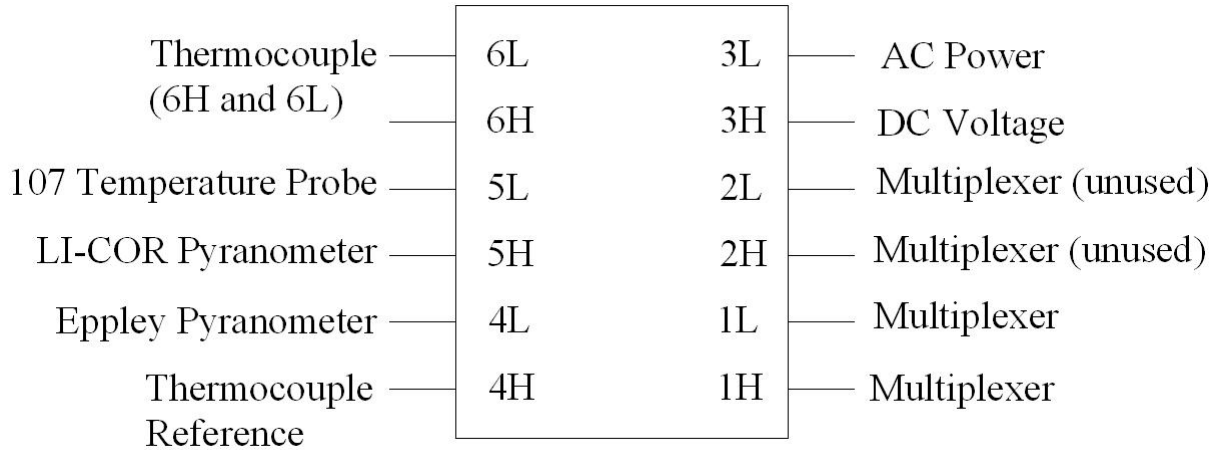


Figure 11. Data Logger Channels

The data logger program was set up to take a data point from each instrument every 30 seconds. This data would then be averaged every 15 minutes and that data point would be stored in the data logger. From time to time, the data stored would be downloaded to a laptop for analysis. For certain tests, the storage time was reduced to one minute. This was done to get more frequent data points.

2.2. Pyranometers

The pyranometers measure the solar intensity in watts per square meter. Two different pyranometers were employed, an Eppley and a Li-Cor. The pyranometers were mounted at the same angle of the roof at the bottom-west side of the roof. The two pyranometers measure different sections of the solar spectrum and were used as a check against each other. Figure 12 shows the two pyranometers mounted on the garage in the plane of the roofline. The Eppley pyranometer is the larger device on the right and the Li-Cor is on the left.



Figure 12. Eppley and Li-Cor Pyranometers

The Eppley pyranometer produces a voltage signal proportional to the solar intensity, which is then converted with a multiplier into the correct units. The multiplier used was $124.82 \frac{\text{watts} / \text{m}^2}{\text{mV}}$. This value comes from a calibration done by NREL (National Renewable Energy Laboratory).

The Li-Cor pyranometer uses a small photovoltaic sensor to measure the solar intensity and outputs a current proportional to the solar intensity. The current is sent through a 147 ohm resistor and the data logger measures the voltage drop across the resistor. The solar intensity measured is proportional to the current output of the pyranometer multiplied by the constant shown below.

$$\text{Solar Intensity} = 12.55 \times 10^6 \frac{\text{watt/m}^2}{\text{Amp}} \cdot \text{Current Output}$$

This current is sent through a resistor and using Ohm's law, the current output can be determined.

$$\text{Voltage Drop} = \text{Current Output} \cdot 147\Omega$$

$$\text{Current Output} = \frac{\text{Voltage Drop}}{147\Omega}$$

Combining two equations gives the power output in a form proportional to the voltage output.

$$\text{Solar Intensity} = 12.55 \times 10^6 \frac{\text{watt/m}^2}{\text{Amp}} \cdot \frac{\text{Voltage Drop}}{147\Omega}$$

$$\text{Solar Intensity} = 85.374 \cdot (\text{mV Output})$$

Thus 85.374 is the multiplier used in the data logger program to determine the Li-Cor measured solar flux.

2.3. DC Voltage

The DC voltage of the system is measured using an Ohio Semitronics voltage transducer (model # VT7). The VT7 receives the DC voltage from the current monitoring enclosure in the attic of the AFV garage and converts it to a current output. This current passes through a 2000-ohm resistor and the data logger measures the voltage drop across that resistor.

2.4. AC Power

The inverter converts DC power into AC power that can be fed to the power grid. An Ohio Semitronics GWV5 power transducer measures the AC power and outputs a voltage that can be converted into an AC power reading.

The available monitoring equipment however has some limitations. The power transducer measures power up to 1000 watts and the solar array is capable of generating up to 2500 watts. The data logger accepts voltages up to 2.5 volts while the power transducer produces 5 volts at the top of its range. The power transducer produces 0-5 volts over a range of 0-1000 watts. Since the data logger can only accept 2.5 volts, the maximum power the transducer can measure is 500 watts. A current transformer was used to bring the current going into the power transducer within allowable limits.

The voltage measurement is a direct measurement between the two lines going out to the power grid. The current measurement is done with a current transformer using three turns on the primary. This allows a finer resolution of the power to be determined without bringing the voltage output of the power transducer to a level too high for the data logger.

Figure 13 shows a diagram of how the AC power is measured.

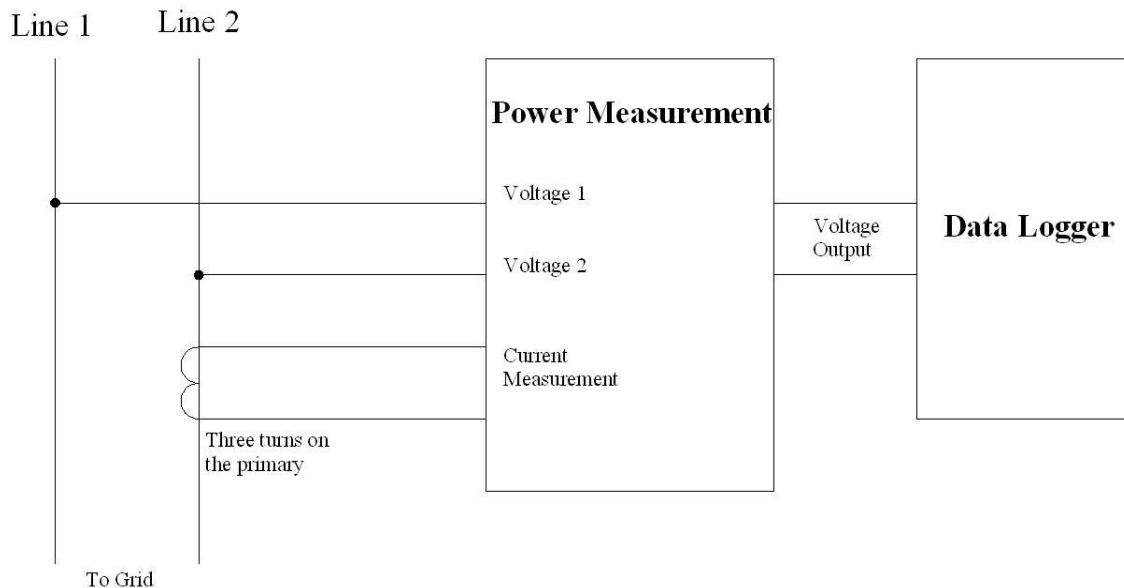


Figure 13. AC-Power Measurement Diagram

The following set of equations show the calculations used to determine the multiplier used to convert the voltage output from the power transducer to units of power. The actual power output is the AC voltage multiplied by the AC current. Three turns on the primary were used so the current transformer input ($I_{CTInput}$) should be three times the actual current.

$$\begin{aligned}\text{Power} &= V_{AC} \cdot I_{AC} \\ I_{CTInput} &= 3 \cdot I_{AC}\end{aligned}$$

The current transformer will output a 5 amp current for a 100 amp input giving a ratio of input to output of 20:1.

$$I_{CTOutput} = \frac{I_{CTInput}}{20}$$

In order to get the ratio of measured power to actual power, a few substitutions had to be made. The equations below show one of the substitutions required to determine the measured power.

$$\begin{aligned}I_{CTOutput} &= \frac{3}{20} I_{AC} \\ \text{Power Measured} &= V_{AC} \cdot I_{CTOutput}\end{aligned}$$

Then,

$$\text{Power Measured} = V_{AC} \cdot \frac{3}{20} I_{AC}$$

Finally the ratio of measured power to actual power can be determined with a third substitution using the original power equation.

$$\text{Power Measured} = \frac{3}{20} \text{Power}$$

The power transducer outputs a voltage range of 0-5V over a 0-1000W power input. The equation below shows the constant needed to convert from the voltage into the data logger to the power measured.

$$\frac{3}{20} \cdot \text{Power} = \text{Voltage Read} \cdot \frac{1000 \text{ Watts}}{5000 \text{ mV}}$$

A final combination of these last two equations gives the constant needed to convert the data logger voltage into the actual power.

$$\text{Power} = 1.333 \cdot \text{Data Logger Voltage}$$

With this information a multiplier of 1.333 was added into the data logger program in order for it to output the data in units of power.

2.5. Panel Currents

The 24 panels on the roof are tied together in pairs in order to generate a voltage that the inverter can accept. In the current monitoring enclosure in the attic, the current from each circuit is sent through a 10 mΩ current shunt (see Figure 5). By measuring the voltage drop across the shunt, the current through each circuit can be determined.

With this information, the performance of the solar array can be evaluated. Any differences in the current outputs of each circuit would indicate that all the panels are not operating at expected output.

Using the sum of the twelve currents and the array DC voltage, a DC power can be calculated. A comparison of the DC power to the AC power would give a measure of inverter efficiency.

2.6. Temperature Measurements

Temperature measurements were taken of the ambient air temperature and the PV array. A 107-temperature probe measured the ambient air temperature and the PV array temperature was measured by a thermocouple on the back of a single panel. The 107-temperature probe was placed underneath the side roof overhand to protect the probe from rain. The probe was placed inside a radiation shield to prevent any sunlight from interfering with the temperature measurement.

A thermocouple was placed on the back of one of the solar panels to measure the panel temperature. Temperature has a significant effect on photovoltaic performance. Increased temperatures lower the voltage output of the panels.

