SPECIFIC ENERGY YIELD OF LOW-POWER AMORPHOUS SILICON AND CRYSTALLINE SILICON PHOTOVOLTAIC MODULES IN A SIMULATED OFF-GRID, BATTERY-BASED SYSTEM

HUMBOLDT STATE UNIVERSITY

By

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Some amorphous silicon (a-Si) photovoltaic (PV) manufacturers claim that their power ratings at standard test conditions (STC) understate the performance of their modules because of a-Si technology’s ability to achieve 10-15% higher energy yield per rated peak power ($W_p$) than crystalline silicon (c-Si) technology. I tested this claim in a simulated off-grid, battery-based system through a 12-month study of the energy yield of five a-Si and five c-Si PV modules with ratings between 14 to 20 $W_p$. The test was conducted in Arcata California, with a climate characterized by mild, rainy winters and dryer, often foggy, summers. The specific energy yield (energy yield per tested $W_p$) of the different types of modules was correlated to temperature, insolation, and clearness index (C.I.) data and compared between the groups and between individual modules.

The a-Si group outperformed the c-Si group in specific energy yield ($Wh/W_p$) over the 12-month period by 2.7%. While it was statistically difficult to isolate the effects of temperature and C.I. on specific energy yield, the results indicated that the a-Si group’s higher specific energy yield is due more to better performance in higher
temperatures rather than in low C.I. conditions. Two reasons that may account for a lower
difference in specific energy yield than reported in previous studies are Arcata’s mild
climate and the absence of a maximum power point tracker in the system. Both the best
and worst performing individual modules were a-Si, which illustrates that individual
module quality can outweigh any improved performance of a-Si technology.
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Many people were instrumental in helping me complete this project. First, I would like to thank my advisor and friend Arne Jacobson for conceiving of the idea and entrusting it to me, as well as for all of the guidance and instruction he gave me during my less-than-the-shortest-distance-between-two-points pursuit of my Masters Degree.

Charles Chamberlin served on my committee and provided valuable insight throughout the project. Sharon Brown was an original member of my committee and helped conceptualize the project as a whole. After she moved away from the area, Chris Dugaw stepped in to serve on my committee and helped bring this project to completion.

I have to thank everyone at the Schatz Energy Research Center who provided technical and moral support during this project, particularly Scott Rommel who masterminded the electronics of the array and shared in the frustrations of getting everything running right. My fellow students were a continual source of inspiration and amusement. Ranjit Deshmukh helped edit the data processing software, and Douglas Saucedo’s brilliant data analysis and modeling skills were essential in the beginning phases of the project. Without the aid of Marty Reed, Equipment Technician and all around nice guy, the array would have fallen apart multiple times.

Thanks to my parents for providing support, encouragement, and patience through my many years of schooling. Finally, thank you to my wife Allyson and our daughter Leela for helping me stay focused on the important things in life.
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Four plots showing the four clearness index (C.I.) bins on a graph of average module temperature (T_a) versus percent difference in specific energy yield, with standard error bars shown.
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INTRODUCTION

As society recognizes the demand for clean, renewable energy, more effort is placed on the improvement of technologies such as solar photovoltaic (PV) modules. Two common types of modules are crystalline silicon (c-Si) and amorphous silicon (a-Si). Ratings for PV modules are generally reported as peak power ($W_p$) for standard test conditions (STC) of 1000 watts per square meter ($W/m^2$) insolation direct normal to the module and 25ºC, measured in a controlled laboratory setting. Real-world conditions rarely match the testing laboratory conditions exactly, so it can be difficult to accurately predict how an individual or type of module will perform in particular light and temperature conditions. Some a-Si PV manufacturers claim that their STC power ratings understate the real-world performance of their modules because of a-Si technology’s ability to achieve 10-15% higher specific energy yield, the energy yield per $W_p$, than c-Si technology, due to higher relative efficiencies both in diffuse light and at higher temperatures (Jacobson and Kammen, 2007, Van Cleef, 2001, Jansen, 2006).

Having a rating system that accurately reflects the expected energy yield of a PV module is important because consumers may wish to use the ratings to compare different products. Inaccurate ratings, whether because of the differences in technologies or poor quality control, may affect the acceptance of PV as a viable energy source. The typical user will not know if the rating of the module is accurate, only if the system is producing sufficient energy. In addition to any differences in the energy yield of the different
technologies, the measured peak power of most of the modules in this project was lower than their nominal ratings.

I conducted a 12-month study of the energy yield of ten low-power PV modules in a simulated off-grid, battery-based system. The study included five a-Si and five c-Si modules with ratings between 14 to 20 W_p. All of the amorphous modules were single junction a-Si PV technology, while the c-Si modules included a mix of monocrystalline and polycrystalline technologies. I measured the actual peak power for each of the modules and calculated the specific energy yield, defined as energy yield per tested peak power. The specific energy yield was correlated to temperature, insolation, and clearness index (C.I.) data and comparisons were made between the two groups and among the individual modules.

The project array location was on the roof of the Science D Building at Humboldt State University in Arcata, California (see map in Figure 1). Arcata is located in coastal Northern California and has a climate characterized by mild, rainy winters and dryer, often foggy, summers.

Twelve months of data, from July 2006 through June 2007, were used for this analysis. Data collection occurred every minute of daylight hours for the voltage, current, and temperature of each module, as well as ambient temperature, total solar insolation (power from the sun in W/m^2), and the voltage setpoint for the array. The voltage setpoint also changed every 30 minutes controlled by an algorithm based on battery voltages directly measured in small off-grid Kenyan systems.
Figure 1. Project location on the roof of the Science D Building, Humboldt State University in Arcata, California.
Two methods were used to analyze the data and report the findings. First, sums of daily average specific energy yield were reported for each month. These data show the a-Si group outperforming the c-Si group in the months of April through October by a small margin. The largest difference in specific energy yield between the two groups was 7.4% in July. The a-Si group is equal to or slightly below the c-Si group in November through March. The a-Si group also outperformed the c-Si group on average over the entire year by 2.7%. This suggests that while the a-Si modules in this study show a definite advantage over the c-Si modules in specific energy yield, the cause is more likely due to better performance in higher temperatures experienced in the summer months than any benefit in diffuse light conditions.

To further examine the effects on specific energy yield from temperature and diffusivity, the data were separated into nearly 20,000 ten-minute intervals through the year. The clearness index was calculated for each of the intervals by taking the ratio of the solar energy measured by the pyranometer at the array and the available solar energy at the same tilt at the edge of the atmosphere. The intervals were divided into a four-by-four matrix of average module temperatures ($T_a$) and clearness index. The a-Si group outperformed the c-Si group across the range of temperatures and clearness indexes except for in the bin with the lowest $T_a$ and C.I. values.

As in the monthly analysis, the a-Si group had an average specific energy yield 2.7% higher than the c-Si group over the 12-month period. Temperature appeared to play a greater role in the a-Si group’s improved performance than clearness index, although
the two effects are difficult to isolate statistically. The mild temperatures of the testing location may have contributed to the small relative difference between the two groups.

Furthermore, the worst individual performer was an a-Si module, so the differences between modules may be greater than the differences between groups. This study presents no clear support for a different rating system for a-Si modules alone. An overall change in the rating system for all PV modules that more accurately predicts the expected energy yields could be warranted. Finally, failure of one out of the twelve original modules and the low tested to rated peak power ratio for all of the modules both call for greater diligence in the manufacture and testing of low power PV modules sold in markets like they are in Kenya. In addition to what was learned from the data collection, we have also acquired considerable knowledge and experience in conducting long-term PV tests and will be able to build on that experience for future testing projects and make it available to others wishing to conduct similar experiments.

This project is a continuation of the work performed by my advisor, Dr. Arne Jacobson, in his Ph.D dissertation (Jacobson 2004), and in subsequent research (Jacobson and Kammen, 2007). My involvement in the project began as a graduate student research assistant at the Schatz Energy Research Center (SERC) at Humboldt State University in 2006. Dr. Jacobson had conceived of an idea to test a-Si solar module manufacturer’s claims that their modules had higher specific energy yields in high temperature and diffuse light conditions. I was involved in all aspects of the project, from the design,
construction, and wiring of the test array through the day-to-day maintenance, troubleshooting, and data collection, to the final analysis and reporting of the data.

The next chapter is a literature review with discussions on the research leading up to this project, how PV works, and previous energy yield tests. The remainder of this thesis report consists of a discussion of the methodology, the results of the data analysis, and conclusions and recommendations. A glossary of some common electrical terminology used throughout this thesis report is included as Appendix A. Appendices B through H contain background material and sample spreadsheets used in the analyses.
LITERATURE REVIEW

This chapter begins with an introduction to how PV works and some of the differences between a-Si and c-Si technologies. Next is a discussion of research on the issues of PV product quality in Kenya, which provides much of the background for this thesis project. Following is a review of some of the applicable research done on the energy yields of specific PV technologies, both by independent research laboratories and in manufacturer-sponsored reports.

How PV Works

Photovoltaic modules directly convert the sun’s power into electricity. This section will provide a brief description of how photons from the sun are converted into electricity that can be used to power loads or charge batteries.

A PV cell is made up of two or more layers of a semiconductor material, most commonly silicon. The layers are intentionally doped with impurities, generally phosphorous and boron. The silicon layer doped with phosphorous is called n-type and has extra electrons. The boron layer is called p-type and has fewer electrons. When struck by a photon of sunlight, an electron is freed and travels from one layer to the other. The electron is directed through a path along positive and negative leads to flow through a circuit to return to its original layer. This flow of electrons through a circuit produces a current, which is electricity that can be used to power loads. In addition to the silicon
layers, a typical solar module will also have a protective glass cover, an anti-reflective coating, and contact grid layers (US Department of Energy 2006).

A c-Si module is made up of a number of pairs of thin slices of crystals wired together in parallel (positive connected to positive, negative connected to negative) to increase the voltage. An a-Si module is composed of a non-crystalline form of silicon layered in thin sheets. Amorphous silicon modules require less energy input to produce, resulting in lower costs. Crystalline silicon modules have greater efficiencies than a-Si modules in terms of power output per surface area. This means that to have the same power output, an a-Si module would need to be larger than a c-Si module of the same rating. In terms of cost per watt they would be approximately equal or the a-Si may be somewhat less. (US Department of Energy, 2006).

Amorphous silicon modules experience an initial period of performance drop, known as Staebler-Wronski degradation, during their first few months of exposure to sunlight. The amount of degradation and time before stabilization varies between manufacturers, so it is often difficult to predict an a-Si module’s stabilized performance from its initial performance (Staebler and Wronski, 1977, cited in Duke, et al., 2002, and Jacobson and Kammen, 2007). The a-Si modules in this project were all given a “light-soaking” period until their measured peak power output stabilized.

Kenyan Solar

The background for my thesis project stems from Arne Jacobson’s research into the Kenyan solar PV market. In Jacobson and Kammen (2007), the authors discuss issues
in the Kenyan PV market and the results of tests of PV modules commercially available in Kenya.

Kenya has one of the largest per capita solar markets in the developing world, but little oversight has led to concerns about product quality. Five brands of a-Si solar modules available in the Kenyan market were tested in 2004 and 2005 to compare their post light-soaking peak power to the manufacturers’ ratings. Two of the five modules performed well below their rated specifications, while three were measured near 12 W for a 14 W rating. The manufacturers had already said that the correct stabilized power output for their modules was 12 W, so the performance corresponded to expectations. Nonetheless, the modules were being sold on the Kenyan market with a 14 W rating. Jacobson and Kammen’s article also reports on the authors’ tests of Kenyan solar modules in 1999, which resulted in the removal of some underperforming brands from the market, and encouraged other brands to improve their product.

Energy Yield Tests

Some of the a-Si manufacturers claim that brands of a-Si modules have been shown to produce 15% more energy per rated W_P than c-Si modules. In Van Cleef, et al. (2001), the authors observed up to 20% higher energy yield per peak power and attribute this to higher performance in diffuse light and high temperature, and greater tolerance for shading. Tests are cited that indicate higher relative performance by not only the Uni-Solar triple junction a-Si modules, but also show single-junction a-Si modules outperforming c-Si modules.
These claims are based primarily on a Dutch study by Eikelboom and Jansen (2000) using indoor and outdoor tests conducted on nine solar modules of different technologies. I-V curves were taken at a number of temperatures and irradiances using a test rig with a mobile robot positioner and were used to calculate module efficiencies, defined as the ratio between output power and incident irradiation on the entire module area. The a-Si modules were tested pre-degradation and were scaled to yield manufacturer specified nominal power. An indoor flash tester was used to also produce I-V curves as well as temperature coefficients. The resulting data were used in a computer model to estimate annual energy yields per stated peak power.

The modules with the highest specific energy yields (kWh/kW<sub>P</sub>) were both a-Si technology. The researchers attribute the high performance of the a-Si modules to their low temperature coefficients and excellent low light level characteristics.

The results of the Dutch study (Eikelboom and Jansen, 2000) are questionable for several reasons. The methodology for estimating the performance in low light conditions involved tilting the modules away from the sun, which does not accurately simulate all low light conditions. The energy yield data are determined through an untested model as opposed to direct measurements. The a-Si modules were tested pre-Staebler-Wronski degradation, and the peak power was scaled to manufacturers’ stated ratings in a way that may not accurately reflect performance. The researchers also provide the disclaimer that the modules used were not all purchased on the free-market, which allows for the possibility of manufacturers “cherry-picking” their best modules for testing. They also
state that the number of modules in the study is too small to draw any general conclusions. Finally, independent studies by other researchers have not replicated Eikelboom and Jansen’s results.

The following study benefits from being a direct comparison of energy output instead of using a model. Jardine (2002) studied two solar arrays, one in London, UK, and the other in Mallorca, Spain. Both arrays were made up of 11 subarrays of different technologies, including triple, double, and single-junction a-Si, single and multi-junction c-Si, copper indium diselenide (CIS), and cadmium telluride (CdTe) cells. The two arrays were 6.2 kW<sub>P</sub> each, and the subarrays ranged from 512 to 640 W<sub>P</sub> each. The authors did not report the number of modules in each subarray. The array in London was tested for one year and the array in Mallorca was tested for two years. Data were recorded over the course of the test periods and used to calculate specific energy yields.