3. Experiments

Several questions were raised after looking at the initial data from the data logging system. Experiments were designed to answer the following questions:

- Has panel performance changed from three years ago?
- Do the individual circuits have different maximum power operating voltages?
- What is the shape of the current-voltage curve for a good panel and a poor performing circuit?
- How much effect does shading have on panel performance?

Each experiment discussed below attempted to answer one of these questions. The results from the experiments are shown in the next chapter.

All comparisons made were done using identical instruments. Several methods of measuring the solar intensity were used and care was taken to only compare this data against data taken using the same instrument.

3.1. Open Circuit Voltage and Short Circuit Current

The open circuit voltage (V_{oc}) and the short circuit current (I_{sc}) were measured in a previous study conducted from November 2003 to March 2004. To check for degradation similar measurements were made during January and February of 2007 (Appendix C shows an example data set).

To perform these experiments, all of the circuit breaker switches in the combiner box (see Figure 4) were switched off and the DC safety switch was turned off. The open circuit

voltage was measured for each of the twelve circuits independently. The measurement was between the positive voltage coming into the combiner box and the negative bus bar in the combiner box.

The short circuit current was measured by short circuiting the two bus bars in the combiner box. Instead of the current leaving the combiner box and going to the inverter, all of the current went through the ammeter, which was the shorting device. Each breaker was turned on individually so only the current from one circuit was measured at a time. In between each current reading, a solar irradiance measurement was taken using a handheld pyranometer. Since the short circuit current is dependent on the amount of solar irradiance, frequent measurements of the solar irradiance were taken to ensure reliable data.

In addition to the short circuit current and the open circuit voltage, all the information from the inverter was recorded just before this particular experiment was conducted. This includes the operating voltage and AC power output. In addition to the inverter data, weather conditions, ambient temperature and panel temperatures were also recorded.

3.2. Circuit Power Point Tests

An investigation into the operating status of each circuit involved turning off 11 out of 12 of the circuits. This allowed the inverter to find the maximum operating voltage for each circuit rather than having to compromise by finding the maximum operating voltage for the whole array. The readings recorded from the inverter display included the maximum power point voltage (V_{mpp}), the DC voltage, and the AC power output. The solar intensity and circuit currents were also recorded from the data logging system.

To perform this test, one of the twelve circuits was turned on for five minutes. The data logger was set to store data points every minute (instead of every 15 minutes) in order to get readings at the same time as the inverter readings. This allowed time for the inverter to search for the maximum power point. Then the inverter readings were recorded.

During this experiment, some of the circuits produced a very low power output, even in full sun. It is important to note that the inverter efficiency decreases at lower power inputs.

3.3. Current-Voltage Plot Test

A current-voltage plot was generated by connecting the solar panels to a rheostat (i.e. a variable resistor) instead of sending the power to the inverter. This resistance can be varied between $6\ \Omega$ - $28\ \Omega$. A plot of voltage versus the current provides a good indication of panel performance. Refer to Figure 7 to see a typical curve.

Figure 14 shows the setup of the current-voltage curve tracer. The two leads from the solar panels come in from the bottom. The current then flows through the two resistors and the ammeter. The ammeter is required to close the circuit. The voltage meter measures the voltage drop across the two resistors. The resistance is varied using the coarse and fine adjustments and the voltage and current readings from the meters are recorded.

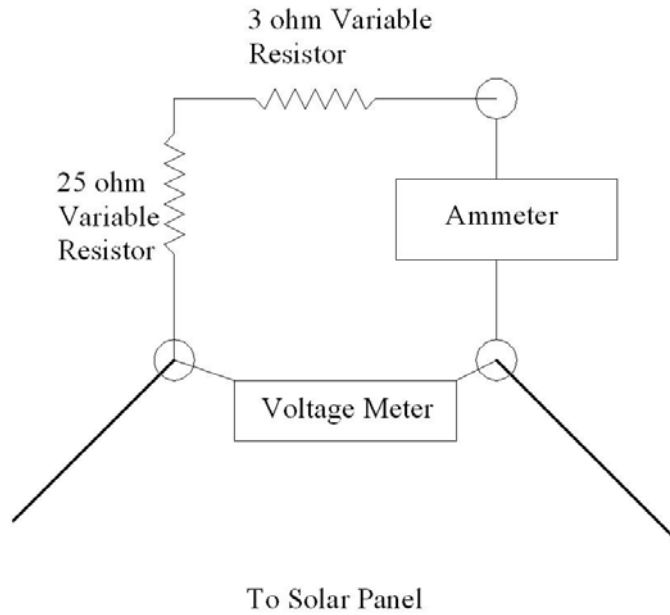


Figure 14. Current-Voltage Curve Tracer

3.4. Shading Tests

Shading can have a dramatic effect on PV system performance. Each panel contains twenty-two 13.25" x 9.5" solar cells. Experiments were conducted under five different cell shading levels defined below:

- unshaded
- $\frac{1}{4}$ cell shaded
- $\frac{1}{2}$ cell shaded
- 1 cell shaded
- $1 \frac{1}{2}$ cell shaded

These levels shade from 0 to 6.8% of the total panel. For most tests, both panels in the circuit being tested were shaded equally. However, for a couple trials, only one of the two

panels was covered. Data for each test was recorded with the data logging system on one-minute intervals.

The current generated by each circuit was the most important parameter. Dividing this recorded current by the pyranometer reading normalized the data to current per unit of solar irradiance. This allows direct comparisons between data points and accounts for any variation in solar intensity. The day chosen for the test was also a clear day around noon when the solar irradiance fluctuates the least. An average normalized value for the unshaded condition was used as the frame of reference to generate percentage values. The unshaded condition was considered maximum current.

$$\frac{\text{Panel Current}}{\text{Pyranometer Reading}} = \text{Normalized Value} \left(\frac{\text{amps}}{\text{watts/meter}^2} \right)$$

$$\frac{\text{Normalized Value}}{\text{Average Normalize Value for Unshaded Conditions}} = \text{Percent of Maximum Power}$$

The percent of maximum values can then be compared to each other. Comparisons are made between the percent of maximum power and the percent of unshaded collector.

4. Results, Conclusions and Recommendations

4.1. Effect of Solar Flux on Array Performance

Data was collected over a period of several months. This summary shows how the array was working during the study with some example data. The summary includes typical irradiance data for clear days and cloudy days and the associated power outputs. A curve showing solar irradiance versus AC power output gives a good overall indication of the power output for a given solar irradiance. This information will be useful to determine degradation of the array in any future work.

Figure 15 shows the relationship between AC power output and solar irradiance based on daytime data collected from February 7, 2007 to February 28, 2007. Points recorded when the open circuit voltage and short circuit current tests were being performed (the AC power output at this point would be zero) are excluded. Solar irradiance data from the Eppley pyranometer are used in this plot.

The trendline shows that there is a linear correlation between solar irradiance and AC power output. The data indicates that in February, the solar array generates approximately 1.78 watts for each watt per square meter of solar irradiance. This is equivalent to the array producing 1780 watts with a solar irradiance of 1000 watts per square meter. This experiment can be repeated for other months to determine the array performance in other seasons.

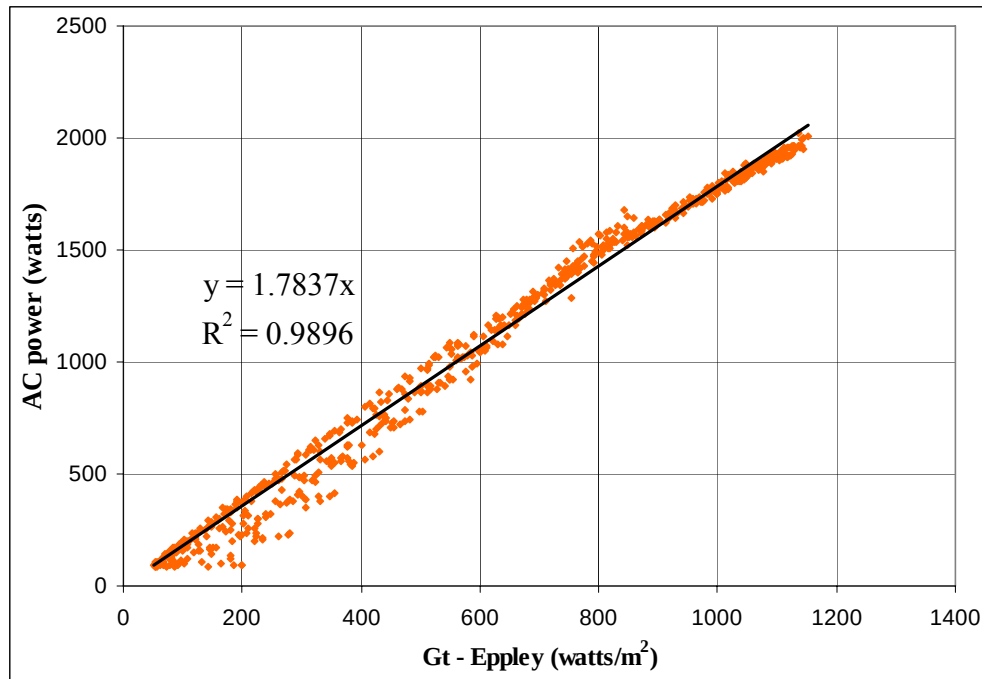


Figure 15. Solar Irradiance versus AC Power Output

Figure 16 shows the solar irradiance for two very different solar days. February 11th was a representative clear day where the solar irradiance steadily increased to a maximum of about 1100 watts per square meter shortly after 12:00 noon. A similar declining profile was seen in the afternoon. Figure 17 shows that the AC power output tracks the solar irradiance very well.

On February 12th, there were scattered clouds throughout the day. Clouds tend to diffuse and reflect the sunlight. Figure 16 shows how the solar irradiance was scattered by the clouds. Thus the solar irradiance curve and the corresponding AC power generation curve for February 12th are similar in their irregularity.

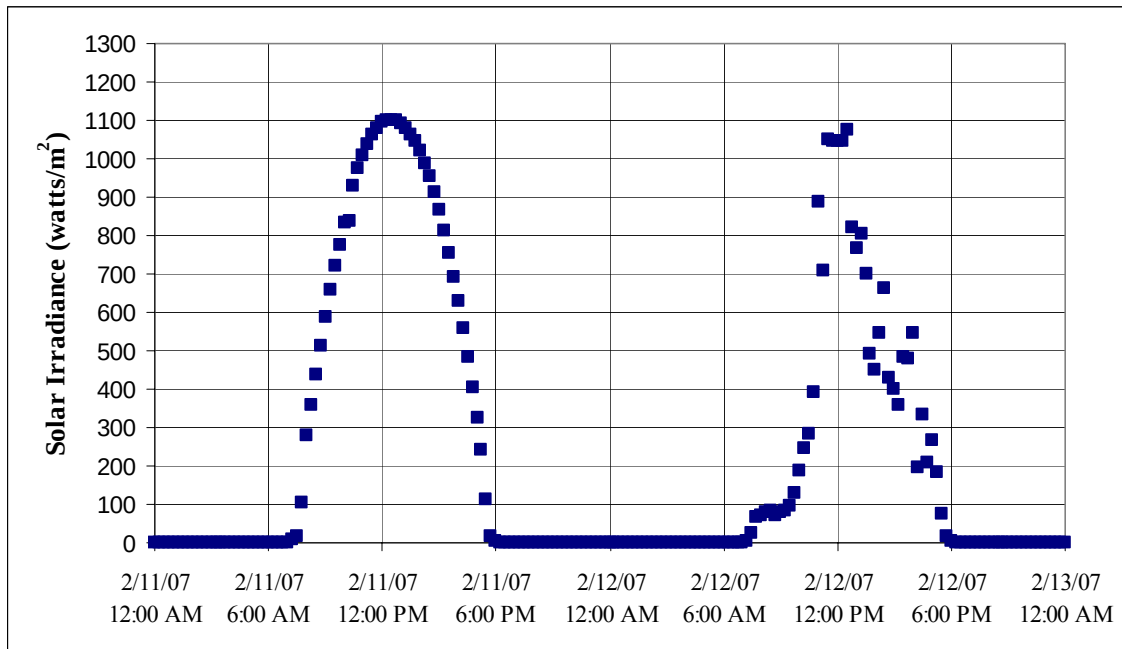


Figure 16. Solar Irradiance on a Clear Day and a Scattered Clouds Day

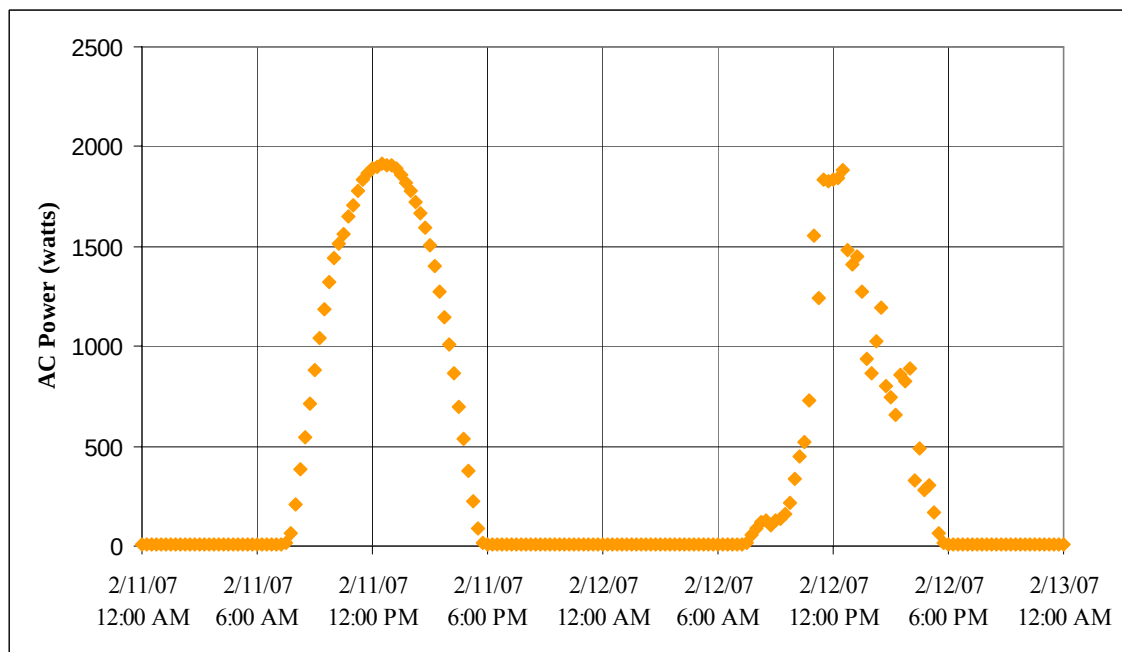


Figure 17. AC Power Output for Solar Conditions shown in Figure 16

4.2. Inverter Efficiency

The next issue to be addressed is inverter efficiency. Two sets of data were considered. The first set focused on sunny days around 12 noon. The data from the data logger was recorded from 11:45 am to 12:15 pm for days with greater than 900 watts per square meter as measured by the Eppley pyranometer. Table 3 shows the qualifying days and the average AC and DC power produced from 11:45am to 12:15pm. Over these 10 days, the average inverter efficiency was found to be 87.4%.

Table 3. Noon Inverter Efficiency Data

Date	AC watts	DC watts	Efficiency
December 27, 2006	1794	2048	87.6%
December 28, 2006	1797	2056	87.4%
January 2, 2007	1795	2055	87.3%
January 3, 2007	1765	2013	87.7%
January 6, 2007	1776	2051	86.6%
January 9, 2007	1844	2111	87.3%
January 10, 2007	1835	2093	87.7%
January 11, 2007	1799	2045	87.9%
January 14, 2007	1746	2005	87.1%
January 19, 2007	1744	1986	87.8%
Average			87.4%

The next step was to evaluate inverter efficiency over a wider range of solar conditions. Using data collected from January 27, 2007 to February 7, 2007, a plot was made of AC power versus inverter efficiency (see Figure 18). Note that the inverter efficiency drops considerably at power outputs below 200 watts.

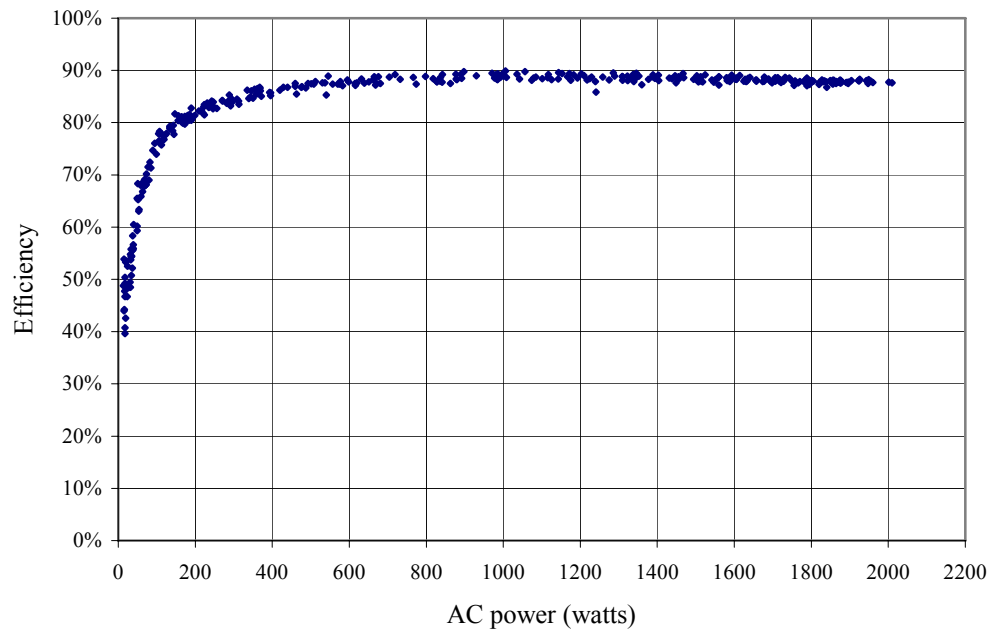


Figure 18. Variation of Inverter Efficiency as a Function of Inverter Output (AC Power)

The efficiency results shown include some losses from wiring. The DC current and voltage measurements are taken in the current monitoring enclosure (see Figure 5). Additional wiring losses also occur between the current monitoring enclosure and the inverter.

4.3. Individual Circuit Performance

One of the first things noticed at the beginning of the study was the large current imbalance between the circuits. Several investigations were initiated to determine exactly how each panel was operating. Figure 19 shows the total energy collected in DC watt-hours by each circuit on January 2, 2007 (a good sunny day). This analysis was repeated frequently on other similar solar days and all displayed the same pattern.

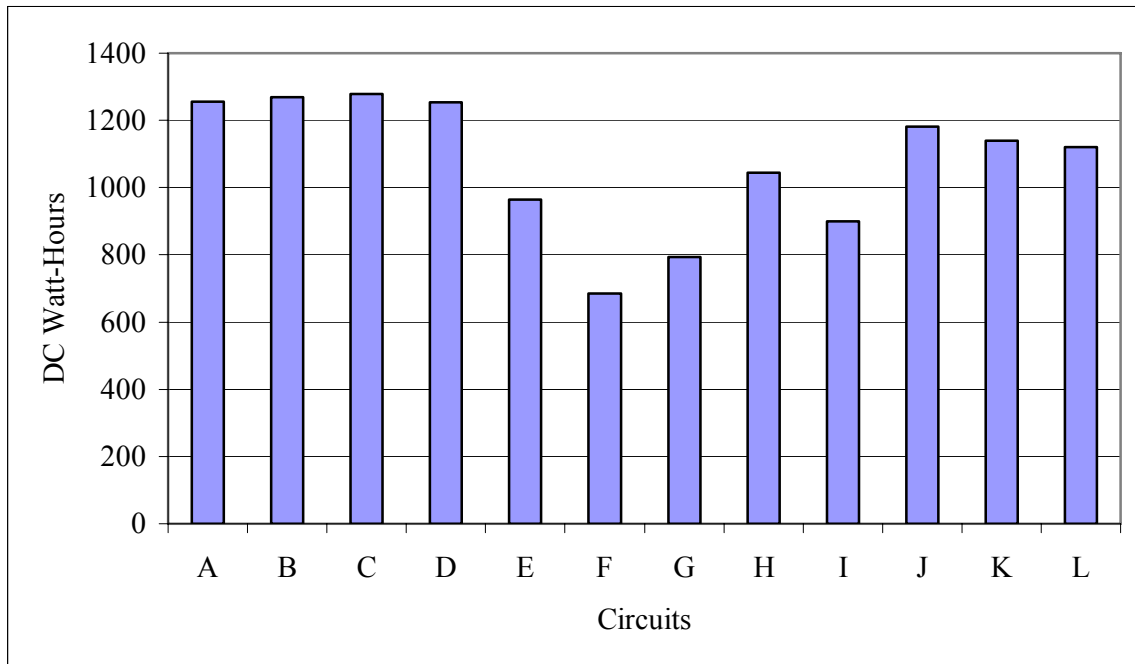


Figure 19. Energy Production for Individual Circuit on January 2, 2007

Circuits A through D utilize the eight newest panels that were laminated to the metal roof on site. These four pairs were consistently the best performing circuits and were always close to each other in power output (see Figure 19). Figure 19 also shows that the performance of the other eight circuits varied widely and produced energy outputs consistently below circuits A through D. This variation prompted a number of additional investigations to determine the cause.