The multi-junction a-Si and CIS subarrays were found to have the highest specific energy yields, while the single junction a-Si and CdTe subarray had the lowest. They also reported that a-Si modules in general perform better than c-Si modules under high temperatures and diffuse lighting, while c-Si modules perform better in low temperature conditions.

Testing a wide variety of modules in different locations set up in subarrays helps instill confidence in the comparison between technologies. While all a-Si modules were found to benefit from high temperature and diffuse light effects, only the multi-junction a-Si modules showed an overall higher energy yield than c-Si modules. The authors
stated that due to potential inaccuracies from manufacturers’ rated peak power, insolation measurements, and inverter power levels, the absolute energy yield values they report may be inaccurate. They attest that the conclusions about the physical responses of the different technologies still hold true. Furthermore, the London array was installed at a tilt of $13^\circ$ and orientation of $5^\circ$ W of south. The Mallorca array was at a $25^\circ$ tilt and orientation $15^\circ$ W of south. Both of the arrays were tilted at a sub-optimal angle that would benefit performance in the hotter summer months when the sun is higher in the sky. This could lead to overall specific energy yield performance results favoring a-Si modules.

The overall energy yield advantage for a-Si modules is contradicted by Fairman, et al. (2003), who report on a year-long study conducted in a desert climate in Israel testing the energy yield of a-Si and c-Si modules. Both mono and polycrystalline c-Si modules were used. Monthly hourly energy yield averages, irradiance data, and measured peak power output were used to calculate system efficiency and specific energy yield. The results showed higher specific energy yields (termed specific energy delivery) for the a-Si modules throughout the months from March through September, with the c-Si modules performing slightly better for the rest of the year. The data were then examined on an hourly basis for the months of March, June, September, and December. For the first three months, the a-Si modules outperform the c-Si modules during the mid hours of the day, while for all hours in December and the morning and evening hours for the entire year, the c-Si modules performed better. Overall, both the multi and mono-c-Si modules
had a higher specific energy yield than the a-Si modules, though the difference was only 3% from highest to lowest. The authors attribute the differences between the modules types to spectral shifts in light and temperature effects. The two effects are related and not isolated in this study. This report uses the measured peak power values rather than the rated values, which makes it similar to my project. The data are examined only on a monthly basis for the year and hourly for four months. Temperature and insolation conditions are presumed by time of day and year rather than from actual measurements. These shortcomings make it difficult to accurately assess the effects of temperature and insolation on specific energy yield, although it should not affect annual results. Considering the evidence for a temperature effect on a-Si modules specific energy yields, especially through direct measurements of temperature coefficients, it is surprising that the warmer desert climate did not produce higher results for the a-Si modules.

While the studies cited above have conflicting results, the evidence builds that peak power at STC alone does not accurately predict the energy yield of different technology PV modules. A case is made for a photovoltaic rating system based on energy yield over a range of temperatures and insolation rather than peak power at standard test conditions in two recent articles by Kenny, et al. (2005 and 2006). Tests were made in the laboratory and then specific climatic data were used to make energy predictions. Energy yield data were then collected for the same modules over the course of the year and compared to the energy yield predictions, with favorable results. The goal of the
experiment was to develop an energy yield rating system that would be both relatively simple to execute while more accurately predicting performance than the current STC rating system. For simplicity, the authors did not consider effects of light diffusivity or spectral differences.

They concluded that using only insolation and temperature data is not sufficient to accurately predict the energy yield of thin film PV modules, and that the effects of spectral variations must be accounted for. The tests are conducted by taking multiple I-V curve measurements throughout the day while the module is mounted on a solar tracking device to keep it oriented directly normal to the sun. The purpose of the solar tracker is to negate any effect of angle of incidence. The spectral variations are calculated from the amount of air mass the sunlight must pass through at the time of the test. The results show that the performance of the thin film modules is influenced by changes in the solar spectrum. Accounting for changes in the solar spectrum in energy yield is difficult, however, because haze and clouds significantly modify the spectrum and are difficult to predict.

The multi-junction a-Si and CIS modules were the best performers in specific energy yield. The a-Si modules overall performed better in higher temperatures, while the c-Si modules performed better at lower temperatures. As in other studies, this study used the manufacturers’ rated peak power instead of the actual tested peak power.

An article by Drews, et al. (2008), discusses the use of irradiation maps to predict the energy yield of PV installations based on their rated peak power. Ten PV installations
in the German state of Saxony ranging from 0.75 to 92 kW_p of installed power
were tested. The specific energy yield (kWh/kW) was predicted using the irradiation
maps and compared to the actual specific energy yields. The relative errors between the
modeled and measured specific energy yields ranged from -7.3 % to 8.4%, with the mean
of absolute errors being 4.65%. This result shows the potential for inaccuracies in energy
yield predictions using rated peak power at STC and irradiation data and the need for a
more refined approach to rating PV modules.

Another example of an a-Si PV manufacturer claiming better energy yield
performance is found in an article by K.W. Jansen, et al. (2006). The study, published by
researchers at Energy Photovoltaics, Inc, an American subsidiary of a German PV
manufacturer, claims 18% greater specific energy yields for a-Si PV modules compared
to c-Si over the course of a one-year test in central Florida, with the greatest gains during
high temperature times. While the results coming directly from a manufacturer should be
interpreted with caution, the article is interesting in that it also calculates the total
installed cost for electricity. The cost for electricity for the a-Si arrays was calculated at
$0.168 - $0.190/kWh compared to $0.203/kWh for the c-Si. The results are also in doubt
because they were based on the rated peak power of two nine-module a-Si arrays,
potentially hand-selected by the manufacturer, and a single, un-specified c-Si module.

*Differences between this Project and Previous Research*

My thesis project adds some different elements and procedures to the research
discussed above. This project investigates the energy yield of low-power modules in a
simulated battery-based, off-grid system. Previous studies concentrated on higher power modules in grid-connected AC arrays. This difference will yield results more applicable to the type of modules and available in markets in sub-Saharan Africa and other “developing world” markets.

The voltage setpoint in this study was determined by a probability algorithm based on actual recorded voltages from Kenyan households with battery-based PV systems instead of the maximum power point trackers used in other studies. Maximum power point trackers keep the voltage at the point that will maximize the product of the current and voltage, resulting in peak power output (see the following chapter for more discussion on calculating peak power from I-V curve measurements).

This study differs from previous research not only in the how the data are collected, but how they are analyzed. Instead of calculating specific energy yield using the rated peak power, as in most of the previously cited reports, I use my I-V curve test results to calculate the modules’ actual peak power. The resulting specific energy yield more closely compares differences in PV technology because inaccuracies in modules ratings are removed as a contributing variable. Also, statistical methods are used to attempt to isolate the effects of temperature and clearness index on the differences in specific energy yield.

Finally, the climate in Arcata is also different than that in other studies. The mild, foggy summers are likely a contributing factor in the smaller difference in specific energy yields compared to some reported by other research.
METHODOLOGY

This chapter includes discussions of the mechanics of setting up the test array, descriptions of the modules used, I-V solar module testing procedures, and the algorithm for setting the module voltage operating points during the test. The collection, processing, and analysis of the data are discussed in the data collection and analysis section at the end of this chapter.

Description of Modules in the Project

Thirteen PV modules were tested throughout this project, with the data from ten being used in the final analysis. The study initially began with twelve PV modules: six a-Si and six c-Si. One of the a-Si modules, ICP-2, failed in November 2006 and was removed from the array and replaced with another a-Si module, Sunsei-1. Data for these two modules were not included in this report or in any of the averages. A decision was made to not include data from the c-Si module Sangyug-1 because it does not appear to have the same type of anti-reflective coating found on the other modules; this factor could be a separate variable influencing its performance. All of the modules were purchased on the open market in Kenya and represent the type of low-power modules available for sale from different manufacturers and distributors. Detailed discussion of solar PV market conditions can be found in Arne Jacobson’s Ph.D. dissertation (Jacobson, 2004), and other research (Duke, et al., 2002; Jacobson and Kammen, 2007).
The thirteen modules used throughout this project, their specifications, country of origin, and manufacturers’ ratings are listed in Table 1. All of the a-Si modules had been light soaked for at least six months prior to their inclusion in this study and consecutive I-V tests indicated that their maximum power had stabilized following Staebler-Wronski degradation. (See the Literature Review chapter for more information on a-Si technology and Staebler-Wronski degradation.)

Test Array

The test array was built in the spring of 2006. The twelve modules were mounted on a wooden rack facing due south at a 41° tilt: this tilt angle is approximately equal to the 40.87° latitude of the test site (Arcata, CA). Figure 2 is a photo of the array showing the location of each of the modules. The modules were spaced so that both the two groups of modules and modules of the same manufacturer would be spread out on the array. Also, a wind block was constructed behind the array to prevent uneven cooling from the breeze.

Positive and negative leads from each of the modules were connected to the control and datalogging box, which is shown in Figure 3, with a description of the major components in Table 2. Figure 4 is a photo from underneath the array showing the module positive and negative leads and thermocouple wiring. Figure 5 provides a simplified schematic of the overall system. The modules’ positive leads first pass through a 2 amp fuse to protect the datalogging equipment, then to a bus bar connected to an Executive Engineering EE30180A electronic load, regulated by a Campbell Scientific
Table 1. The thirteen solar PV modules in the study array. Module 5a failed in November 2006 and was replaced by module 5b. Results from module 1 were not used in the analysis because it does not appear to have an anti-reflective coating.

<table>
<thead>
<tr>
<th>Location</th>
<th>Module ID</th>
<th>Company/Brand</th>
<th>Country</th>
<th>Type</th>
<th>W_p</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sangyug</td>
<td>Sangyug Enterprises</td>
<td>India</td>
<td>c-Si</td>
<td>15</td>
<td>Not included in analysis</td>
</tr>
<tr>
<td>2</td>
<td>Suntech 1</td>
<td>Suntech</td>
<td>China</td>
<td>c-Si</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>FEE 3</td>
<td>Free Energy Europe</td>
<td>France</td>
<td>a-Si</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Photon 1</td>
<td>Photon</td>
<td>China</td>
<td>c-Si</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>5a</td>
<td>ICP-2</td>
<td>ICP Solar</td>
<td>UK</td>
<td>a-Si</td>
<td>14</td>
<td>Failed Nov. 2006. Not included in analysis</td>
</tr>
<tr>
<td>5b</td>
<td>Sunsei 1</td>
<td>ICP Solar</td>
<td>UK</td>
<td>a-Si</td>
<td>14</td>
<td>Added Nov. 2006 to replace 5a. Not included in analysis</td>
</tr>
<tr>
<td>6</td>
<td>FEE 1</td>
<td>Free Energy Europe</td>
<td>France</td>
<td>a-Si</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>SC-1</td>
<td>Solar Cells</td>
<td>Croatia</td>
<td>a-Si</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Solarex 2</td>
<td>Solarex</td>
<td>USA</td>
<td>c-Si</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Solarex 1</td>
<td>Solarex</td>
<td>USA</td>
<td>c-Si</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>SC-2</td>
<td>Solar Cells</td>
<td>Croatia</td>
<td>a-Si</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>ICP-1</td>
<td>ICP Solar</td>
<td>UK</td>
<td>a-Si</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Suntech 2</td>
<td>Suntech</td>
<td>China</td>
<td>c-Si</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>
Figure 2. The project array, located on the roof of Science D building at Humboldt State University, showing the modules listed in Table 1
SDM A04 analog output module and controlled by a Campbell Scientific CR10X datalogger. From there they are connected through 1:20 voltage dividers into a Campbell Scientific AM16/32 voltage multiplexer, from where the voltage is recorded by the datalogger.

The negative leads from the modules are wired into a series of Simpson Electric 25 amp current shunts across which the voltage drop is measured to calculate the current. Type K thermocouples were secured with metallic tape to the back of each module and covered in insulating material. The thermocouples were wired into the control box where the temperature of each of the modules was recorded. The ambient temperature was measured with a Type K thermocouple protected in a radiation shield. The four shade sensors and Eppley PSP pyranometer are also wired into the datalogger. A Campbell Scientific COM200 Modem was used to download the datapoints to a remote PC server.

Every minute the datalogger recorded the following general data: date, time, ambient temperature, voltage setpoint, solar insolation, and control box temperature; and the following module-specific data: voltage, current, and temperature. The datalogger had a memory capacity for just over two day’s of data, and the data were downloaded to the remote server once daily just after midnight. It was important to check the server regularly to make sure the connection to the modem was functioning properly. The downloaded and real-time data were scanned on a regular basis for any irregularities that might indicate any equipment malfunctions. Other general maintenance included cleaning the twelve modules and the Eppley PSP pyranometer on a weekly basis.
Table 2. Description of the major components in the control box shown in Figure 3, and the two pyranometers.

<table>
<thead>
<tr>
<th>ID (in Figure 3)</th>
<th>Part</th>
<th>Manufacturer</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Datalogger</td>
<td>Campbell Scientific</td>
<td>CR10X</td>
</tr>
<tr>
<td>2</td>
<td>Electronic Load</td>
<td>Executive Engineering</td>
<td>EE30180A</td>
</tr>
<tr>
<td>3</td>
<td>Voltage Multiplexer</td>
<td>Campbell Scientific</td>
<td>AM16/32</td>
</tr>
<tr>
<td>4</td>
<td>4-Channel Continuous Analog Output Module</td>
<td>Campbell Scientific</td>
<td>SDM-A04</td>
</tr>
<tr>
<td>5</td>
<td>Thermocouple Multiplexer</td>
<td>Campbell Scientific</td>
<td>AM25T C/S</td>
</tr>
<tr>
<td>6</td>
<td>25 A Current Shunts</td>
<td>Simpson Electric</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>12 V Battery</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>12 V Power Supply</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Desiccant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>2 A Fuses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Modem</td>
<td>Campbell Scientific</td>
<td>COM200</td>
</tr>
<tr>
<td>Figures 2 and 5</td>
<td>Pyranometer</td>
<td>Eppley</td>
<td>Eppley PSP</td>
</tr>
<tr>
<td>Figure 8</td>
<td>Pyranometer</td>
<td>Licor</td>
<td>LI-200SA</td>
</tr>
</tbody>
</table>

See manufacturers’ websites for specifications:

http://www.campbellsci.com/
http://www.simpsonelectric.com
http://www.eppleylab.com/
http://www.exec-eng.com/product/product.htm
http://www.licor.com/
Figure 3. The control and datalogging box, with the main components numbered referring to their descriptions in Table 2.
Figure 4. View beneath the array showing the wiring of the thermocouples and modules positive and negative leads. The thermocouple sensors are attached to the center of the back of the modules and covered in insulating material.
Figure 5. Simple flowchart showing the data collection process for the PV array. For readability, the 12 PV modules and 4 shade sensors are grouped in the flowchart, but they are wired separately in the array. Major components are listed in Table 2.
Sensor Precision

The precision of the measurements was dependent on the precision of the sensors used in the array. The ranges and precisions of these devices are summarized in Table 3. The array insolation was measured by the Eppley PSP pyranometer, which has an operating range of 0-2800 W/m² and a stated precision of ±30 W/m². Because the array insolation is a common measurement for all the modules, this precision does not affect the direct comparison between the modules or the calculations of specific energy yield. The clearness index is calculated from the ratio measured insolation to extra-terrestrial insolation, so the resulting potential error in clearness index is the sensor error divided by the average extra-terrestrial insolation: ± 30 Wm⁻² / 1367 Wm⁻² = ± 0.02.