4.4. Performance Analysis of Individual Circuits

4.4.1. Current-Shunt Consistency Tests

One of the first investigations was to check for a problem with the current monitoring enclosure (see Figure 5). The DC current was measured to determine if the

resistors in the enclosure were all 10 milliohms. The shunts were checked by directly measuring the current by bypassing the shunts and then comparing that value to the measured voltage drop across the 10 mΩ shunt. It was found that all current measuring shunts had a resistance of 10 mΩ and were measuring the current accurately.

4.4.2. Individual Panel Operating Voltage Comparisons

Next, the operating voltages on the individual panels within a circuit were compared. If one of the two panels was carrying a greater percentage of the voltage then the overall performance would be reduced. Circuits C and F were selected for this test, since they represented good and poor circuits. Voltages were measured at the junction box of each of the four panels involved. As shown in Table 4 below, there is no significant voltage imbalance occurring in the panel of either circuit. This indicates that voltage imbalance is not the cause for the poor performance of circuit F.

Table 4. Individual Panel Voltages

Panel	Voltage
C1	29.9 - 30.5
C2	29.1 - 30.1
F1	29.0 - 29.5
F2	30.5 - 31.0

4.4.3. Circuit Maximum Power Operating Voltage

The next test conducted was the circuit power point test to find maximum power operating voltages for each circuit (refer to Section 3.2 Circuit Power Point Tests for test procedure). The initial expectation was that each circuit would have a different maximum power operating voltage. If that were the case, then the inverter would have to compromise

to find a best overall voltage at which to hold the entire array. If each circuit could have its own operating voltage, a higher maximum power could be achieved. The inverter would then need multiple inputs for multiple maximum power point voltages. The circuit power point test looks at each circuit individually to find the circuit's maximum operating voltage.

These tests were conducted on January 24, 2007 and found no correlation between the power produced by the circuits and the maximum power point voltage. The solar intensity was very consistent throughout the test. Figure 20 shows a bar graph of the max power point voltage for each circuit.

No correlation is seen between the imbalance in watt-hours produced (in Figure 19) and the max power point voltage (in Figure 20). For example, circuit F produced the lowest amount of energy, but circuit G had the lowest MPPT voltage. This suggests that there must be another cause for the current imbalance in the circuits.

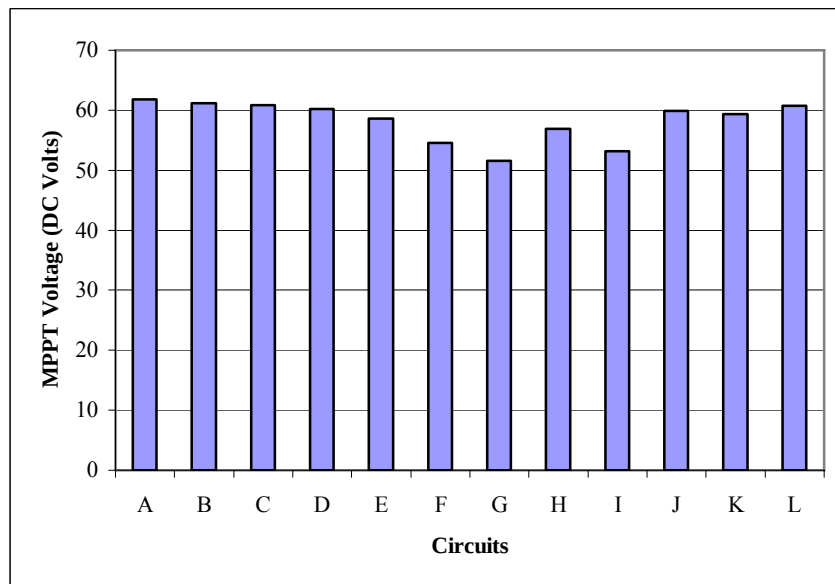


Figure 20. Max Power Point Voltage for Individual Circuits

4.4.4. Circuit Comparison of DC Watt-Hours to AC Maximum Power

Another variable recorded during the circuit power point test was the AC power output from the inverter as shown in Figure 21. The power levels recorded from the inverter were all below the design level for the inverter. However, a comparison of Figure 19 and Figure 21 shows a strong correlation between energy produced in DC watt-hours and power produced in AC watts. Circuits A through D are the strongest performing circuits in both sets of data and circuit F is the weakest performing pair in both sets of data. The difference in the two figures is exaggerated because circuit F is operating at a lower inverter efficiency.

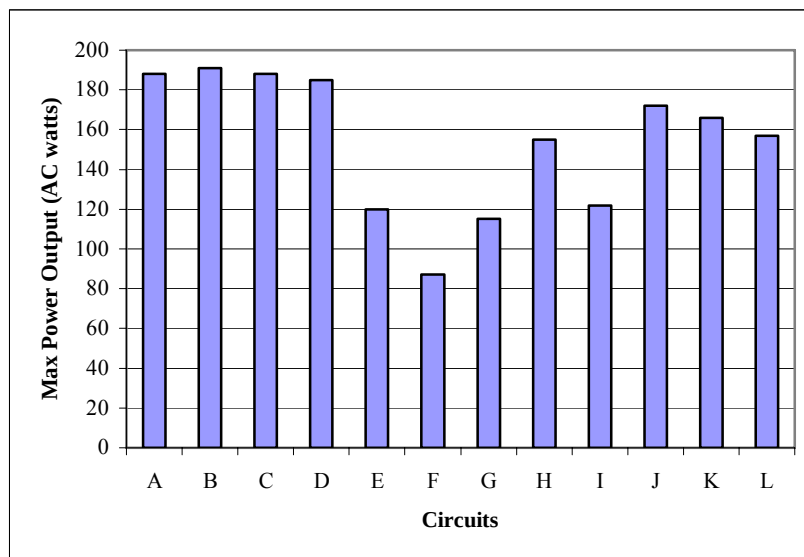


Figure 21. Max Output Power for Individual Circuits

4.4.5. Comparison of Current-Voltage and Power Voltage-Curves for Circuits D and F

In order to get a more detailed evaluation of individual circuit performance, an individual current-voltage (I-V) plot was made for circuit D and circuit F (refer to Section 3.3 Current-Voltage Plot Test for test procedure). These two circuits were chosen because they are at opposite extremes. Figure 22 provides a comparison of I-V plots of circuits D and F and shows that circuit D consistently outperforms circuit F.

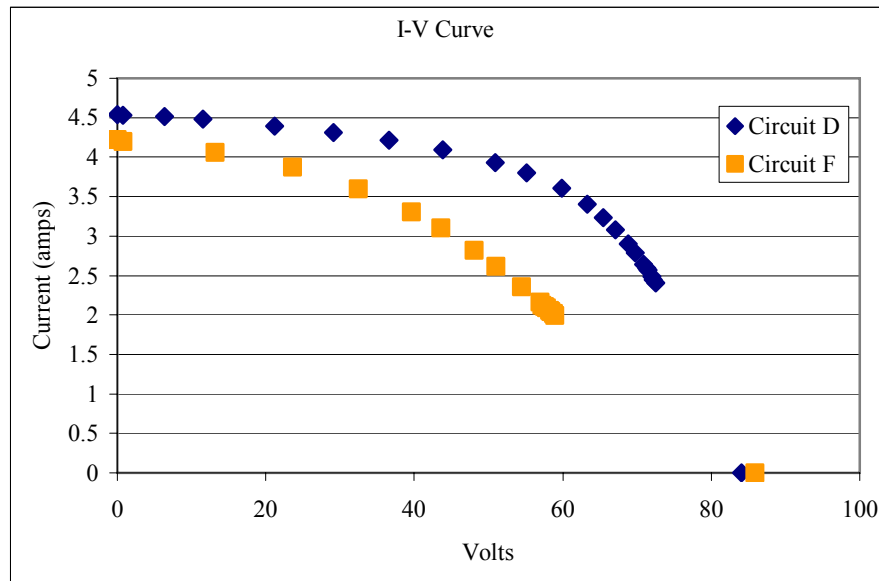


Figure 22. Current-Voltage Curve for Circuits D and F

Figure 23 shows the power-voltage curve for circuits D and F and confirms that circuit D always gives a higher power output for any given voltage.

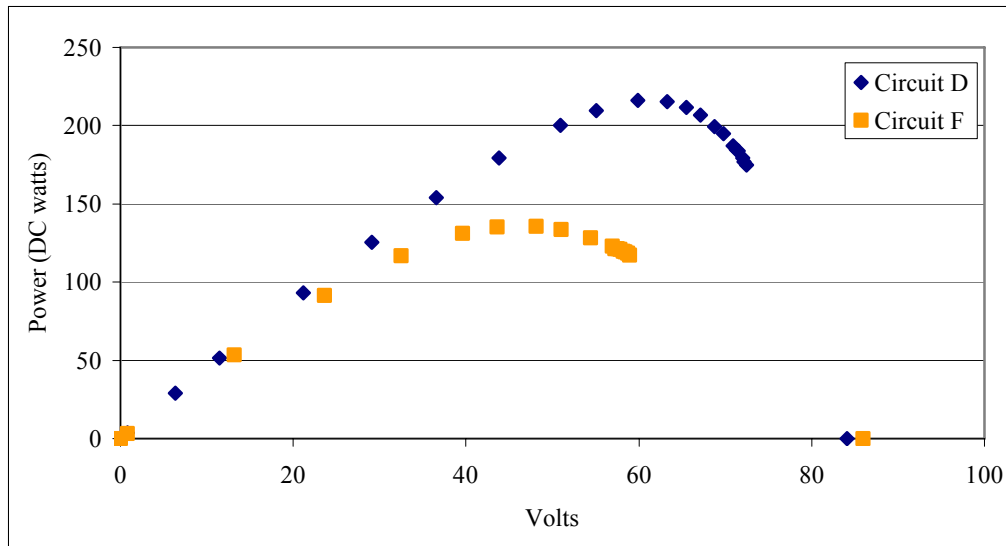


Figure 23. Power-Voltage Curve for Circuits D and F

These tests were conducted on February 5, 2007. The ambient temperature was 40°F with a solar radiation 1022 watts/square meter. The solar radiation was measured with the handheld pyranometer.