The temperature was measured using Type K thermocouples, with an operating range of -201150 °C with a precision of ± 2.2°C. The thermocouple multiplexer has a range of -4085 °C with a precision of ±0.4 °C. The total potential temperature measurement error is ±2.9 °C. This error affects the ambient temperature and average module temperature used to distribute the specific energy yields into bins. The comparison between modules is not affected because the same average module temperature is used for all modules.

Potential error in the current and voltage measurements stems from the 1:20 voltage dividers and current shunts, both of which have error of ±1% of the total measurement. Both the voltage and current recordings were calibrated against direct measurements made with a voltmeter to correct for this error, so potential measurement error is considered negligible.
Table 3. Sensor equipment, ranges, and precisions.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Range</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eppley PSP Pyranometer</td>
<td>0-2800 W/m²</td>
<td>± 30 W/m²</td>
</tr>
<tr>
<td>Type K Thermocouple</td>
<td>-40 - 333 °C</td>
<td>± 2.2 °C</td>
</tr>
<tr>
<td>Thermocouple multiplexer</td>
<td>-40 - 85 °C</td>
<td>± 0.4 °C</td>
</tr>
<tr>
<td>Simpson 25 A Current Shunts</td>
<td>± 1%</td>
<td></td>
</tr>
<tr>
<td>Voltage Dividers</td>
<td>± 1%</td>
<td></td>
</tr>
<tr>
<td>CR10X Datalogger</td>
<td>±2500 mV</td>
<td>±333µV</td>
</tr>
</tbody>
</table>

The Campbell Scientific CR10X datalogger has a precision of ±333µV in the full scale input range of ±2500 mV. For a voltage measurement of 8 V, which records as 400 mV after the voltage dividers, the potential error is less than 0.1%.

Voltage Setpoints

Every 30 minutes, the voltage setpoint is changed based on a probability algorithm developed from recordings of actual operating voltages. These operating voltages were collected from multiple Kenyan battery-based off-grid PV systems by Jacobson during 2003 (Jacobson, 2004). Battery voltages for fifteen household PV systems in two communities were collected on five-minute intervals for periods ranging from four to six months. Douglas Saucedo, a graduate student at HSU and research assistant at SERC, created a random voltage setpoint generator based on the probability
distribution of the collected data. He used a stochastic model to generate voltage levels that closely approximate the distribution of the sampled data, tested against 300 days of randomly selected battery voltage data from 11 different households. See Appendix B for a more detailed explanation of the battery voltage probability analysis. An Executive Engineering E830180 electronic load controlled by a Campbell Scientific SDM A04 four-channel continuous analog output module regulated the voltage setpoint based on a 5th degree polynomial algorithm. A histogram and a cumulative probability graph of the voltage setpoints for the simulation and measured battery voltages from in the Kenyan PV systems are shown in Figure 6. The distribution of the test system’s voltage setpoints closely approximates the actual Kenyan battery voltage data.

*I-V Curve Testing*

To determine the actual peak power point ($W_p$) of the individual PV modules, I-V curve measurements were taken at regular intervals throughout the testing period. An I-V curve is a plot of the modules’ current (I) in amperes (commonly shortened to amps) and the voltage (V) in volts measured over a varying load or resistance. The test measurements are normalized for the standard test condition (STC) temperature of 25º C and insolation of 1000 W/m². Current is affected primarily by changes in the insolation
Figure 6. A cumulative probability diagram and histogram comparing the distributions of 31 days of simulated voltages and 300 days of randomly selected battery voltages as measured in 11 Kenyan off-grid PV systems.
striking the module, and voltage is affected primarily by the temperature, so current and voltage are normalized for STC accordingly using Equations 1 and 2, respectively (Chamberlin et al., 1995). The module temperatures during the I-V tests ranged from 48.1 to 65.4 °C, and the insolation ranged from 976 to 1037 W/m².

\[
I_n = I_m \left( \frac{1000 \text{w/m}^2}{E} \right) \tag{Equation 1}
\]

where: \( I_n \) = normalized current (A)  
\( I_m \) = measured current (A)  
\( E \) = mean measured insolation on plane of PV module (W/m²)

\[
V_n = V_m + V_m \times \left\{ b \times (25°C - T) \right\} \tag{Equation 2}
\]

where: \( V_n \) = normalized voltage (V)  
\( V_m \) = measured voltage (V)  
\( b \) = temperature coefficient (1/°C)  
\( T \) = mean measured module temperature during test (°C)

The temperature coefficient is a measurement of the temperature effect on each module and is described further in the next section. Current in amps multiplied by voltage in volts equals power in watts (see Appendix A for a glossary of common electrical terminology used in this report). Figure 7 shows an I-V curve for the module Solarex 2. The peak power point is indicated with dashed lines, showing the rectangle with the greatest area that can be inscribed beneath the curve. As shown in the sample I-V curve in Figure 7, current is plotted against voltage producing a characteristic curve. The peak
power point is found near the knee of the curve, where amps multiplied by volts yields the highest value for watts.

Figure 8 shows a typical I-V set up for one of the test modules. A sunny day, free from haze and clouds, is chosen for the I-V test. The tests for the 12 modules are all completed on the same day, in a time window near solar noon when the atmospheric air mass, a measurement of the path length in the atmosphere sunlight needs to travel through to reach the Earth’s surface, is less than two. The module is prepared for testing

Figure 7. An I-V curve for module Solarex2, taken at the end of the year of data collection, July 2, 2007. Two runs are graphed with the data corrected for standard test conditions (25°C and 1000 W/m²). The peak power point ($W_P$) is indicated by the dashed blue line.
by removing it from the test array, cleaning it, and placing it on a test rack. The test rack holds the module in the same plane as a Licor pyranometer, which has been calibrated against the Eppley PSP pyranometer from the array, and uses a simple tube device to allow the tester to orient the module’s surface directly normal to the sun. A type K thermocouple is attached to each module to record the temperature. The positive and negative leads of the module are connected to the variable resistive load and I-V tester. The pyranometer and thermocouple are both connected to multimeters. The rack is then

![Figure 8. The author performing an I-V test on an a-Si PV module.](image)
oriented to be directly normal to the sun and the load is increased from $I_{SC}$ to $V_{OC}$ while the average insolation and temperature are recorded by two multimeters. To ensure precision, two runs are taken for each module. To smooth the curve and correct for the possibility of missing datapoints, an $8^{th}$ degree polynomial was fit to the curve. The polynomial equation is used to compute values for voltage and current, and the peak power point is determined from the maximum value of the product. A sample I-V curve spreadsheet is included in Appendix C. See Jacobson, et al (2000) for a more detailed description of the I-V testing method and equipment.

The ten modules were tested four times to measure their peak power output. The first test occurred well before the data collection period, and other tests were conducted at the beginning, middle, and end of the data collection period. The second set of I-V tests, conducted just before the beginning of the test period on June 20, 2006, was used to calculate the specific energy yield values. For an explanation as to why these maximum power values were used, see the section titled Rated vs. Tested Maximum Power on page 43, later in this chapter.

Every module, except for the Photon, tested lower than the manufacturers’ STC ratings. Table 4 shows the results of the four tests and rated peak power output for the ten modules in the study. Lower test results than the rated peak power values indicate that the module’s performance will be lower than claimed by the manufacturer. In the last test on July 2, 2007, the tested peak power for six out of the ten modules rose by some amount.
Table 4. The rated peak power at standard test conditions and results of the four I-V tests done throughout the testing period.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>FEE1</td>
<td>14</td>
<td>11.4</td>
<td>11.3</td>
<td>11.1</td>
<td>10.6</td>
</tr>
<tr>
<td>FEE3</td>
<td>14</td>
<td>10.9</td>
<td>10.8</td>
<td>10.4</td>
<td>10.2</td>
</tr>
<tr>
<td>ICP1</td>
<td>14</td>
<td>11.1</td>
<td>10.1</td>
<td>9.7</td>
<td>10.1</td>
</tr>
<tr>
<td>Photon1</td>
<td>20</td>
<td>23.9</td>
<td>21.8</td>
<td>21.9</td>
<td>20.9</td>
</tr>
<tr>
<td>SC1</td>
<td>14</td>
<td>11.4</td>
<td>10.9</td>
<td>10.6</td>
<td>11.2</td>
</tr>
<tr>
<td>SC2</td>
<td>14</td>
<td>11.9</td>
<td>11.9</td>
<td>11.4</td>
<td>12.2</td>
</tr>
<tr>
<td>Solarex1</td>
<td>20</td>
<td>17.7</td>
<td>17.4</td>
<td>16.2</td>
<td>17.5</td>
</tr>
<tr>
<td>Solarex2</td>
<td>20</td>
<td>18.0</td>
<td>17.7</td>
<td>17.3</td>
<td>17.8</td>
</tr>
<tr>
<td>Suntech1</td>
<td>20</td>
<td>18.3</td>
<td>17.3</td>
<td>17.2</td>
<td>15.7</td>
</tr>
<tr>
<td>Suntech2</td>
<td>20</td>
<td>18.0</td>
<td>17.4</td>
<td>16.9</td>
<td>17.7</td>
</tr>
</tbody>
</table>

**Temperature Coefficients**

To normalize the measured I-V data to STC conditions I had to calculate individual temperature coefficients for each module. The effect of temperature is primarily on the module’s voltage, so only the voltage measurement was normalized using the following procedures.

All of the modules were removed from the array on the evening of October 24, 2006, and kept inside overnight. On the morning of October 25, 2006, I cleaned the modules and brought them out onto the solar test rack one at a time. A type K thermocouple was attached to the back of the module and connected to a thermocouple...
reader, and the positive and negative leads from the module were connected to a
multimeter. Module temperature and $V_{OC}$ measurements were taken simultaneously as
the modules warmed up until the temperature stopped increasing. The temperature
coefficient was calculated with Equation 3, resulting in linear plots:

$$b = \left( \frac{V_{OC_i} - V_{OC_f}}{V_{OC_{ave}}} \right) / (T_f - T_i)$$

Equation 3

where: $b$ = temperature coefficient (1/°C)
$V_{OC_i}$ = the initial open circuit voltage (V)
$V_{OC_f}$ = the final open circuit voltage (V)
$V_{OC_{ave}}$ = the average open circuit voltage (V)
$T_i$ = initial temperature (°C)
$T_f$ = final module temperature (°C)

Temperature coefficients calculated using only open-circuit voltages were
considered sufficient for the low power modules in this study. A detailed discussion on
the importance of temperature coefficients in calculating PV module peak power and
some of the other methodology used can be found in a Sandia National Laboratories

The temperature coefficients for each of the modules are shown in Table 5 and the
spreadsheet showing the calculations and measurements is in Appendix D. The c-Si
group has a 19.2% lower temperature coefficient on average than the a-Si group. This has
important implications for the different technologies’ responses to temperature, and is
discussed in the next chapter.
Table 5. Temperature coefficients for the ten study modules. The c-Si group average is 19.2% lower than the a-Si group average.

<table>
<thead>
<tr>
<th>Module</th>
<th>Type</th>
<th>Temperature Coefficient (1/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suntech 1</td>
<td>c-Si</td>
<td>-0.0029</td>
</tr>
<tr>
<td>Photon 1</td>
<td>c-Si</td>
<td>-0.0026</td>
</tr>
<tr>
<td>Solarex 1</td>
<td>c-Si</td>
<td>-0.0035</td>
</tr>
<tr>
<td>Solarex 2</td>
<td>c-Si</td>
<td>-0.0035</td>
</tr>
<tr>
<td>Suntech 2</td>
<td>c-Si</td>
<td>-0.0029</td>
</tr>
<tr>
<td>FEE 1</td>
<td>a-Si</td>
<td>-0.0026</td>
</tr>
<tr>
<td>FEE 3</td>
<td>a-Si</td>
<td>-0.0027</td>
</tr>
<tr>
<td>SC 1</td>
<td>a-Si</td>
<td>-0.0022</td>
</tr>
<tr>
<td>SC 2</td>
<td>a-Si</td>
<td>-0.0025</td>
</tr>
<tr>
<td>ICP 1</td>
<td>a-Si</td>
<td>-0.0023</td>
</tr>
<tr>
<td>c-Si Group Mean</td>
<td>c-Si</td>
<td>-0.0031</td>
</tr>
<tr>
<td>a-Si Group Mean</td>
<td>a-Si</td>
<td>-0.0025</td>
</tr>
<tr>
<td>percent difference</td>
<td>Ave_{a-Si} – Ave_{c-Si}/ Ave_{c-Si}</td>
<td>19.2%</td>
</tr>
</tbody>
</table>

Shade Sensors and Analysis

The ten modules were fixed in position on the rack and the rack was oriented to maximize the amount of time all modules were not shaded by surrounding objects.

Because of the location of the array and seasonal changes in the path of the sun, however, it was impossible to not have some periodic partial shading of the array. Collecting data at these times of partial shading would skew the results in favor of those modules receiving more sun, because energy yield is a direct result of the total amount of insolation hitting the module over time.
Four inexpensive Electronix Express GM 684 12V 60mA PV modules (available at http://www.elexp.com/index.htm) were placed at each corner of the array with the idea that if the output from any of them differed significantly from the rest, partial shading was occurring (see Figure 2). Visual inspection and testing with a Solar Pathfinder™ ruled out the possibility of partial shading occurring without any of the corners being shaded. A Solar Pathfinder™ is a tool that can show the sun’s path across the sky through the year and any shading that will occur on a monthly basis. It is often used to estimate solar resource availability for a solar installation at a specific location (more information available at http://www.solarpathfinder.com/).