4.4.6. Comparison of Current-Voltage Plots for Individual Panels within Circuit F

To confirm the above data, a second set of tests was performed on the individual panels within circuit F. Figure 24 shows the current-voltage curves for these two panels to be virtually identical. This is surprising since it was thought that poor circuit performance was due to a difference in individual performance of panels F1 and F2.

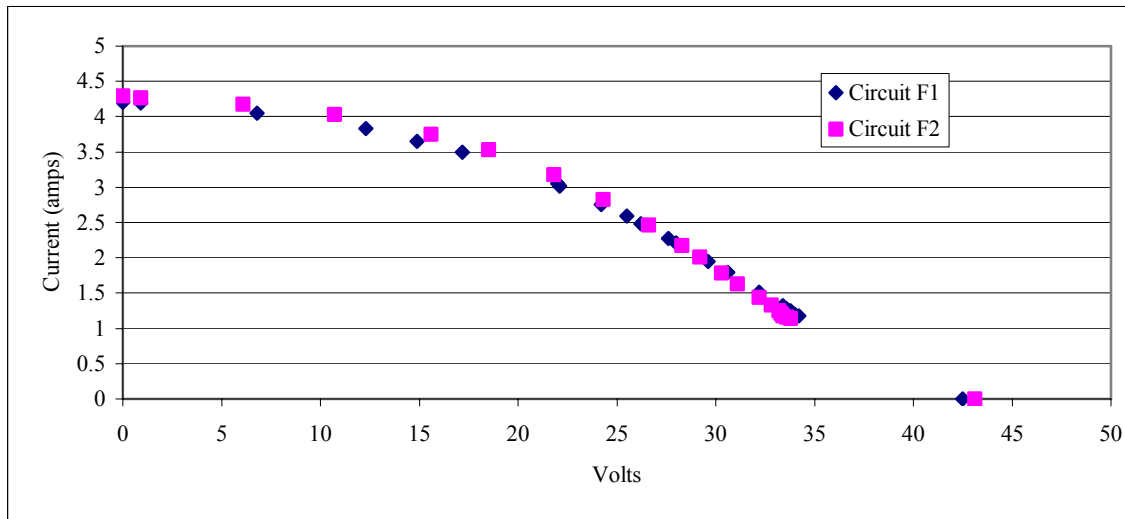


Figure 24. Current-Voltage Curve for Individual Panels within Circuit F

These tests show that a maximum power voltage compromise is not causing circuits E through L to produce less power than circuits A through D. It seems that while circuits A-D are all operating fairly well, the other panels have some sort of unusual operating problem. This problem could be a manufacturing defect or some sort of degradation that occurred while the E-L panels were in storage waiting to be placed on the roof.

4.5. Deterioration

Amorphous silicon solar collectors are a newer technology with system lifetimes not as well established as for crystalline silicon panels. This unknown made system performance deterioration an important aspect of the subject study. To answer some of these deterioration questions, 2007 data was compared to that collected during 2003-2004.

4.5.1. Tilted Global Irradiance versus AC Power Output

The last study conducted on the AFV garage solar array was performed from November 2003 to April 2004. The level of deterioration in the solar panels since then was considered important to investigate. Most of the data from the 2003-2004 test period is short circuit current and open circuit voltage data for each circuit. This data was taken when the panels were disconnected from the inverter. The operational data that was taken included the inverter data, the most important of which is the AC power output.

From the 2003-2004 data, a solar irradiance versus AC power plot was created. The short circuit current measurements were all accompanied by a solar irradiance measurement with a handheld pyranometer. If the pyranometer readings were all fairly constant during that test, then the data from that day was used. The inverter AC power output was also recorded during these tests. Figure 25 shows the resulting AC power output versus solar irradiance. The resulting trendline shows that the AC power output for a clear day with a solar irradiance of 1000 watts per square meter in 2003-2004 was 2089 watts.

The data collected in 2007 used with the same equipment. The handheld pyranometer was placed in the same position as in 2003-2004. In addition to the points collected during the short circuit current and open circuit voltage tests, some data points were taken simply by measuring the solar radiation and the AC power from the inverter. Figure 26 shows the 2007 version of Figure 25. Figure 15 uses the same type of performance data but uses a different pyranometer and cannot be compared to the 2003-2004 data. Figure 26 shows that for a clear day at 1000 watts per square meter of solar irradiance, the array now produces 1899 watts, a reduction of 9% since 2003.

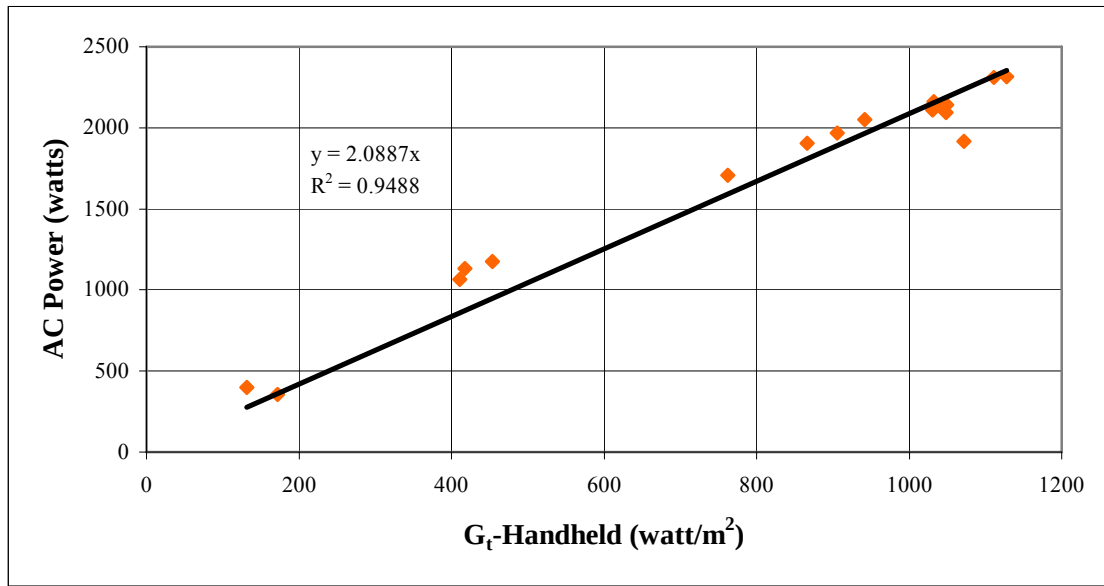


Figure 25. 2003 to 2004 Solar Radiation versus AC Power Output

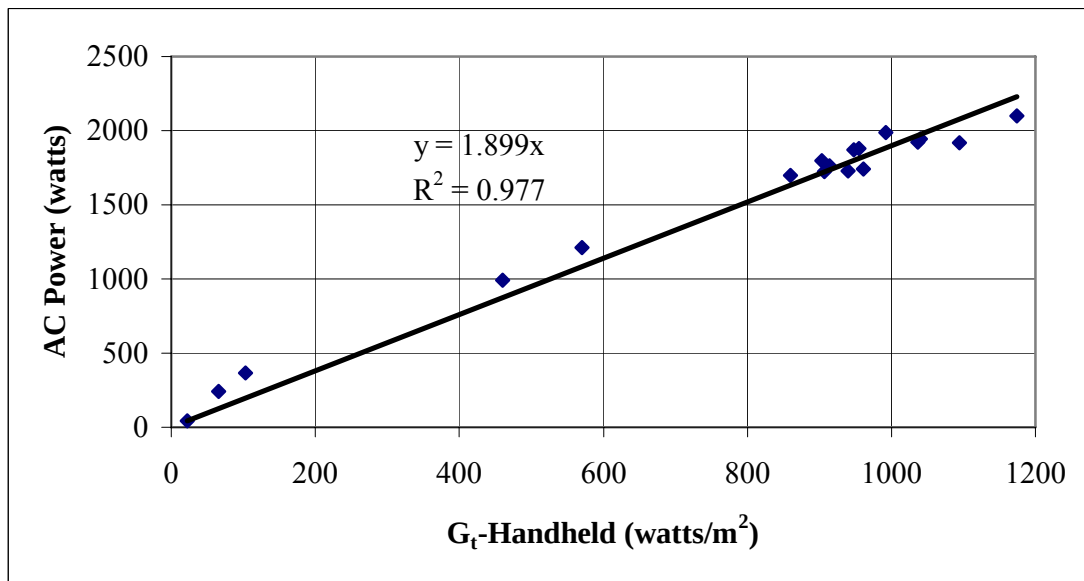


Figure 26. 2007 Solar Radiation versus AC Power Output

This comparison is not ideal, however, because it does not take into account temperature effects. If the temperatures were colder during the 2003-2004 test period, then better performance during that earlier period could be attributed to the lower voltage loss at lower panel temperatures.

According to these results the panels have degraded in the three years since installation. The 9% reduction shown in AC power production is significant. However, further study would provide a more definitive answer to the level of degradation.

4.5.2. Tilted Global Irradiance versus Short Circuit Current

A second comparison was made between the short-circuit currents measured during the two test periods (refer to Section 3.1 Open Circuit Voltage and Short Circuit Current for test procedure). The short circuit current represents the maximum current a panel can produce. Currents were recorded for each circuit, along with a pyranometer reading from the handheld pyranometer.

To find these values, all of the data for each circuit was plotted and a trendline for short circuit current versus solar irradiance was found using Microsoft Excel. Figure 27 shows an example plot for circuit 'A'.