It proved to be challenging to determine what difference between the shade sensors’ outputs would indicate partial shading. The difference needed to be high enough to prevent false positives, i.e., a situation when the shade sensors indicate the corner of the array was shaded when it actually was not, and low enough to prevent false negatives, i.e., a situation when the shade sensors indicate the corner of the array was not shaded when it actually was. The output of the modules varied when all four were unshaded, and the degree of deviation from the mean changed with the amount of solar insolation. As solar insolation increases, the deviation from the mean for each of the modules changed at a different rate. Further complicating the process was the rapid degradation and failure of Shade Sensor 1. When installed they were nearly equal, while seven months later there was a 30% difference between the sensors with the highest and lowest average power output. Shade Sensor 1 was replaced with a new module in April 2007.
The winter months were of particular concern, because the sun’s low path across the sky results in the full array being unshaded for only a few hours a day. The Solar Data Cruncher (SDC) program, which was used to process the raw data and is described in the next section, was designed to discard all data collected when the deviation from the mean for the output of any of the four sensors was more than a set amount. Initial runs of the program with a single set deviation value yielded a large number of false positive events (i.e., data were discarded although no partial shading event had occurred). Tests with the Solar Pathfinder™ indicated that even near the Winter Solstice the entire array should be unshaded for at least a few hours each day.

After careful analysis of the data and repeated testing with the SDC program, I concluded that a stepped function of deviation values based on total insolation at the array was the most accurate method for determining partial shading events. When the insolation measured between 0 and 100 W/m², a difference above 15% indicated a partial shading event; from 100 to 600 W/m², the tolerance was 20%; above 600 W/m² the tolerance was 30%. The data were run through the program using the step function and then cross-checked point by point to determine if shade and non-shade events were occurring at logical times.

**Solar Data Cruncher Program**

The initial processing of the raw data was done using a MatLab® program titled the Solar Data Cruncher (SDC). This program was written by a fellow Humboldt State University graduate student and Schatz Energy Research Center employee, Douglas
Saucedo. Ranjit Deshmukh, another fellow Humboldt State University graduate student and Schatz Energy Research Center employee, assisted with later editing of the program. The full program code is provided in Appendix E.

The SDC program calculated watt-hours and efficiency for each module, and the average, minimum, and maximum module temperature. Using the shade sensing methodology described in the previous section, the program screens data occurring during partial shading events of the array. Data are also screened for times when the insolation recorded by the Eppley PSP pyranometer in the plane of the array is less than 10 W/m². Output files are in the form of either a monthly report with daily averages, or a daily report with minute by minute results. Both types of output were used in the analysis.

Data Analysis

The raw data for the two groups of modules, processed by the SDC program described above, were analyzed on the basis of monthly averages and in ten-minute intervals. The specific energy yield performance of the individual panels was also compared. This section also includes discussion on two decisions regarding which data to use in calculating and analyzing the specific energy yield. These decisions resulted in using the measured peak power point instead of manufacturers’ ratings, and the average module temperature instead of the ambient temperature or specific module temperature.
Monthly Summaries

The data were first analyzed on a monthly basis using daily averages. Appendix F contains sample spreadsheets that were used for this analysis. The monthly data generated by the SDC were used to calculate the average daily watt-hours and specific energy yield using both tested and rated peak power values. Maximum, minimum, and average values for module and ambient temperature were also calculated. From these calculations, averages were calculated for the a-Si and c-Si groups for all of the above data categories. The percent difference between the groups for all data categories was calculated by the Equation 4:

\[
\text{Percent difference} = \frac{\text{Ave}_{a-Si} - \text{Ave}_{c-Si}}{\text{Ave}_{all}}
\]

Equation 4

Based on local climate history, the percent difference provided an indication of the conditions under which each type of module performed the best. See the Results chapter for a discussion of the outcome of this analysis.

Ten-Minute Intervals

Because clearness and temperature conditions change multiple times throughout the day, data were next analyzed on a ten-minute basis. Periods of high temperature and high clearness are closely related, making it difficult to isolate their respective effects on specific energy yield. I hoped by analyzing the data in smaller time frames I might be able to isolate periods when the temperature was high but the clearness was low, or vice
versa. Daily summaries were run in the SDC for each of the 361 days for which there were usable data. The four missing days were July 14 and 31, 2006 and March 9 and 10, 2007, when datalogging malfunctions resulted in a loss of data.

Each day’s data were imported into a Microsoft® Excel spreadsheet (see sample day spreadsheet in Appendix G) that separated the data into 10-minute intervals and calculated a clearness index for each interval. The clearness index is the ratio of the solar insolation measured at the array and the calculated solar insolation available at the same tilt angle at the edge of the atmosphere. This calculation provides a reference, from 0-1, for the clearness of any given time of year. A low clearness index value means that there is little insolation reaching the array compared to the insolation available at the edge of the atmosphere. A clearness index of 1 means that the insolation reaching the array is equal to the insolation at the edge of the atmosphere, and none is being blocked. On rare occasions, a clearness index over 1 can occur due to light focusing by clouds. The formulae and constants involved in calculating the clearness index were adapted from Duffie and Beckman (1991) and are presented in Equations 5 through 15:

\[
C.I. = \frac{I_a}{I_T} \tag{Equation 5}
\]

\[
I_T = I_o \times R_b \tag{Equation 6}
\]
\[
I_0 = \frac{12 \times G_{sc}}{\pi} \times \left(1 + 0.033 \times \cos \left(\frac{360 \times n}{365}\right)\right) \times \\
\left(\cos(\Phi) \times \cos(\delta) \times (\sin(\omega_2) - \sin(\omega_1)) + \left(\pi \times \frac{\omega_2 - \omega_1}{180}\right) \times \sin(\delta) \times \sin(\Phi)\right)
\]
Equation 7

\[
R_h = \frac{\cos(\theta)}{\cos(\theta_2)}
\]
Equation 8

\[
\cos(\theta_2) = \sin(\delta) \times \sin(\Phi) + \cos(\delta) \times \cos(\Phi) \times \cos(\omega)
\]
Equation 9

\[
\cos(\theta) = \cos(\Phi - \beta) \times \cos(\omega) \times \cos(\delta) + \sin(\delta) \times \sin(\Phi - \beta)
\]
Equation 10

\[
(\omega = t_{solar} - 12) \times 15
\]
Equation 11

\[
\delta = 23.45 \times \sin \left(360 \times \frac{284 + n}{365}\right)
\]
Equation 12

\[
E = 229.2 \times \begin{pmatrix}
0.000075 + 0.001868 \cos(B) - 0.032077 \sin(B) - \\
-0.014615 \cos(2B) - 0.04089 \sin(2B)
\end{pmatrix}
\]
Equation 13

\[
B = (n - 1) \times \frac{360}{365}
\]
Equation 14

\[
t_{solar} = 4(L_n - L_{loc}) + E + t_{sid}
\]
Equation 15
where:  
C.I. = Clearness Index

$I_T$ = Extra-terrestrial solar radiation at tilt (Wh/m$^2$)

$I_o$ = Extra terrestrial flat plane solar radiation (Wh/m$^2$)

$I_a$ = Solar radiation at array (Wh/m$^2$)

$R_b$ = Tilt Factor

$\theta_z$ = Zenith angle (degrees)

$\theta$ = Angle of incidence (degrees)

$\omega$ = Hour angle (degrees) calculated every minute. The subscripts 1 and 2 indicate the hour angles at the beginning and end of each interval.

$\delta$ = Declination (degrees)

$E$ = Equation of time

$B$ = Day of year equation

$t_{solar}$ = Solar time

$t_{std}$ = Standard time

$n$ = Day of year = 1 to 365

$\beta$ = Array tilt (degrees) = 41°

$\Phi$ = Latitude at array (degrees) = 40.87°

$L_{loc}$ = Longitude at array (degrees) = 124.09°

$L_{st}$ = Standard meridian (degrees) = 120°

$G_{sc}$ = Solar Constant (W/m$^2$) = 1367 W/m$^2$

The ten minute intervals were checked for continuity (no missing data points within the interval) and to ensure that the clearness index, angle of incidence, and zenith angle all fall within appropriate ranges. The intervals were then imported into a new spreadsheet where the resulting 19,916 datapoints were separated into a 4x4 matrix of 16 bins by temperature and clearness index (see spreadsheet excerpt in Appendix H).

Excel’s data analysis tools were used to analyze the data and the results are presented in the Results and Discussion Chapter.

**Rated vs. Tested Maximum Power**

IV curves were measured for each of the tested modules to determine their actual peak power output ($W_P$) before, during and after the testing period. There was some
question as to which value for peak power to use for analysis. All of the modules tested lower than their rated power, and most degraded to some degree during the testing period.

    The specific energy yield (the ratio of energy yield over energy generating potential) for the modules could be reported in multiple ways:

1. Wh/rated $W_P$ ($W_{P_1}$)
2. Wh/tested $W_P$ at the beginning of the test period ($W_{P_i}$)
3. Wh/tested $W_P$ at the end of the test period ($W_{P_f}$)
4. Wh/most recently tested $W_P$ through the test period ($W_{P_c}$)

This analysis is meant to test the energy yield between the two technologies, not the accuracies of the manufacturers’ ratings, so using the manufacturers’ claimed peak power value would not give an accurate representation of the modules’ actual energy yield compared to its potential. Using the final or an average peak power value could potentially reward the modules for degrading over the testing period, because a lower peak power value would result in a higher specific energy yield value. The initial peak power value was selected because it most accurately answers the question of how much energy a module will yield compared to its potential. The degradation over time and the inaccuracies in ratings are also interesting and are reported and discussed, but not used in the analysis.

Note that all a-Si modules have an initial degrading period, and so all of the modules were allowed to “light-soak” for a period of at least six months until their measured peak power performance stabilized. See the Literature Review chapter for more information on a-Si technology and Staebler-Wronski degradation.
Ambient vs. Module Temperatures

The temperatures of the individual modules as well as the ambient temperatures were recorded. Careful attention was taken to construct and arrange the array so that the two types of modules were spread out and not exposed to systematically and significantly different weather and heat conditions. Higher temperatures reduce module efficiency and energy yield, but manufacturers and some studies have suggested that this effect is lower with a-Si than c-Si technology (see the Literature Review Chapter for more of this discussion). Three different temperature values were considered for use in the analysis for isolating the temperature effect on energy yield: i) ambient temperature, ii) average of all module temperatures, and iii) individual module temperatures.

For an accurate comparison, the modules need to be compared at identical conditions. The a-Si modules were consistently hotter than the c-Si modules in the same ambient temperatures (see Figure 9). Therefore, if individual module temperatures were used to examine the effect of temperature on specific energy yield, any reduction in efficiency losses inherent to a-Si technology could be cancelled out by their higher operating temperatures.

The efficiency of the modules is affected not directly by the ambient temperature, but indirectly by the effect of the ambient temperature on the module temperature. It is the physical properties of the materials and their temperatures that cause losses in efficiency, not the temperature of the air surrounding them. The module temperatures cannot respond immediately to fluctuations in ambient temperatures; the thermal mass in their materials would take some amount of time to release or absorb heat. Therefore, the
average of all module temperatures was selected to examine how the specific energy yield is affected by the operating temperature. The ambient temperature may have brief fluctuations while the modules may take longer to heat up or cool down. Using the ambient temperature could potentially misrepresent the actual operating temperatures of the modules when such instances occur. Examples of such potential instances are when a cloud briefly obstructs the sun but the modules remain warm or in the morning when the sun heats the air faster than the air heats the modules.

Figure 9. Average monthly daytime a-Si, c-Si, and ambient temperatures. The a-Si group runs consistently hotter than the c-Si group.
RESULTS AND DISCUSSION

In this chapter I present the results of the average and annual specific energy yields of the two groups of modules, their performance as a function of operating temperature and clearness index, and the specific energy yield performance of the individual modules. Please refer to the Methodology Chapter for a detailed description on these data analyses.

The a-Si group is shown to have a 2.7% higher annual specific energy yield on average than the c-Si group. The a-Si group performed better in the warmer summer months relative to the c-Si group, and equal to or poorer than the c-Si group for the rest of the year. This suggests that higher temperature has a stronger correlation than low clearness index to the improved specific energy yield of a-Si over c-Si PV technology. The examination of the smaller interval datasets confirms, though not conclusively, this result. The analysis of the specific energy yield of the individual modules shows the deviance between individual panels to be greater than that between groups. Individual module quality can negate any advantages a-Si technology has over c-Si technology in relative energy yield performance.

Monthly Average Specific Energy Yield

Using monthly outputs from the SDC program, I calculated average daily specific energy yield for each month (excerpts from the Daily Monthly Summaries spreadsheet are included in Appendix F). Figure 10 is a graph of the percent difference in average
monthly specific energy yields between the a-Si and c-Si groups. The a-Si modules outperform the c-Si on average over the entire year by a 2.7% margin. The summer months have the highest difference in specific energy yield between the two groups, with July the highest at 7.4%. The c-Si group outperforms the a-Si group in December, January, and February. This suggests that while the a-Si modules in this study show an advantage over the c-Si in specific energy yield, the cause is more likely due to better performance in higher temperatures experienced in the summer months than any benefit in diffuse light conditions.

Figure 10. Percent difference in average monthly specific energy yields between the a-Si and c-Si groups. The annual average percent difference is 2.7%.
To further isolate the effects of temperature and clearness on the specific energy yield of the two groups of modules, I plotted the percent difference of average specific energy yields between the a-Si and c-Si groups versus the average module temperatures (Figure 11) and versus average daily insolation measured on the plane of the array (Figure 12). The similar appearance of both plots is a result of the strong correlation between temperature and insolation. As both the temperature and insolation increase, so

![Figure 11. Percent difference in monthly average specific energy yields \((\text{Ave}_{\text{a-Si}} - \text{Ave}_{\text{c-Si}})/\text{Ave}_{\text{all}}\) versus average module temperatures. A positive value indicates the amount by which the a-Si outperformed the c-Si modules. The two outlier points below the trendline are from December 2006 and January 2007.](image-url)
does the percent difference between the specific energy yield of the two groups of modules. Linear trendlines were added to check for correlation between the indicators of temperature and insolation and the percent difference in specific energy yield. Both plots have linear trendlines with low R² values; 0.50 for the Average Module Temperature plot and 0.69 for the Average Daily Insolation plot. This suggests that average daily insolation is a slightly better indicator than average module temperature for the difference in specific energy yields, but that neither is very good.

![Figure 12](image)

Figure 12. Percent difference in monthly average specific energy yields \([(Ave_{a-Si} - Ave_{c-Si})/Ave_{all}]\) versus average daily insolation. A positive value indicates the amount by which the a-Si outperformed the c-Si modules.
**Ten-Minute Intervals**

Using output from the SDC program, I calculated specific energy yields for each of the modules for every minute of data collection. Using the methodology described in the previous chapter, I also calculated a clearness index and average module temperatures for each minute. The temperature and clearness index ranges are shown in Table 6. The average module temperature ranges from -4.19 to 62.43 °C with a mean of 28.56 °C. The range of clearness indexes is from 0.01 to 1.05 with a mean value of 0.41. The clearness index values over 1.0 occurred in two consecutive ten-minute intervals in the late afternoon on May 2, 2007 and are most likely the result of an isolated incident of cloud focusing of sunlight on the array.

I divided the data into 19,916 ten-minute intervals and created a 4x4 matrix of average module temperature and clearness index. Figure 13 shows a plot of clearness index versus average module temperature with the 16 bins indicated. Table 7 lists the upper and lower bounds of average module temperature and clearness index for each of the 16 bins, the count of datapoints in each bin, and the percentage of the total for each bin. Bin 2,1 is the highest frequency bin, with 21.02 % of the total intervals, and three bins have less than 0.1 %, including bin 4,1 with no values.
Table 6. Average, maximum, and minimum values of average ten-minute module temperature ($T_a$) and clearness index (C.I.) over the course of the 12-month testing period.

<table>
<thead>
<tr>
<th></th>
<th>$T_a$ (°C)</th>
<th>C.I.</th>
</tr>
</thead>
<tbody>
<tr>
<td>average</td>
<td>28.56</td>
<td>0.41</td>
</tr>
<tr>
<td>maximum</td>
<td>62.43</td>
<td>1.05</td>
</tr>
<tr>
<td>minimum</td>
<td>-4.19</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Comparison of Specific Energy Yields

The average percent difference in specific energy yield across all of the 19,916 ten-minute intervals is 2.69% with a standard error of 0.11%. Not surprisingly, this result is identical to the difference calculated from the analysis of monthly summaries. After separating the ten-minute intervals into 16 bins, I used Microsoft® Excel’s Data Analysis Tools to produce a multiple linear regression between the percent difference in specific energy yield of the a-Si and c-Si modules and average module temperature and clearness index data, using an intercept of zero.
Figure 13. Distribution of average module temperature and clearness index (C.I.). The C.I. values over 1.0 occurred in two consecutive intervals in the late afternoon on May 2, 2007 and are most likely the result of an isolated incidence of cloud focusing of sunlight on the array.
Table 7. Summary of bins for 4x4 matrix, showing the upper and lower bounds, the count, and the percentage of total datapoints in each bin for average module temperature (T_a) (°C), and clearness index (C.I.),

<table>
<thead>
<tr>
<th></th>
<th>C.I.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.25≥C.I.&lt;0.50</td>
<td>0.50≥C.I.&lt;0.75</td>
<td>0.75≥C.I.&lt;1.10</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>T_a ≥-5</td>
<td>3,664 (18.40%)</td>
<td>444 (2.23%)</td>
<td>219 (1.10%)</td>
<td>1 (0.01%)</td>
</tr>
<tr>
<td></td>
<td>T_a &lt;15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>T_a ≥15</td>
<td>1,845 (9.26%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T_a &lt;30</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>T_a ≥30</td>
<td>2,650 (13.31%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T_a &lt;45</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>T_a ≥45</td>
<td>1,871 (9.39%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T_a &lt;65</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 14 is a graph of the results of the linear regression showing the estimated percent difference in specific energy yield between the a-Si and c-Si groups for each of the 16 bins, with the associated one standard deviation error bars. For each of the ten-minute intervals, the percent difference in specific energy yield is calculated as \((\text{Ave}_{\text{aSi}} – \text{Ave}_{\text{cSi}})/\text{Ave}_{\text{cSi}}\). Positive values indicate the percentage amount the a-Si modules outperform the c-Si modules on average in specific energy yield. The same data are presented in a tabular format in Table 8.
The a-Si group outperforms the c-Si group in all but one of the bins. The biggest difference is seen in Bin 2,3, at over 10%. Bin 2,3 represents the middle-low $T_a$ range (15-30 °C) and the middle-high C.I. range (0.5-0.75). The only bin in which the specific energy yield of the c-Si group is more than the a-Si group is Bin 1,1; the lowest $T_a$ and C.I. bin. The specific energy yield for Bins 1,4 and 2,4 are not statistically significantly different from zero in terms of standard error, and Bin 4,1 has no datapoints.

![Graph showing the percent difference in specific energy yield for each of the 16 bins with error bars reflecting one standard deviation. Positive values indicate percent by which the a-Si group outperforms the c-Si group. The percent difference is calculated as \([(\text{Ave}_{a\text{Si}} - \text{Ave}_{c\text{Si}})/\text{Ave}_{c\text{Si}}]\).]
Table 8. Coefficients and standard errors of 4x4 linear regression for percent difference in specific energy yield. The higher the coefficient, the more the a-Si group outperforms the c-Si group. Sample sizes are given in Table 7.

<table>
<thead>
<tr>
<th>$T_a$ (°C)</th>
<th>C.I.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5 $\leq T_a &lt; 15$</td>
<td>0 $\leq$ C.I. $&lt; 0.25$</td>
<td>$-0.019$</td>
<td>$0.034$</td>
<td>$0.081$</td>
<td>$0.077$</td>
</tr>
<tr>
<td></td>
<td>(±0.003)</td>
<td>(±0.007)</td>
<td>(±0.010)</td>
<td>(±0.151)</td>
<td></td>
</tr>
<tr>
<td>$15 \leq T_a &lt; 30$</td>
<td>0 $\leq$ C.I. $&lt; 0.25$</td>
<td>$0.007$</td>
<td>$0.038$</td>
<td>$0.105$</td>
<td>$0.012$</td>
</tr>
<tr>
<td></td>
<td>(±0.002)</td>
<td>(±0.004)</td>
<td>(±0.005)</td>
<td>(±0.013)</td>
<td></td>
</tr>
<tr>
<td>$30 \leq T_a &lt; 45$</td>
<td>0 $\leq$ C.I. $&lt; 0.25$</td>
<td>$0.053$</td>
<td>$0.056$</td>
<td>$0.043$</td>
<td>$0.034$</td>
</tr>
<tr>
<td></td>
<td>(±0.020)</td>
<td>(±0.005)</td>
<td>(±0.003)</td>
<td>(±0.005)</td>
<td></td>
</tr>
<tr>
<td>$45 \leq T_a &lt; 65$</td>
<td>No data</td>
<td>$0.062$</td>
<td>$0.035$</td>
<td>$0.054$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(±0.042)</td>
<td>(±0.004)</td>
<td>(±0.003)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Correlations between Average Module Temperature, Clearness Index, and Specific Energy Yield

In order to provide a clearer indication of correlation between the a-Si group’s higher specific energy yields and the two factors of average module temperature and clearness index, I examined the correlation among the difference in specific energy yield and average module temperature, clearness index, and the product of the two factors. The results of this test are shown in Table 9. Not surprisingly, high average module temperature, clearness index, and their product are all closely correlated, because higher
Table 9. Correlation test results suggesting little correlation between the factors of average modular temperature (Ta), clearness index (C.I.), or the product of the two variables and the difference in specific energy yield \[\frac{(\text{Ave}_{a\text{Si}} - \text{Ave}_{c\text{Si}})}{\text{Ave}_{c\text{Si}}}\] between the two types of modules.

<table>
<thead>
<tr>
<th>% difference: [\frac{(\text{Ave}<em>{a\text{Si}} - \text{Ave}</em>{c\text{Si}})}{\text{Ave}_{c\text{Si}}}]</th>
<th>Ta</th>
<th>C.I.</th>
<th>Ta x C.I.</th>
</tr>
</thead>
<tbody>
<tr>
<td>% difference: [\frac{(\text{Ave}<em>{a\text{Si}} - \text{Ave}</em>{c\text{Si}})}{\text{Ave}_{c\text{Si}}}]</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ta</td>
<td>0.10</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>C.I.</td>
<td>0.15</td>
<td>0.86</td>
<td>1.00</td>
</tr>
<tr>
<td>Ta * C.I.</td>
<td>0.12</td>
<td>0.95</td>
<td>0.94</td>
</tr>
</tbody>
</table>

temperatures occur at times of higher clearness. The correlation results between the percent difference in specific energy yield and any of the three factors are all under 0.2, with the clearness index factor the highest at 0.15, the average module temperature factor 0.10, and the product of the two 0.12. Unfortunately, these results provide little help in solving the riddle of what contributes to the higher specific energy yield of the a-Si group.
Figure 15 is a series of four graphs plotting the four average module temperature bins on a graph of clearness index versus percent difference in specific energy yield between the two groups of modules. Error bars indicate the standard error from the linear regression. The higher the percentage difference, the more the a-Si group outperforms the c-Si group in specific energy yield.

The below 15°C plot begins with a -2% difference, indicating that the c-Si group outperformed the a-Si group at the lowest average module temperature and clearness index bin, and it shows an increase in the difference in specific energy yield as the clearness index increases. The final data point on this curve has a high standard error because of small sample size, so the leveling off of the tail at the end is not statistically significant. The 15-30°C plot shows an increase in the difference as the clearness index increases, until the highest clearness index when it drops. The 30-45°C and above 45°C plots both show much more level curves around 5% difference in specific energy yields.

The effect of clearness index on the difference in specific energy yield is more pronounced in the lower temperature conditions. The effect is that as clearness index increases, so does the amount by which the a-Si group outperforms the c-Si group in specific energy yield, at least until the highest clearness index bin. If the a-Si modules had a benefit in more diffuse light conditions, indicated by a lower clearness index value, the curve should have been reversed.
Figure 15. Four plots showing the four average module temperature (Ta) bins on a graph of clearness index (C.I.) versus percent difference in specific energy yield, with standard error bars shown.
Figure 16 is a series of four graphs plotting the four clearness index bins on a graph of average module temperature versus percent difference in specific energy yield between the two groups of modules. Error bars indicate the standard error from the linear regression. As in the plots in Figure 15, the higher the percentage difference, the more the a-Si group outperforms the c-Si group in specific energy yield.

Except for the clearness index range of 0.50 – 0.75, the difference in specific energy yield increases as average module temperature increases. The steepest curve, indicating the most dramatic effect of average module temperature on specific energy yield, comes in the lowest clearness index range. The percent difference in specific energy yield between the two module groups in the lowest clearness index range goes from the c-Si group outperforming the a-Si group by about 2% in the lowest average module temperature bin, to the a-Si group outperforming the c-Si group by over 5% in the third average module temperature bin. There are no datapoints in the highest average module temperature, lowest clearness index bin. The clearness index range of 0.25-0.50 shows a lower increase in difference in specific energy yield, going from under 4% to just over 5% from the lowest to highest temperatures. The highest clearness index range also shows a steady increase. The lowest average module temperature point can be ignored because the bin contains only a single datapoint and therefore has a high degree of error. The C.I. range from 0.50 to 0.75 begins with an increase in the difference in specific energy yield from the lowest to the second lowest average module temperature bins to
Figure 16. Four plots showing the four clearness index (C.I.) bins on a graph of average module temperature ($T_a$) versus percent difference in specific energy yield, with standard error bars shown.
over 10%, but then drops to under 5% in the next two bins. Average module temperature seems to be correlated to the difference in specific energy yield. The degree of effect, however, seems to be dependent on clearness index

**Temperature Coefficients**

Temperature coefficient testing found that the c-Si group has a 19.2% lower temperature coefficient on average than the a-Si group (see the section titled Temperature Coefficients on page 34 in the Methodology Chapter). This has important implications to the different technologies’ responses to temperature. Note that in using Equation 2 to normalize voltage to STC (25°C) conditions, when the temperature is greater than 25°C, a higher temperature coefficient results in a lower STC voltage. When the temperature is lower than 25°C, a higher temperature coefficient results in a higher STC voltage. Also, a higher temperature coefficient indicates that the voltage drops more slowly as the temperature increases. This lessened voltage drop at higher temperatures means that the higher temperature coefficients of the a-Si modules could result in higher specific energy yields at temperatures over 25°C.

This effect would be most pronounced when the voltage is near the maximum power point, such as when using a maximum power point tracking device. This project simulates a system in which the PV module voltage is regulated by the level of charge in a battery. The operating voltage of a battery is often below the maximum power point voltage of the PV module, so the effect of the temperature coefficient on the energy yield is reduced.
Individual Module Performance

The final analysis I performed was to examine the performance of the individual modules used in this study. I did this by calculating each module’s average daily specific energy yield as a percent difference from the average of all ten modules for each month and the entire year. I also did the same calculation for the averages of the a-Si and c-Si groups. Table 10 shows the results of this calculation.

Over the course of the year, the a-Si group averaged 1.36% better than the mean. The best and worst performing modules were both manufactured by Free Energy Europe. FEE-3 had an annual average of daily specific energy yield 4.69% below the mean, while FEE-1 had an annual average of daily specific energy yield 6.43% above the mean.

Neither module showed a significantly different level of degradation during the 12-month testing period in the I-V curve testing, and both began with W_P measurements within 0.5 watt of each other (see Table 4).

All of the c-Si modules except for the Solarex-1 averaged below the mean, and the Solarex 2 was only 0.01% below. Two of the a-Si modules averaged below the mean, the SC-1 as well as the FEE-3.
Table 10. Monthly and annual specific energy yield percent difference from mean for the individual modules and two groups.