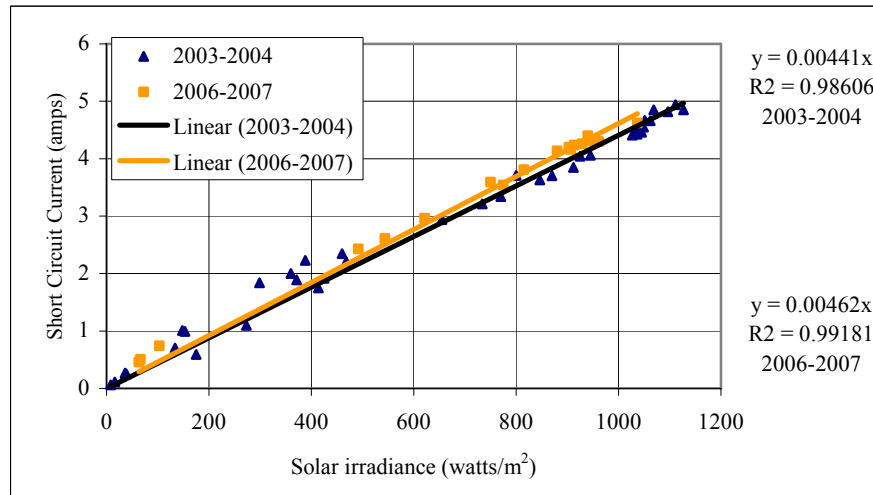


Figure 27. Circuit A Short Circuit Current Comparison

Using the trendline slope for each circuit, the short circuit current at 1000 watts per square meter was found using data from the 2003-2004 study and the 2006-2007 study. Table 5 shows the short circuit currents calculated for each circuit at 1000 watts per square meter.

Table 5. Short Circuit Current Comparison

Panel	Short Circuit Current at 1000 W/m² (amps)		
	2003-2004	2006-2007	% change
A	4.41	4.62	4.8%
B	4.40	4.58	4.1%
C	4.47	4.65	4.0%
D	4.43	4.50	1.6%
E	4.27	4.40	3.0%
F	4.22	4.24	0.5%
G	4.31	4.39	1.9%
H	4.22	4.35	3.1%
I	4.28	4.36	1.9%
J	4.37	4.50	3.0%
K	4.39	4.42	0.7%
L	4.36	4.41	1.1%
Overall	4.35	4.46	2.5%

For every circuit, the short circuit current has risen between 0.5% and 4.8% (with an average increase of 2.5%). The increase in short circuit current is small and could be due to minor differences in technique, temperature, and/or equipment used. From the above table, one can conclude that the short circuit current has not degraded over the three years (since the system was installed).

4.5.3. Energy Production over Study Periods

A third measure of possible system degradation compares the energy produced during the two test periods. Table 6 gives a summary the data collected. The kWh readings were recorded several times during both studies. A daily average was found for each study period. The 2003-2004 period produced 8.54 kWh per day and the 2006-2006 period produced 7.79 kWh per day.

No continuous solar irradiance data was collected in the 2003-2004 study. However, the State Climate Office of North Carolina has several weather stations throughout the state and two of these stations in Raleigh, NC measure solar radiation. An average solar radiation was found for each period using the data from the State Climate Office. The average solar radiation during the 2003-2004 period was 114.8 watts per square meter (this value is low because it is averaged over a 24 hour period). The average solar radiation during the 2006-2007 period was 103.5 watt per square meter.

The kWh per watt/m² was found for each study period. For 2003-2004, the value is 0.074 kWh per watt/m² and for 2006-2007 the value is 0.075 kWh per watt/m². These values are almost identical and indicate no degradation has occurred during the last three years.

Table 6. Energy Production Over Each Study

	2004-2004	2006 to 2007
Start Date	2-Dec-03	2-Dec-06
kWh reading	194	9947
End Date	2-Mar-04	2-Mar-07
kWh reading	971.5	10648
Days in period	91	90
kWh Difference	777.5	701
kWh per day	8.54	7.79
Average Solar Irradiance (w/m²)	114.8	103.5
kWh per watt/m²	0.074	0.075

4.6. Shading

The shading experiment was performed on February 28, 2007, a day with clear skies. A variety of shading configurations were used on circuit A to test the effect of shading on individual panel output (refer to Section 3.4 Shading Tests for test procedure). Table 7 shows a summary of the data collected that day. A1 and A2 refer to individual panels within circuit A. These were usually shaded equally, except for two trials when one cell of one panel shaded.

Table 7. Shading Data

% unshaded	Level of Shading	percent of maximum current
100.0%	no shading	100.0%
98.9%	A1 and A2 have 1/4 cell shaded	95.4%
97.7%	A1 has 1 cell shaded	96.5%
97.7%	A2 has 1 cell shaded	98.8%
97.7%	A1 and A2 have 1/2 cell shaded	94.1%
95.5%	A1 and A2 have 1 cell shaded	93.6%
93.2%	A1 and A2 have 1 1/2 cells shaded	83.9%

An examination of the data in Table 7 suggests that the reduction in current is not proportional to the amount of shading on the panel. A small amount of shading can greatly affect the power output of a solar cell. The shading of 4.5% or 1 cell of each panel causes a 6.4% drop in current output. The shading of 6.8% of the array or 1½ cells of each panel causes a 16.1% drop in current output.

The large current drop of the panel can be explained by the current-voltage curve of the solar panels. Figure 28 shows a hypothetical example of how the panel current-voltage curve could be affected. The unshaded case is the same as Figure 7. The shaded cases drop the voltage proportional to the amount of the panel shaded. Shading 2 out of 22 cells shades 9.1% of the panel and drops the maximum power voltage from 33 volts to 30 volts, a drop of 9.1% (see Figure 29).

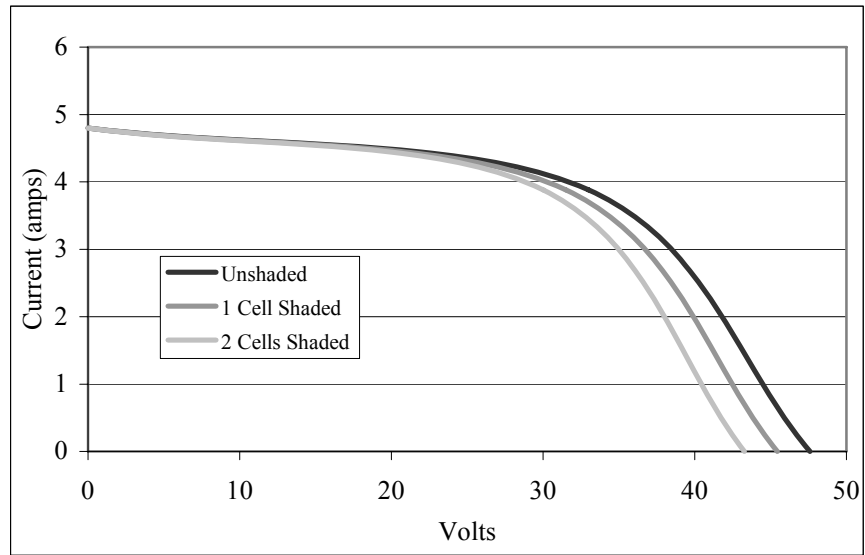


Figure 28. Hypothetical Shading Effects on Panel Current-Voltage Curve

Figure 29 shows the power-voltage curve for the hypothetical case shown in Figure 28.

Note the reduction in the maximum power voltage as the shading is increased.

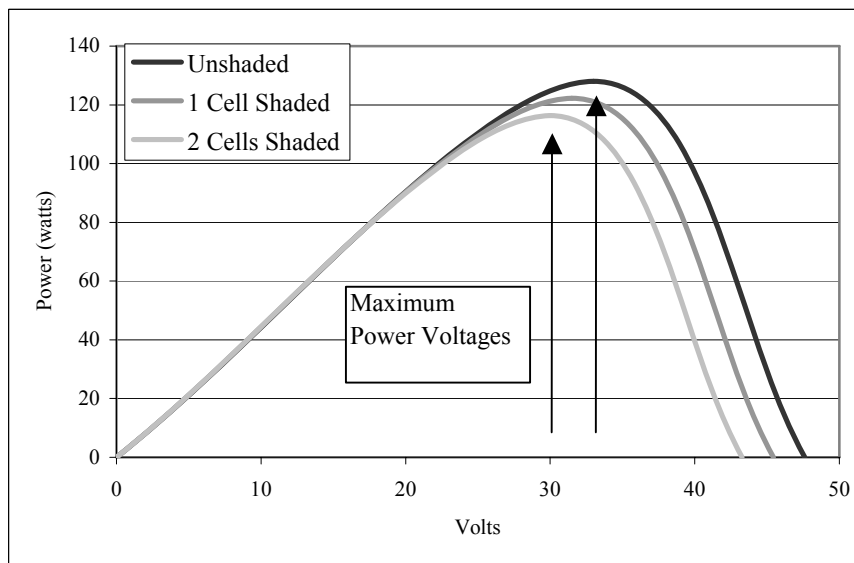


Figure 29. Shading Effect on Power-Voltage Curve

The inverter keeps all twelve circuits of the array at the same operating voltage. The entire array is not drastically affected by the shading of one panel. The other 11 circuits keep the system DC voltage at about the same level with or without the small amount of shading on one panel. This causes the shaded panel to operate at a voltage higher than its maximum power voltage. Figure 28 shows that the current of a shaded circuit falling off sooner than the unshaded circuit. This shows why shading has such a significant effect on panel performance and why the current (and therefore power) of a shaded panel drops off at a faster rate than the amount of panel shading.

A review of Table 7 suggests that the shading of $\frac{1}{2}$ of a cell has a similar effect as shading an entire cell. For example, when $\frac{1}{2}$ of one cell is shaded, the current drops to 94.1%; and when a full cell is shaded, the current drops to 93.6%. These are almost equal power reductions. Thus, partial shading of a cell has almost the same effects as full shading.

4.7. Comparisons

4.7.1. Manufacturer Data

It is difficult to compare experimental data with manufacturer's specifications developed under manufacturer's test conditions. Typical manufacturer test conditions are a solar radiation of 1000 watts per square meter and a panel temperature of 25°C. In real world conditions, a panel temperature of 25°C is unrealistic for a solar radiation of 1000 watts per square meter. A more realistic temperature might be 55°C.

4.7.2. PV Watts

A simple web based program used to calculate photovoltaic potential is PV Watts. The program is located on the National Renewable Energy Laboratory's website. A measure of overall system performance over 3 years could be considered. PV Watts predicts a kWh production of 3905 kWh over a 12 month period. The kWh meter reading on November 14, 2003 was 44 kWh. The reading on November 14, 2006 (three years later) was 9825 kWh. Using that data, the solar array on the AFV garage produced an average of 3260 kWh per year. This is 16.5% lower than the kWh production predicted by PV Watts. The reduction is due, in part, to the underperforming panels in place.

4.8. Conclusion Summary

Many tests were performed during the study and Table 8 shows a summary of the tests performed and the conclusions made from the tests.

Table 8. Conclusion Summary

Test	Conclusions
-Current measured on twelve individual circuits with the data logger system	-Data Logger shows current imbalance between individual circuits
-Tested current enclosure shunts to confirm the resistance was still 10 mΩ	-Shunts all have 10 mΩ resistance
-Tested for voltage imbalance between the two panels in a circuit	-No imbalance found between individual panels
-Tested for different maximum power voltages for each circuit	-No correlation between energy production imbalance and maximum power voltages
-Comparison of energy production to individual circuit power production	-Correlation seen between energy production and individual power production
-Generation of current-voltage curve for circuits D and F	-Circuit D has a good current-voltage curve while circuit F has a very poor current-voltage curve
-Generation of current-voltage curve for panels within circuit F	-Very similar curves for each panels, both are poor curves
-Deterioration test using global irradiance versus AC power output	-Shows a 9% drop in power production
-Deterioration test using global irradiance versus short-circuit current	-Shows no deterioration, 2.5% increase in overall short-circuit current
-Deterioration test using kWh production over three month period with comparison to solar radiation data	-Shows no deterioration

4.9. Future Work

There are several options for future work. The degradation work can be continued using the additional data provided by this study. Ambient and panel temperatures were

measured during the subject study but the effects of temperature were never considered. A substantial amount of work could be performed in this area.

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Appendix

A. Data Logger Program Code

This appendix shows the program code uploaded to the data logger. A separate program called Shortcut was used to write the code. This program is downloadable from the Campbell Scientific at:

<http://www.campbellsci.com/downloads>

To communicate with the data logger a serial port and a Campbell Scientific program are required. The programs PC208W and PC200W can both be used to connect to the data logger. PC200W is also available for download at the Campbell Scientific website. The file uploaded must be a *.DLD file.

The scan interval is 30 seconds and this data is averaged every 15 minutes. This information is recorded in a comma delimited text file. Using Microsoft Excel to open the files the data was placed into tables. Table 9 below shows an example of how the data looks. The top row is not included in the data output; it is there to show what each column is.

Table 9. Example Data Logger Output

Table Index	year	day	time	Eppley	Li-Cor	Ambient Temperature	DC Volts	AC Power	Panel Temperature	Circuit A Current	Circuit B Current
101	2007	38	1215	848	868	52.01	58.11	1521	116.9	3.003	2.993
101	2007	38	1230	1025	1044	51.45	57.62	1825	119.3	3.626	3.616
101	2007	38	1245	1031	1047	52.52	55.92	1839	122.8	3.718	3.682

Circuit C Current	Circuit D Current	Circuit E Current	Circuit F Current	Circuit G Current	Circuit H Current	Circuit I Current	Circuit J Current	Circuit K Current	Circuit L Current
3.02	2.975	2.235	1.574	1.84	2.41	2.068	2.768	2.659	2.593
3.636	3.577	2.653	1.846	2.169	2.865	2.453	3.318	3.197	3.162
3.712	3.655	2.76	1.946	2.315	2.977	2.579	3.421	3.3	3.269

```

};CR10X
;15min.DLD
;Created by Short Cut (2.5)
;$
;;Batt_Volt:Prog_Sig :Panel_I_1:Panel_I_2:Panel_I_3
;;Panel_I_4:Panel_I_5:Panel_I_6:Panel_I_7:Panel_I_8
;;Panel_I_9:Panel_I_10:Panel_I_11:Panel_I_12:Panel_I_13
;;Panel_I_14:Panel_I_15:Panel_I_16:Panel_I_17:Panel_I_18
;;Panel_I_19:Panel_I_20:Panel_I_21:Panel_I_22:Panel_I_23
;;Panel_I_24:Panel_I_25:Panel_I_26:Panel_I_27:Panel_I_28
;;Panel_I_29:Panel_I_30:Panel_I_31:Panel_I_32:DC_Volt
;;AC_Power :Reference:Eppley :LiCor :Ambient
;;Panel_T
;$

;:
;Final Storage Label File for: 15min.SCW
;Date: 3/19/2007
;Time: 21:58:21
;
;101 Output_Table 15.00 Min
;1 101 L
;2 Year_RTM L
;3 Day_RTM L
;4 Hour_Minute_RTM L
;5 Eppley_AVG L
;6 LiCor_AVG L
;7 Ambient_AVG L
;8 DC_Volt_AVG L
;9 AC_Power_AVG L
;10 Panel_T_AVG L
;11 Panel_I_9_AVG L
;12 Panel_I_11_AVG L
;13 Panel_I_13_AVG L
;14 Panel_I_15_AVG L
;15 Panel_I_17_AVG L
;16 Panel_I_19_AVG L
;17 Panel_I_21_AVG L
;18 Panel_I_23_AVG L

```

```
;19 Panel__25_AVG L
;20 Panel__27_AVG L
;21 Panel__29_AVG L
;22 Panel__31_AVG L
,
;Estimated final storage locations used per day: 2112
;%
```

```
MODE 1
SCAN RATE 30.0000
```

```
1:P10
1:1
```

```
2:P92
1:0
2:1440
3:30
```

```
3:P19
1:2
```

```
4:P95
```

```
5:P86
1:41
```

```
6:P87
1:0
2:16
```

```
7:P90
1:2
```

```
8:P86
1:72
```

```
9:P22
1:1
2:0
3:1
4:0
```

```
10:P2
1:2
2:24
3:1
4:3--
5:.1
6:0.0
```

```
11:P95
```

```
12:P86
1:51
```

```
13:P1
1:1
2:24
3:5
4:35
5:.300
6:0.0
```

```
14:P1
1:1
2:25
3:6
```

4:36
5:1.33333
6:0.0

15:P11
1:1
2:7
3:1
4:37
5:1
6:0

16:P1
1:1
2:23
3:8
4:38
5:124.82
6:0.0

17:P1
1:1
2:23
3:9
4:39
5:85.3741
6:0.0

18:P11
1:1
2:10
3:21
4:40
5:1.8
6:32.0

19:P14
1:1
2:1
3:6
4:1
5:37
6:41
7:1.8
8:32

20:P92
1:0
2:15
3:10

21:P80
1:1
2:101

22:P77
1:1220

23:P71
1:1
2:38

24:P71
1:1
2:39

25:P71
1:1

2:40

26:P71

1:1

2:35

27:P71

1:1

2:36

28:P71

1:1

2:41

29:P71

1:1

2:11

30:P71

1:1

2:13

31:P71

1:1

2:15

32:P71

1:1

2:17

33:P71

1:1

2:19

34:P71

1:1

2:21

35:P71

1:1

2:23

36:P71

1:1

2:25

37:P71

1:1

2:27

38:P71

1:1

2:29

39:P71

1:1

2:31

40:P71

1:1

2:33

MODE 2

SCAN RATE 10.0000

1:P96

1:71

MODE 3

MODE 10

1:41

2:139

3:0

MODE 12

1:0000

2:0000

3:0000

B. PV Log

The PV log recorded information from the inverter. The log was updated several times per week during the subject study.

Table 10. PV Log

Date	Time	sunny, partly cloudy, cloudy, rainy	Ambient Temp. F					Time online today	Lifetime Energy kWh	kWh	Gt
				Vac	Vdc	Watts	Today				
11/14/2003			55							44	
11/18/2003			73							64	
9/14/2006	4:00 PM									9266	
10/3/2006	5:00 PM									9478	
10/24/2006	10:00 AM									9635	
10/25/2006	10:08 PM	sunny	49	251	59.6	1428	1275	2:24:26	9736.4	9648	
10/27/2006	11:06 AM	cloudy	50	249	54.3	62	195	3:04:12	9757.8	9669	
10/31/2006	10:10	m sunny	68	249	59.1	1762	2111	3:10:16		9707	
11/1/2006	10:35	sunny	70	249	56.3	1776	3526	3:37	9805.5	9715	
11/3/2006	10:25	sunny	51	250	57	1749	3498	3:26	9826.8	9736	
11/6/2006	10:41	m sunny	57	249	57.1	1746	3467	3:43	9863.5	9773	
11/8/2006	10:54	cloudy	62	245	58	60	676	3:48	9872	9781	
11/9/2006	16:51	dusk-sunny	68	247	66	21	12074	9:44	9884	9793	
11/10/2006	10:18	sunny	73	249	54	1605	3030	3:10	9887.9	9795	
11/12/2006	14:02	cloudy	53	249	58.8	262	1509	6:00	9909.1	9815	
11/13/2006	10:47	p cloudy	58	250	57.1	1900	2357	3:33	9911.7	9818	
11/14/2006	10:00	m sunny	59	250	59.4	1628	1887	2:53	9918.7	9825	
11/15/2006	11:24	cloudy	57	248	58	125	1202	3:58	9927.7	9834	
11/17/2006	10:27	sunny	50	251	57.2	1746	3321	3:15	9936.8	9844	
11/20/2006	10:43	p cloudy	45	251	60	1499	995	3:18	9960.5	9872	
11/27/2006	9:33	sunny	54	249	58.4	1347	1614	2:15	10010.9	9914	
11/28/2006	15:26	p cloudy	69	249	58.4	651	8715	8:03	10029.2	9933	
11/29/2006	10:52	cloudy	64	247	57	493	1848	3:30	10031.4	9934	
12/2/2006	10:42	m sunny	47	252	56	1760	3408	3:18	10045.2	9947	
12/4/2006	10:08	sunny	43	252	60.2	1579	2239	2:30	10060	9963	
12/6/2006	10:15	p cloudy	47	250	60	1576	2373	2:50	10083.3	9984	
12/9/2006	12:36	sunny	43	254	28.3	1851	6657	5:09	10116.5	10016	
12/13/2006	13:23	cloudy	58	249	60.7	736	1406	5:15	10154.8	10054	

Table 10 (continued).