<table>
<thead>
<tr>
<th></th>
<th>crystalline silicon (c-Si)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>c-Si group</th>
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<tr>
<td></td>
<td>Suntech1</td>
<td>Photon1</td>
<td>Solarex 2</td>
<td>Solarex 1</td>
<td>Suntech 2</td>
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<td>-4.99%</td>
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<td>1.04%</td>
<td>-3.76%</td>
<td>-2.53%</td>
</tr>
<tr>
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<td>-4.69%</td>
<td>-1.42%</td>
<td>1.77%</td>
<td>-3.49%</td>
<td>-2.08%</td>
</tr>
<tr>
<td>Oct-06</td>
<td>-1.92%</td>
<td>-4.32%</td>
<td>-1.36%</td>
<td>2.19%</td>
<td>-3.62%</td>
<td>-1.81%</td>
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<td>-4.04%</td>
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<tr>
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<td>-2.14%</td>
<td>-0.66%</td>
</tr>
<tr>
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<tr>
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<td>0.43%</td>
<td>-3.07%</td>
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<tr>
<td>annual avg</td>
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<td>-0.01%</td>
<td>2.28%</td>
<td>-2.98%</td>
<td>-1.36%</td>
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<table>
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<tr>
<th></th>
<th>amorphous silicon (a-Si)</th>
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<tr>
<td></td>
<td>FEE3</td>
<td>FEE1</td>
<td>SC1</td>
<td>SC2</td>
<td>ICP1</td>
<td></td>
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<td>7.00%</td>
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<td>4.93%</td>
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<tr>
<td>Jan-07</td>
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<td>Mar-07</td>
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<td>Apr-07</td>
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<td>Jun-07</td>
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<td>annual avg</td>
<td>-4.69%</td>
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<td>-0.69%</td>
<td>2.18%</td>
<td>3.58%</td>
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</table>
CONCLUSIONS AND RECOMMENDATIONS

The results of the 12-month study of a-Si and c-Si PV modules in a simulated battery-based, off-grid system indicate that the specific energy yield of the a-Si group of PV modules is approximately 2.7% higher than that of the c-Si group. The monthly averages analysis indicates that the a-Si group outperforms the c-Si group in specific energy yield, both annually and in the warmer months. The difference in specific energy yield between a-Si and c-Si modules is lower than has been reported in previous studies. Two possible explanations are the mild climate where this test was conducted and the absence of a maximum power point tracker in the system.

The analysis of the ten-minute intervals suggests there is a stronger correlation between improved a-Si specific energy yield and higher average module temperatures, than there is with clearness index. The effect of module temperature appears dependent on clearness index. The a-Si group performed better in the higher average module temperature bins, but the greatest percent difference in specific energy yield between the two groups is shown to be in a middle range bin. A correlation test between the percent difference in specific energy yield and the factors of temperature, clearness index and their product show very low degrees of correlation.

Direct measurements of the temperature coefficients of the ten modules found that the c-Si group has a 19.2% lower temperature coefficient on average than the a-Si group. This suggests that the a-Si modules would have a higher specific energy yields at module
temperatures higher than standard test condition (STC) of 25°C. This effect would be greatest if the voltage were maintained at the value that maximized the peak power point. Because the operating voltage was controlled by a simulated battery voltage that was below the maximum power point voltage and not a maximum power point tracker, this effect was reduced.

The analysis of individual performance of the modules shows little consistency within groups. Both the best and worst performers are not only both from the a-Si group but are also from the same manufacturer, Free Energy Europe. The I-V curves measured throughout the testing period did not show a significantly different degradation between the highest and lowest performing individual module, so the difference in specific energy yield is due to performance over time. However, four of the five the c-Si modules showed specific energy yields below the mean while three of the five a-Si were above the mean.

Overall, the project was successful, resulting in useful data and experience in testing the energy yield of solar PV modules. Shading due to testing location is an issue to be addressed in future projects. Shading of the modules placed in the lowest row of the array, especially in the winter months, contributed to the loss of potential datapoints. Because of the failure of one of the shade sensor modules, it was difficult to accurately determine some shading instances. This problem was overcome by a careful analysis of the shade sensor outputs correlated with Solar Pathfinder measurements and examination of the corresponding readings from the test modules, and it should not account for a significant source of error.
The data collection intervals could also be reconsidered in future tests. The large amount of data points collected on a once-per-minute basis caused some problems with both the datalogging equipment and complicated the analysis without providing any significant benefit. A five or ten-minute interval might be more appropriate and would help prevent loss of data due to datalogger memory issues. This could also be addressed with increased datalogger memory capacity.

Additional testing may help isolate the effects of module temperature and clearness index on specific energy yield. Possible experiments could include manually controlling the module temperatures with an outside heat source and partially filtering the sun’s light while recording the voltage and current data, or running tests on overcast days. The influence of other variables on specific energy yield could also be explored, such as angle of the sun’s light on the module, partial shading of the modules, the voltage setpoint, and particular wavelengths of solar radiation. Identical test arrays in different climate regimes may also help provide results that better explain the effects of temperature and clearness, because the energy yield could be compared between the different conditions.

In conclusion, while the a-Si group outperformed the c-Si group in specific energy yield, the difference is only 2.7%. This small difference is likely a result of the mild Arcata climate and the absence of a maximum power point tracker. Furthermore, the worst individual performer is an a-Si module, and the differences between individual modules are greater than the differences between groups. No concrete evidence is seen
for causation from either higher temperatures or lower clearness, although the data suggest that higher temperature may be a greater factor. This study presents no clear support for a different rating system for a-Si modules alone. An overall change in the rating system for all PV modules that more accurately predicts the expected energy yields could be warranted. Finally, failure of one out of the twelve original modules, and the low tested to rated peak power ratio both call for greater diligence in the manufacture and testing of low power PV modules in the Kenyan market.
REFERENCES


APPENDIX A: COMMON ELECTRICAL TERMINOLOGY

The following are some electrical terminology used throughout this thesis project and are provided here for reference. Capitalization of unit names follows the protocol of the Bureau International des Poids et Mesures’ (BIPM) S.I. Brochure, Section 5.2, “In English, the names of units start with a lower-case letter (even when the symbol for the unit begins with a capital letter), except at the beginning of a sentence or in capitalized material such as a title.” (http://www.bipm.org/en/si/si_brochure/chapter5/5-2.html).

Voltage (V) is the potential for electrical flow through a circuit. It is analogous to water pressure in a pipe. Voltage is measured in volts.

Current (I) is a rate of flow of electrons, measured in amperes. Using the water pipe example, there is always water pressure to a faucet (assuming it is hooked up to the water system), but there is no flow until the faucet is opened. Similarly, a circuit attached to a battery or other energy source will have voltage, but there is no current until it is attached to a load or the circuit is closed (short-circuited). Voltage multiplied by current results in Power.

Power is a measurement of the ability to do work or provide some useful service such as illumination or heat. Power is a rate, which means there is a unit of time in the expression. Common units of power are horsepower (hp), watts (W), kilowatts (1 kW = 1000 W), and British Thermal Units per hour (BTUH). While a watt doesn’t appear to have a unit of time, it is defined as one Joule per second. Appliances and lights are generally given a rating in watts.
Energy is an amount of work, often determined by multiplying a unit of power (the rate of doing work) by a unit of time. Utility companies bill their customers in units of energy such as kilowatt-hours (kWh) and therms (100,000 BTUs). For example, a lightbulb rated at 100 watts of power does not use any energy until it is turned on. If left on for one hour, it has used 100 watt-hours, or 0.1 kWh, of energy.

Peak Power \((W_P)\) of a PV module is the point where the product of the module’s voltage and current is the greatest, producing the most power. Solar modules are designed to operate near their peak power range.

Short-Circuit Current \((I_{SC})\) is the current measured when the positive and negative ends of the current are connected. The short-circuit current is the highest current produced in a circuit from a power source such as a solar module.

Open-Circuit Voltage \((V_{OC})\) is the voltage measured when the positive and negative leads are not connected to any load. The open-circuit voltage is the highest voltage produced from a power source such as a battery or solar module.

Insolation is a measurement of the available power from the sun, usually given in units of watts per square meter \((W/m^2)\).

Standard Test Conditions (STC) are defined as 25 °C and 1000 W/m² of insolation in the plane of the array. Standard test conditions are created in the laboratory to measure the performance of solar modules. The I-V tests performed in this study are corrected for STC using widely accepted equations.
This project simulates how the PV modules would operate in an Off-Grid PV System. In an off-grid system, the PV module(s) converts the sun’s energy into direct current (DC) electricity, which is used to charge a battery or is stored in some other device. The loads draw electricity from the storage device, either as DC or through an inverter, which converts it to alternating current (AC). The use of a battery or other storage device allows for electricity use when the sun is not shining.

In a Grid-Connected PV System, the DC electricity from the solar modules is converted into AC and fed into an electric grid operated by a utility company. When the PV system is producing more electricity than is being used by the loads, the electricity flows into the grid and the electric meter spins backwards. When the sun is not shining or other times when more electricity is being used than produced, the meter spins forward and electricity is being drawn from the grid. A grid-connected system does not require a separate storage device. There are also many types of Hybrid PV Systems that contain elements of grid-connected and off-grid systems.
APPENDIX B: BATTERY VOLTAGE DATA ANALYSIS AND STOCHASTIC MODELING

The following is a draft report written by Douglas Saucedo in March 2006, chronicling the battery voltage data analysis and modeling methodology used following work done by Douglas Saucedo, Arne Jacobson, and Stephen Kullmann. The draft report was edited to be included in this thesis by Stephen Kullmann.

The Kenyan data were analyzed to produce a temporally distributed stochastic model. The random variable of the model is the battery voltage applied to a rural photovoltaic system. Daily battery voltages for each household were randomly selected, filtering out any days with missing or erroneous data resulting from data collection errors. The data were used to produce bulk data representing the entire sample population. The sample population data were then broken down into a set of discrete time blocks. The battery voltage’s inverse cumulative distribution functions (ICDF) were calculated for each time block. These ICDFs were modeled with a series of fifth order polynomials meeting programming precision criteria for a Campbell Scientific data logger. The Campbell Scientific data logger was used to perform a Monte Carlo Simulation of operating voltages for an experimental set of photovoltaic modules.
The following section outlines the methods employed in the creation of the temporally distributed stochastic battery voltage model. The topics discussed are as follows:

- Data selection, efficacy, and partitioning criteria
- Distribution analysis
- Modeling objectives and constraints

**Data Selection and Partitioning Algorithm**

The data selection and partitioning process can be summarized in three steps: random selection of battery voltage data, solar altitude angle filtering, and solar hour partitioning. The random data selection process consisted of taking inventory of the data available, writing a random data selection generator, checking the randomly selected data for errors, and compiling the selected data series. The solar hour partitioning process calculated the solar altitude angle for the entire data series and removed data occurring when the solar altitude angle indicated the sun was not in the sky. The remaining data were broken into discrete time blocks for statistical analysis.

The random selection of the data was governed by a random date generation algorithm. The first step in producing this algorithm was to inventory the months available for each household at each location (Table B-1). Once this table was built, a random number generator was used to select an inventoried month and a randomly selected day within the inventoried month for each household. This randomly selected day was then checked for data errors resulting from problems with data collection.
Randomly selected days were checked for data quality since the inventory processes did not filter for deleterious data conditions, such as missing data points. The data were investigated to ensure that no sign of battery disconnect or data logger removal existed within the data series. If deleterious conditions were detected, the randomly selected day was discarded and the random selection processes were repeated.

Each household was randomly sampled 20 times, each sample consisting of a full day’s worth of data, to build an aggregate sample population for battery voltages. The total number of days sampled was 300. The data were compiled into a spreadsheet where additional data filtering removed battery voltages associated with times between dusk and twilight. The data were kept separated by location in order to calculate the solar geometry associated with the different latitudes.

The battery voltage removed from the sample population was associated with times when the solar altitude angle, $\alpha$, was less than $0^\circ$. When $\alpha$ is less than $0^\circ$ the sun has either not risen above the horizon (pre-dawn) or the sun has fallen below the horizon (dusk). Voltage data not satisfying $\{\alpha | \alpha \geq 0^\circ\}$ were excluded from the stochastic model formulation since this data corresponds to when the array is in the dark. Once the dark battery voltages were removed, the data was partitioned into two-hour time blocks.
Table B-1  Inventory of available battery voltage data listed by location and household. Note that $n$ denotes the number of months available.

<table>
<thead>
<tr>
<th>Location</th>
<th>Households</th>
<th>$n$</th>
<th>Month Inventory (listed by month number [1,12])</th>
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</thead>
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<td></td>
<td></td>
<td></td>
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<tr>
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<td><strong>Othaya</strong></td>
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<td>Gitice</td>
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<td>Muchiri</td>
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<td>1</td>
</tr>
</tbody>
</table>
The voltage data were broken into time blocks to produce a discrete set of time-dependent battery voltage distributions. The possible $t$, solar time, events consisted of the following set: $S=${$t < 08:00$, $08:00 \leq t < 10:00$, $10:00 \leq t < 12:00$, $12:00 \leq t < 14:00$, $14:00 \leq t < 16:00$, $t \geq 16:00$}. Once the battery voltages were partitioned by solar time $S$, the samples from each household-day were averaged over the two hour block. These two-hour averaged battery voltages provided 300 datapoints for each solar time event in the sample space $S$.

**Stochastic Model Development**

The two-hour averaged battery voltage data were used to produce a sequence of time-dependent, discrete, inverse cumulative distribution functions (ICDFs) for each solar-time event in $S$. Each discrete ICDF was produced with battery voltage bins of 0.1V precision to agree with the precision of the Kenyan battery voltage data sampling precision. The resulting ICDFs were then splined with a series of polynomial equations. These spline equations mapped the unit uniform variance (UUV) to a sample battery voltage by using a random number generator (0-1) to return the percentile battery voltage from the cumulative distribution function for the specific time period.

The ICDFs were constructed by first evaluating the discrete histogram for each time block’s sample set. The histogram information provided the probability mass function, $f(x)$, with a 0.1V resolution over battery voltages domain. The cumulative distribution function, $F(x)$ was evaluated by noting:
\[ F(x_j) = \sum_{i=1}^{j} f(x_i) \quad \text{Equation B-1} \]

The target hardware for the battery voltage simulation model was a Campbell Scientific Data Logger Model CR10X. This hardware did not contain an intrinsic UUV random number generator. Further, the hardware constrained the precision for the polynomial parameters and the degree of the polynomial used to spline the ICDF.

**Modeling Constraints and Objectives**

The modeling constraints of the Campbell Scientific CR10X datalogger used in this study are constrained are a maximum 5\textsuperscript{th} order polynomial function and floating point limitation of -99999. \(\leq\) F5 \(\leq\) 99999.

While performing the polynomial spline for the ICDFs, care was taken to satisfy its inherent statistical properties. The ICDF is the inverse function of the cumulative distribution function which is a monotonically increasing function with a range that varies between 0 and 1 within the domain of the random variable. As a result, the ICDF is a monotonically increasing function that varies with the range of the random variable within the domain of 0 and 1. Care was taken to avoid non-monotonically increasing regions while splining the ICDF with up to 5\textsuperscript{th} order polynomials. The objective for limiting non-monotonically increasing regions was coupled with the objective to obtain a relatively high \(r^2\) value. The target \(r^2\) value when splining subdomains was 0.95. These coupled objectives resulted in the required use of at least three subdomains for each time step’s ICDF polynomial spline. Although a large number of first order polynomials could
spline the ICDFs, programming and hardware limitations dictated the use of fewer higher-order polynomials. As a result, an ancillary objective was to reduce the number of polynomials needed to approximate the ICDFs.

Stochastic Model Validation

The polynomial splines resulting from the constraints were tested using a Monte Carlo simulation and were compared to the original sample data. The Monte Carlo simulation was performed using a custom set of Matlab® subroutines. The subroutines contained the proposed UUV random number generator for use with the Campbell Scientific. The random number generator used a mod100 based discrete-iterative map to approximate a UUV.

\[ UUV = \text{mod100}((UUV \times 502247 + 12345) / 3) / 100 \]  

Equation B-2

where the initial \( UUV \) is the random number generator seed.

Results and Discussion

The following section presents a subset of the results produced in the Monte Carlo simulation. The results are discussed in brief with regard to stochastic model’s ability to replicate the time varying distribution of battery voltages. The results are listed by sample time block noted in the sample space \( S \). Figure B-1 through B-6 show the comparison between a simulated ICDF curve using 1640 simulated battery voltages and the randomly sample Kenyan battery voltages for six different two-hour time blocks. For each of the time blocks shown, the comparative results for between the actual Kenyan battery voltage
distribution and the Monte Carlo simulated distribution suggests that the stochastic model provides a close approximation.

The purpose of this model is to provide an algorithm to keep the voltage setpoints of a simulated battery-based PV system where they would approximate the loads found in rural Kenya. There are some minor discrepancies in the lower tails of the before 8 am and 8 am to 10 am time blocks that were not overcome by the stochastic model. As these discrepancies are in the lower probability ranges and are on the magnitude of 1% of a 12V battery’s nominal voltage, they have been deemed acceptable.
Figure B-1 – The comparative results for the before 8 am time block between the actual Kenyan battery voltage distribution and the Monte Carlo simulated distribution suggests that the stochastic model provides a close approximation.
Figure B-2 – The comparative results for the 8 am to 10 am time block between the actual Kenyan battery voltage distribution and the Monte Carlo simulated distribution suggests that the stochastic model provides a close approximation. However, significant deviation is observed close to 1.
Figure B-3 – The comparative results for the 10 am to 12 pm time block between the actual Kenyan battery voltage distribution and the Monte Carlo simulated distribution suggests that the stochastic model provides a close approximation.
Figure B-4 – The comparative results for the 12 pm to 2 pm time block between the actual Kenyan battery voltage distribution and the Monte Carlo simulated distribution suggests that the stochastic model provides a close approximation.
Figure B-5 – The comparative results for the 2 pm to 4 pm time block between the actual Kenyan battery voltage distribution and the Monte Carlo simulated distribution suggests that the stochastic model provides a close approximation.
Figure B-6 – The comparative results for the after 4 pm time block between the actual Kenyan battery voltage distribution and the Monte Carlo simulated distribution suggests that the stochastic model provides a close approximation.
APPENDIX C: I-V CURVE SPREADSHEET

The following is an excerpt from the I-V curve spreadsheet created for module FEE3. The I-V test was completed June 20, 2006.
APPENDIX D: TEMPERATURE COEFFICIENTS TEST

The following are the results of the temperature coefficient test for the test modules, completed on October 25, 2006.
<table>
<thead>
<tr>
<th>Solarex 1</th>
<th>Suntech 2</th>
<th>ICP1</th>
<th>SC2</th>
</tr>
</thead>
<tbody>
<tr>
<td>start time</td>
<td>10:50</td>
<td>start time</td>
<td>11:15</td>
</tr>
<tr>
<td>end time</td>
<td>11:28</td>
<td>end time</td>
<td>11:45</td>
</tr>
<tr>
<td>T (°C)</td>
<td>V_{oc} (Volts)</td>
<td>T (°C)</td>
<td>V_{oc} (Volts)</td>
</tr>
<tr>
<td>21.6</td>
<td>20.99</td>
<td>21.7</td>
<td>21.77</td>
</tr>
<tr>
<td>30.8</td>
<td>20.30</td>
<td>30</td>
<td>21.09</td>
</tr>
<tr>
<td>40.0</td>
<td>19.63</td>
<td>40</td>
<td>20.49</td>
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<tr>
<td>45.6</td>
<td>19.30</td>
<td>50</td>
<td>19.96</td>
</tr>
<tr>
<td>49.5</td>
<td>19.05</td>
<td>55.3</td>
<td>19.63</td>
</tr>
<tr>
<td>54.1</td>
<td>18.76</td>
<td>59.6</td>
<td>19.48</td>
</tr>
<tr>
<td>T coeff.(1/°C)</td>
<td>-0.0035</td>
<td>T coeff.(1/°C)</td>
<td>-0.0029</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ICP2</th>
<th>FEE1</th>
<th>SC1</th>
<th>Solarex 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>start time</td>
<td>11:57</td>
<td>start time</td>
<td>12:08</td>
</tr>
<tr>
<td>end time</td>
<td>12:25</td>
<td>end time</td>
<td>12:32</td>
</tr>
<tr>
<td>T (°C)</td>
<td>V_{oc} (Volts)</td>
<td>T (°C)</td>
<td>V_{oc} (Volts)</td>
</tr>
<tr>
<td>23.3</td>
<td>23.01</td>
<td>21.6</td>
<td>22.57</td>
</tr>
<tr>
<td>30</td>
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<td>30</td>
<td>21.98</td>
</tr>
<tr>
<td>40</td>
<td>21.82</td>
<td>42.6</td>
<td>21.21</td>
</tr>
<tr>
<td>51.3</td>
<td>21.22</td>
<td>50</td>
<td>20.84</td>
</tr>
<tr>
<td>55.2</td>
<td>21.08</td>
<td>55.1</td>
<td>20.71</td>
</tr>
<tr>
<td>60</td>
<td>20.76</td>
<td>T coeff.(1/°C)</td>
<td>-0.0028</td>
</tr>
<tr>
<td>Time</td>
<td>Voltage (Volts)</td>
<td>Time</td>
<td>Voltage (Volts)</td>
</tr>
<tr>
<td>----------</td>
<td>-----------------</td>
<td>----------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Photon</td>
<td></td>
<td>FEE3</td>
<td></td>
</tr>
<tr>
<td>end</td>
<td>13:25</td>
<td>end</td>
<td>13:37</td>
</tr>
<tr>
<td>T (°C)</td>
<td>23</td>
<td>T (°C)</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>20.82</td>
<td>22.2</td>
<td>20.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>22.39</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>22.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>22.23</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T coeff.</td>
<td>-0.0026</td>
<td>T coeff.</td>
<td>-0.0027</td>
</tr>
</tbody>
</table>

\[ T \text{ Coeff} = \frac{(V_{oc} - V_{oc,f})}{V_{oc,ave}(T_i - T_f)} \]

Procedure: I removed the panels from the rack the evening of Oct. 24, 2006 and stored them in a cool closet indoors. On the morning of October 25, I cleaned the panels one at a time and placed them on the testing rack and measured the open circuit voltage and temperature. I would test two panels concurrently, and the tests lasted approximately 20-30 minutes. I took readings approximately every 10 degrees C until the temperature stopped climbing, which was at a different point for each panel.
APPENDIX E: SOLAR DATA PROCESSING CODE

The following is code for the Solar Data Cruncher (SDC) program, written by Douglas Saucedo and revised by Ranjit Deshmukh and Stephen Kullmann.

```matlab
% Solar Data Cruncher (SDC) Function Set
% Date Last Modified
% YYYYMMDD Author:
% 20061126 Douglas Saucedo (doug@humboldt.edu)
% % SYNTAX
% [dates,daily_summary]=...
% SDC
(path_in,path_out,module_area,shade_tol,insol_tol,output_flag);
% % SDC takes a data file from the Humboldt State University photovoltaic
% module testbench and performs a filtered data analysis. The analysis
% includes the calculation of daily insolation, energy produced by the
% modules, module efficiency, ambient temperature metrics, and module
% temperature metrics.
% % The function is configured to handle the data file format dated with
% the
% % author name above.
% % NOTES:
% % To change the valid range of the input variables, see the
% % function TolScreen
% % The input variable module_area can be embedded into SDC so that
% loading
% % this parameter set can be skipped. Simply use any input value
% % for the module_area input and make sure that module_area is
% % properly defined shortly after the function initiation.
% % % VARIABLE GLOSSARY
% % % Output Variables:
% % dates - a string array with the date of the daily summary record
% % stored in daily summary.
% % daily_summary - an n x m array containing the daily summary
% % information.
% % n = (number of days in data file)
% % m is the sum of the columns in the prescribed output variable set
% % described as follows:
% % For the i'th record, the columns are defined as follows:
% % daily_summary(i,:)=
% [nUsed,faults,insolWh,modWh,modEff,Tamb,Tmod];
% % Note:
% % nmods is the number of modules and is defined by the number of
% columns in module_area. module_area is defined under the
% input
% % variable section.
```
% nUsed - 1 column
% Tallies the number of records used for calculating the
% screened parameters. Screening can occur due to data not
% meeting the shading tolerance, insolation tolerance, or
% if any of the measured data is outside the bounds
% defined in the function TolScreen.
%
% faults - 1 column
% Tallies the number of records containing parameters outside
% of the valid boundaries.
%
% insolWh - 2 columns
% First column is the solar insolation in Wh with shading,
% insolation, and data bound screening.
% Second column is the solar insolation in Wh without
% screening.
%
% modWh - 2 x nmods columns
% First nmod columns contains daily module energy collection
% in Wh with screening for each module in sequential
% order.
% Second nmod columns contains the daily module energy
% collection
% in Wh without screening for each module in sequential
% order.
%
% modEff - 2 x nmods columns
% First nmod columns contains daily average module efficiency
% with screening for each module in sequential order.
% Second nmod columns contains the daily average module
% efficiency without screening for each module in
% sequential
% order.
%
% Tamb - 3 columns
% First column contains Tamb_min - the minimum daily ambient
% temperature in degrees Celsius.
% Second column contains Tamb_ave - the average daily ambient
% temperature in degrees Celsius.
% Third column contains Tamb_max - the maximum daily ambient
% temperature in degrees Celsius.
%
% Tmod - 2 x nmods columns
% First nmods columns contains the average daily module
% temperature in degrees Celsius for each module in
% sequential
% order.
% Second nmods columns contains the maximum daily module
% temperature in degrees Celsius for each module in
% sequential
% order.
%
% Input Variables:
% path_in - a string specifying the input data file path relative to the
% active directory.
%
% path_out - a string specifying the output path relative to the active
% directory.
%
% module_area - a row vector size (1 x nmods) containing the module area
% in sq.m.
%
% shade_tol - a decimal proportion deviation from the average shading
% voltage value necessitating exclusion. eg 0.15 = 15% deviation
% insol_tol - minimum insolation, in W/sq.m, needed to include data for consideration.
% output_flag - signal controlling the production of daily output files.
% output_flag = 0 : no daily output files or summary file
% output_flag = 1 : no daily output files; output summary file
% output_flag = 2 : daily output files and output summary file

% SYNTAX
% [dates,daily_summary]=...
% SDC(path_in,path_out,module_area,shade_tol,insol_tol,output_flag);
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% function [dates,daily_summary] = ...
% SDC(path_in,path_out,module_area,shade_tol,insol_tol,output_flag)
% % module area effective 20061112
% %module_area = [0.233,0.177,0.293,0.253,0.315,0.293,0.299,0.222];
% % query the number of modules in data set
% % module_area = size(module_area,2); % module area must be a row vector
% % define data array metric locations
% % number of columns must match nmods
% volt_col = 10:3:43; % columns for module voltage
curr_col = 11:3:44; % columns for module current
Tmod_col=12:3:45; % columns for module temperature
Tamb_col=9; % column for ambient temperature
shade_col=46:49; % columns for shading sensor
insol_col=7; % column for global radiation
if(size(volt_col,2)~=nmods)||...
(size(curr_col,2)~=nmods)||size(Tmod_col,2)~=nmods),
SDC_ERROR('SDC: module_area is not consistent with data allocations.');
return
end
% open the input data file
data_fid = fopen(path_in,'r');
% open the output data file for daily summary
if(output_flag == 1) || (output_flag == 2)
daily_summary_fid = fopen([path_out,'Daily_st',... int2str(floor(shade_tol*100)),'_it',... int2str(floor(insol_tol)),'.csv'],'wt');
% print a header line to the summary file
header = DailySummaryHeader(nmods);
fprintf(daily_summary_fid,header);
end
% cycle trough each day in the file, execute analysis subroutines, and record data accordingly
i = 0; iostat=1;
while (iostat==1) % read through the remaining days while we can get data day
if(i==0)
[dates_day,nlines,iostat]=...
GetDataDay(data_fid,[],0,0);
else
[dates_day,nlines,iostat]=...
GetDataDay(data_fid,dates_day(nlines+1,:),1,1);
end
i=i+1;
% begin daily operations - calculate daily information
[screen,shading,faults] = ...
To1Screen(data_day,nlines,...
volt_col,c curr_col,Tamb_col,Tmod_col,shade_col,insol_col,...
shade_tol,insol_tol); nUsed = sum(screen(1:nlines,1));