12/14/2006	11:10	sunny	60	248	56.3	1460	3236	3:36	10160.3	10059	
12/15/2006	10:34	sunny	55	251	55.9	1573	2396	2:51	10167.9	10066	
12/19/2006	13:30			249	55.9	1395	6254	5:53	10212.5	10111	
1/3/2007	11:59	sunny	57	251	56.6	1789	5061	4:15	10299.4	10194	
1/5/2007	12:30	cloudy	64	245	58.7	94	516	3:33	10311.3	10205	
1/10/2007	10:08	sunny	40	253	61	1484	1992	2:26	10342	10235	
1/11/2007	10:49	sunny	40	254	63	1679	2984	3:08	10354.7	10247	
1/12/2007	15:56	p cloudy	60	249	60.6	581	6501	8:09	10369.1	10262	
1/15/2007	10:44	p cloudy	63	248	58	1048	1241	2:53	10385.7	10277	
1/16/2007	13:53	cloudy	52	248	57	240	704	4:52	10390.4	10283	
1/17/2007	10:34	m sunny	35	251	61.1	1089	2467	2:55	10393	10284	
1/22/2007	12:09	cloudy	35	249	58.6	122	482	4:05	10414.2	10305	
1/23/2007	10:41	p cloudy		249	58.8	1054	2369	2:52	10417.4		
1/25/2007	11:04	sunny	51	251	58.6	1798	2934	3:06	10431	10323	
1/26/2007	13:13	sunny	40	254	58.8	1880	7711	5:36	10441.3	10334	
1/29/2007	10:51	sunny	32	253	60	1741	3247	3:15	10460.8	10354	
1/30/2007	11:23	m sunny	39	254	59.3	1695	2745	3:43	10469.5	10364	
2/2/2007	10:55	cloudy	36	251	60.2	409	495	2:33	10489.9	10384	
2/5/2007	11:37	sunny	40	254	57.6	1922	4286	4:01	10516.2	10408	
2/6/2007	11:08	sunny	35	253	58.6	1872	3948	3:38	10524.9	10418	
2/7/2007	11:08	sunny	48	252	57.3	1763	3046	3:24	10536	10428	
2/9/2007	10:48	m sunny		250	58.1	1729	3255	3:22	10553.9	10447	
2/12/2007	10:58	p cloudy	47	252	59.4	1985	1166	3:35	10585.8	10479	992
2/14/2007	10:45	cloudy	36	247	61.3	366	300	2:48	10594.2	10487	103
2/15/2007	11:50	p cloudy	31	252	59.2	991	5015	4:33	10606.1	10498	460
2/19/2007	10:31	sunny	36	252	57.6	1700	2942	3:17	10647.5	10538	860
2/23/2007	15:37	sunny	50	250	58.1	1213	12276	8:23	10697.4	10590	570
2/27/2007	12:12	sunny	56	248	52.7	1918	5982	9:06	10726.2	10618	1094
3/1/2007	16:19	cloudy	61	246	53.7	45	3721	9:19	10749.7	10642	22
3/2/2007	13:10	p cloudy	61	249	54.2	2101	7790	6:06	10757.6	10648	
3/5/2007	11:06	sunny	49		57.3	1943	4230	4:00	10794	10684	
DAYLIGHT SAVINGS +1hour			DAYLIGHT SAVINGS +1hour			DAYLIGHT SAVINGS +1hour					
3/14/2007	17:12	cloudy	75	248	55.2	464	6848	9:26	10906.2	10794	

C. Example Short Circuit Current and Open Circuit Voltage Data

This appendix shows an example of the data collected in the 2003-2004 study.

Table 11. Example Open Circuit Voltage and Short Circuit Current Data

Date	1/12/2004			
Circuit	V _{oc}	G _t	I _{sc}	
1	83.5	414	1.75	
2	83.8	405	1.79	
3	83.3	410	1.8	
4	82.8	410	1.8	
5	84.8	406	1.68	
6	84.8	415	1.69	
7	84.8	415	1.72	
8	83.9	418	1.67	
9	84.8	419	1.69	
10	84.9	410	1.7	
11	85.2	407	1.7	
12	85	407	1.69	
T _{ambient}	16.6			
T _{cell}	31.3			
PV meter	536			
Building meter	99594			
Inverter				
	Power		1063	
	Watt hours today		11653	
	Uptime today		8:03	
	Mppt		64.8	
	V _{ac}		254	
	V _{dc}		65.2	
	Lifetime energy		362.5	
Cutoff time			3:43	
Re-activation time			3:51	

Weather

sunny, sparse clouds, cool
clouds not moving

D. Solar Panel Specification Sheet

UNI-SOLAR®

**Field Applied Roofing PV Laminate With Top Termination
For Steel Roofs** Models: PVL-29T, PVL-58T, PVL-64T, PVL-87T, PVL-116T, PVL-128T

Data Sheet

- **Lightweight, Flexible, Durable**
- **Easy to install "peel and apply" application**
- **20 Year warrant** on power output
- **Roll Shippable**
- **Top Termination quick connect, Junction Box, or Junction Box with quick connect**
- **Bypass Diodes for Shadow Tolerance**
- **UL Listed** 



These special roofing laminates are designed to be bonded on 16-inch wide (minimum), flat steel pans. They come with the bonding adhesive factory-installed on the back of the laminate. Included is a rugged, weatherproof junction box and/or Quick Connect Terminals.

Product Description and Application

Each PVL (photovoltaic laminate) utilizes the proprietary Triple Junction solar cells manufactured by *UNI-SOLAR*. These cells are made in a roll-to-roll deposition process on a continuous roll of stainless steel. The result is a unique, flexible, lightweight solar cell.

The *UNI-SOLAR* PV Laminates are encapsulated in UV stabilized polymers making them exceptionally durable.

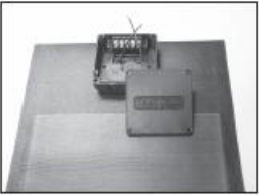
Bypass diodes are connected across each cell, allowing the modules to produce power even when partially shaded.

Application Criterion

- PVDF Coated (Galvalume® or Zinalume®) steel metal pan
- Steel pans with flat surface (without pencil beads or decorative stippling)
- 16" minimum steel pan width
- Installation temperature between 10°C - 40°C (50°F -100°F)
- Maximum roof temperature 85°C (185°F)
- Certified Installer
- Cleaned as per manufacturer's instructions
- New or qualified new roof installations

Quick Connect


Quick Connect With Junction Box


Junction Box


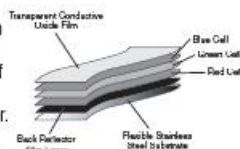
UNI-SOLAR.

Figure 30. Solar Panel Specification Sheet Page 1

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Triple Junction Technology

The foundation of the new UNI-SOLAR PVL is the Triple Junction silicon solar cell unique to UNI-SOLAR. Each cell is composed of three semiconductor junctions stacked on top of each other. The bottom cell absorbs the red light, the middle cell absorbs the green light and the top cell absorbs the blue light. This spectrum splitting capability is the key to higher efficiency.

**United Solar Ovonic**

United Solar Ovonic is the world leader in thin-film technologies. It's a company with years of experience in photovoltaics and is backed by a U.S. technology leader, Energy Conversion Devices, which holds 350 U.S. patents and 800 foreign patents. Our technology has proven itself over decades under the most extreme conditions imaginable, including satellites, ocean buoys and military applications. We offer a proven product, a proven technology, from a proven company.

Dimensions & Specifications**Physical:**

Model Number	Laminate Length	Laminate Width	Laminate Thickness	Weight	Minimum Slope	Maximum Slope
PVL-29T	4 ft. 7 1/2 in.	15 1/2 in.	0.12 in.	4.1 lb.	1:12 (5°)	21:12 (60°)
PVL-58T	8 ft. 6 3/4 in.	15 1/2 in.	0.12 in.	8.2 lb.	1:12 (5°)	21:12 (60°)
PVL-64T	9 ft. 4 1/8 in.	15 1/2 in.	0.12 in.	9 lb.	1:12 (5°)	21:12 (60°)
PVL-87T	12 ft. 6 1/4 in.	15 1/2 in.	0.12 in.	12.3 lb.	1:12 (5°)	21:12 (60°)
PVL-116T	16 ft. 5 1/4 in.	15 1/2 in.	0.12 in.	16.5 lb.	1:12 (5°)	21:12 (60°)
PVL-128T	18 ft.	15 1/2 in.	0.12 in.	17 lb.	1:12 (5°)	21:12 (60°)

Electrical:

Performance	PVL- 29T	PVL- 58T	PVL-64T	PVL-87T	PVL-116T	PVL-128T
Rated Power (Watts)	29	58	64	87	116	128
Nominal Operating Voltage	6	12	12	18	24	24
Operating Voltage (Volts)	7.5	15	16.5	22.5	30.0	33.0
Operating Current (Amps)	3.88	3.88	3.88	3.88	3.88	3.88
Open-Circuit Voltage (Volts)	10.8	21.6	23.8	32.4	43.2	47.6
Open-Circuit Voltage (Volts) at -10°C and 1250 W/m ²	12.3	24.6	27.1	36.9	49.2	54.2
Short-Circuit Current (Amps)	4.8	4.8	4.8	4.8	4.8	4.8
Short-Circuit Current (Amps) At 75°C and 1250 W/m ²	6.3	6.3	6.3	6.3	6.3	6.3
Series Fuse Rating (Amps)*	8	8	8	8	8	8
Min. Blocking Diode (Amps)	8	8	8	8	8	8

NOTES:

During the first 8-10 weeks of operation, electrical output exceeds specified ratings. Power output may be higher by 15%, operating voltage may be higher by 11% and operating current may be higher by 4%.
Electrical specifications (+/-10%) are based on measurements performed at standard test conditions of 1000 W/m² irradiance, Air Mass 1.5, and Cell Temperature of 25°C after long-term stabilization. Actual performance may vary up to 10% from rated power due to low temperature operation, spectral and other related effects.
Maximum system open-circuit voltage not to exceed 600 VDC.
Specifications subject to change without notice.

* Refer to section 690.6 of the National Electric Code for an additional factor of 125%, which may be applicable.

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Figure 31. Solar Panel Specification Sheet Page 2