insolWh = DailyInsolation(data_day,nlines,screen,insol_col);
modWh = DailyPVPower(data_day,nlines,screen,volt_col,curr_col);
modEff = DailyEfficiency(insolWh,modWh,module_area);  
[Tamb,Tmod] = ...  
DailyMaxTemp(data_day,screen,nlines,nmods,Tmod_col,Tamb_col);
% end daily operations
%% get data_day string identifiers
[data_tag,data_date] = MakeDayTag(data_day(1,2),data_day(1,3));
dates(i,:) = data_date; % capture dates for future reference
T0 = (min(data_day(1:nlines,4))); tf = (max(data_day(1:nlines,4)));
display(['Processing: ',data_date,'; nRecords = ',int2str(nlines),...
'; nUsed = ',int2str(nUsed),...
'; Begin Time = ',int2str(T0),'; End Time = ',int2str(tf)])
%% write daily data and screen calculation set to file
if(output_flag == 2),
dayout_fid = fopen([path_out,data_tag,...
'_st',int2str(floor(shade_tol*100)),...
'_it',int2str(floor(insol_tol)),...
'_DataCalcs.csv' '),'wt');
% write header line to file; MODIFY IF DATA_DAY OR SCREEN
changes
header = DailyOutputHeader(nmods);
fprintf(dayout_fid,header);
% specify format for dialy data set
format = '%10s	'; % date and
cols = size(data_day(4:49),2)+size(screen,2)+size(shading,2);
for k = 1:cols, format = [format,' %8.3f	']; end
format = [format,'
'];
% daily summary print to file
for j=1:nlines
fprintf(dayout_fid,format,...
data_date,data_day(j,4:49),screen(j,1),shading(j,:));
end
fclose(dayout_fid);
end
% augment daily_summary array
daily_summary(i,:) = [nUsed,sum(faults(:,1)),...
insolWh,modWh,modEff,Tamb,Tmod];
% write daysum to file
if(output_flag == 1) || (output_flag == 2)
% write a daily sum line to the summary file
format = '%10s	 %4i	 %5i	';
for k = 1:size(daily_summary,2), format = [format,' %8.3f	']; end
format = [format,'
'];
fprintf(daily_summary_fid,format,...
data_date,t0,tf,nlines,daily_summary(i,:));
end
% end daily operations
end
fclose(dayout_fid);
if((output_flag == 1)||(output_flag == 2)),fclose(daily_summary_fid);
end
return

function modEff = DailyEfficiency(insolWh,modWh,module_area)
% This function calculates the module efficiencies with and without the
% data screen.
% nmods = size(module_area,2);
modEff_wScreen = modWh(1,1:nmods)./(module_area*insolWh(1));
modEff_woScreen = modWh(1,nmods+1:2*nmods)./(module_area*insolWh(2));
modEff = [modEff_wScreen,modEff_woScreen];
return
%%

function [Tamb,Tmod] = ...
DailyMaxTemp(data_day,screen,nlines,nmods,Tmod_col,Tamb_col)
% This function calculates temperature metrics for both the ambient and
% module temperatures. The ambient temperature metrics include minimum,
% average, and maximum temperature. The module temperature metrics
% include
% must be reported for each module and is done so in sets. The units
% reported are the same as the units used in the input file.
% Calculate the ambient temperature minimum, mean, and maximum
Tamb_min=99999; Tamb_ave=0; Tamb_max=0;
% calculate the module mean and maximum temperatures while screening
Tmod_ave=zeros(1,nmods); Tmod_max=zeros(1,nmods);
for i = 1:nlines
if(data_day(i,Tamb_col)<Tamb_min)&&(screen(i,1)==1),
    Tamb_min=data_day(i,Tamb_col);
end
Tamb_ave=Tamb_ave+screen(i,1)*data_day(i,Tamb_col);
if(data_day(i,Tamb_col)>Tamb_max)&&(screen(i,1)==1),
    Tamb_max=data_day(i,Tamb_col);
end
Tamb=Tamb_ave/sum(screen(1:nlines,1));
Tamb=[Tamb_min,Tamb_ave,Tamb_max];
Tmod=[Tmod_ave,Tmod_max];
return
%%

function modWh = DailyPVPower(data_day,nlines,screen,volt_col,curr_col)
% This function calculates the module energy collection over the course
% of one day using rectangular integration. The module energy is calculated
% with and without the data screen. The module is reported for each
% sequentially and is reported in Wh.
% Calculate the instantaneous power for the module for each data record.
pvpower = data_day(:,volt_col).*data_day(:,curr_col);
% calculate the screened daily pv power output
modWh_wScreen = zeros(1,size(pvpower,2));
modWh_woScreen = zeros(1,size(pvpower,2));
for i = 1:nlines
% calculate Dt, the change in time
if(i < nlines) % forward difference
    Dt = (time2hrs(data_day(i+1,4)) - time2hrs(data_day(i,4)));
elseif(i == nlines) % backward difference
    Dt = (time2hrs(data_day(i,4)) - time2hrs(data_day(i-1,4)));
end
% use the screen flag to determine whether to use the data or not
modWh_wScreen = modWh_wScreen + screen(i,1)*pvpower(i,:)*Dt;
% calculate the module Watt-Hours without the screen
modWh_woScreen = modWh_woScreen + pvpower(i,:)*Dt;
end
modWh = [modWh_wScreen,modWh_woScreen];
return
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function insolWh = DailyInsolation(data_day,nlines,screen,insol_col)
% This function calculates the daily solar insolation available to the
% modules with and without the data screen. The insolation is reported
% in Wh.
%
% populate the insol data
insol_data = data_day(:,insol_col);
% using trapezoidal integration, calculate the Wh produced per mod
insolWh = zeros(1,2);
for i = 1:nlines-1
    % calculate Dt, the change in time
    if(i < nlines) % forward difference
        Dt = (time2hrs(data_day(i+1,4)) - time2hrs(data_day(i,4)));
    elseif(i == nlines) % backward difference
        Dt = (time2hrs(data_day(i,4)) - time2hrs(data_day(i-1,4)));
    end
    % use the screen flag to determine whether to use the data or not
    insolWh(1) = insolWh(1) + screen(i,1)*insol_data(i)*Dt;
    % calculate the unfiltered insolation
    insolWh(2) = insolWh(2) + insol_data(i)*Dt;
end
return
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
--
function [screen,shading,faults] = ...
TolScreen(data_day,nlines,...
volt_col,curr_col,Tamb_col,Tmod_col,shade_col,insol_col,...
shade_tol,insol_tol)
% This function evaluates the shading tolerance, insolation tolerance, and
% measured variable boundaries so that record screening can be performed.
% The variable boundaries are defined as follows:
Tmin=-20; Tmax=100; % [deg C]
Insol_min=-10; Insol_max=2000; % [W/sq.m]
shade_min=-10; shade_max=2000; % [mV]
Vmin=-1; Vmax=30; % [Volts]
Imin=-1; Imax=10; % [Amps]
% calculate the insolation and shading screen value of 0 or 1
% also assess the bounds for the incoming variable
% i) assign 0 or 1 screen to out of bounds records
% ii) pass along fault string to faults variable ('fault' or 'no fault')
for i = 1:nlines
% what is the average photosensor signal?
shade_ave(i,1) = mean(data_day(i,shade_col));
% if any photosensor is out of range or if the insol is too low,

% the data from consideration.
% check the insolation
if(data_day(i,insol_col)<insol_tol)
screen(i,1) = 0;
else
screen(i,1) = 1;
end
for j = 1:size(shade_col,2)
% calculate the percent difference for each photosensor
shade_RelDif(i,j) = ...
abs((data_day(i,j)+min(shade_col(1,:))-shade_ave(i))./shade_ave(i));
% check the shading tolerances
if(shade_RelDif(i,j) >= shade_tol)
screen(i,1) = 0;
end
end
% assess each parameters compliance to bounds
% check the module voltages, currents, and temperatures
faults(i,1)=0;
for j=1:size(volt_col,2)
if(data_day(i,volt_col(1,j)) < Vmin)||(...
(data_day(i,volt_col(1,j)) > Vmax)
faults(i,1)=1;
screen(i,1)=0;
end
if(data_day(i,curr_col(1,j))<Imin)||...
(data_day(i,curr_col(1,j))>Imax)
faults(i,1)=1;
screen(i,1)=0;
end
if(data_day(i,Tmod_col(1,j))<Tmin)||...
(data_day(i,Tmod_col(1,j))>Tmax)
faults(i,1)=1;
screen(i,1)=0;
end
% check the shading signals
for j=1:size(shade_col,2),
if(data_day(i,shade_col(1,j))<shade_min)||...
(data_day(i,shade_col(1,j))>shade_max),
faults(i,1)=1;
screen(i,1)=0;
end
% check the insolation signal
if(data_day(i,insol_col)<Insol_min)||...
(data_day(i,insol_col)>Insol_max),
faults(i,1)=1;
screen(i,1)=0;
end
% check the Tamb signal
if(data_day(i,Tamb_col)<Tmin)||...
(data_day(i,Tamb_col)>Tmax),
faults(i,1)=1;
screen(i,1)=0;
end
end
% shading=[shade_ave,shade_RelDif];
return
%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%------------------------------------------------------------------
--
function [data_day,nlines,iostat] = ...
GetDataDay(data_fid,day_flag)
This function records data from the file specified in input_path. The function records daily data until either a new day is observed or the end of the file is reached. When a new day is observed, the record is attached as the last data entry in the data_day array. This record is then used to initiate the next data_day extraction and uses nlines=1 to reflect the fact that one line is already populated for the next record.

if(day_flag==1),day = data_day(3); end
while 1 % read each line until a full day is populated
    istat=1;
    % read line from test bench data
    line = fgetl(data_fid);
    % detect for end of file
    if ~ischar(line), istat=0; break, end;
    % parse line into components
    data = sscanf(line,'%f,');
    % check for header lines and skip them
    if ischar(data),
        continue
    elseif(day_flag==0),
        day_flag = 1;
        nlines = nlines + 1;
        day = data(3);
        data_day(nlines,:) = data;
        % counting day and new record is for that day
        elseif((day_flag==1) && (data(3)==day))
            nlines=nlines+1;
            if(size(data,2)==size(data_day,2))
                data = data(1:size(data_day,2));
            end
        end
        data_day(nlines,:) = data;
        % counting a day and new record is for next day
        elseif((day_flag==1) && (data(3)~=day))
            day_flag = 0;
            if(size(data,2)==size(data_day,2))
                data = data(1:size(data_day,2));
            end
            data_day(nlines+1,:) = data;
            break
        else
            SDC_ERROR('DATA_DAY: Logic Error')
        end
    end
end
return

function [data_tag,data_date] = MakeDayTag(year,yearday)
% This function transforms the year day to a date string.
% Variable Definitions:
% Input
% year is the year
% yearday is the year day
% Output
% data_tag is a string containing the date in YYYYMMDD format.
% data_date is a string containing the date in MM/DD/YYYY format.
if(round(year/4) == year/4),
    if(yearday <= 31),
        data_tag = year*10000+100+yearday;
    elseif(yearday <= 60),
        data = year*10000+100+yearday;
    elseif(yearday <= 90),
        data = year*10000+100+yearday;
data_tag = year*10000+200+(yearday-31);
elseif(yearday <= 91)
  data_tag = year*10000+300+(yearday-60);
elseif(yearday <= 121)
  data_tag = year*10000+400+(yearday-91);
elseif(yearday <= 152)
  data_tag = year*10000+500+(yearday-121);
elseif(yearday <= 182)
  data_tag = year*10000+600+(yearday-152);
elseif(yearday <= 213)
  data_tag = year*10000+700+(yearday-182);
elseif(yearday <= 244)
  data_tag = year*10000+800+(yearday-213);
elseif(yearday <= 274)
  data_tag = year*10000+900+(yearday-244);
elseif(yearday <= 305)
  data_tag = year*10000+1000+(yearday-274);
elseif(yearday <= 335)
  data_tag = year*10000+1100+(yearday-305);
elseif(Yearday <= 366)
  data_tag = year*10000+1200+(yearday-335);
else
  SDC_ERROR('MakeDayTag: Somethings up with the leap year.')
end
else
  if(yearday <=31)
    data_tag = year*10000+100+yearday;
  elseif(yearday <= 59)
    data_tag = year*10000+200+(yearday-31);
  elseif(yearday <= 90)
    data_tag = year*10000+300+(yearday-59);
  elseif(yearday <= 120)
    data_tag = year*10000+400+(yearday-90);
  elseif(yearday <= 151)
    data_tag = year*10000+500+(yearday-120);
  elseif(yearday <= 181)
    data_tag = year*10000+600+(yearday-151);
  elseif(yearday <= 212)
    data_tag = year*10000+700+(yearday-181);
  elseif(yearday <= 243)
    data_tag = year*10000+800+(yearday-212);
  elseif(yearday <= 273)
    data_tag = year*10000+900+(yearday-243);
  elseif(yearday <= 304)
    data_tag = year*10000+1000+(yearday-273);
  elseif(yearday <= 334)
    data_tag = year*10000+1100+(yearday-304);
  elseif(yearday <= 365)
    data_tag = year*10000+1200+(yearday-334);
else
  SDC_ERROR('MakeDayStamp: Something is up with the regular year')
end

end
data_tag = num2str(data_tag);
data_date = [data_tag(5:6),'/',data_tag(7:8),'/',data_tag(1:4)];
return

function hr = time2hrs(HourStamp)
% This function transforms the data files hhmm time integer to a number
% representing the decimal hour in the day.
% Variable Definitions:
% Input
% HourStamp is the integer number representing the hhmm.
% hr is a real number representing the day's decimal hour.
% hour stamp to day seconds function
hr = floor(HourStamp/100)+(HourStamp-floor(HourStamp/100)*100)/60;
return

% This function constructs a header line for the daily summary file.
% This header should be changed if changes in the daily summary layout is
% changed. Note that for loops are used to help automate the header
% construction and provide some flexibility with the number of modules
% being analyzed.
function header = DailySummaryHeader(nmods)
    header = ['Date\t start_time\t end_time\t nRecords\t',...`
        ' nUsed\t Faults\t Insol_wScreen\t Insol_woScreen\t'];
    for k = 1:nmods, header=[header,' Mod',int2str(k),'_Wh_wScreen\t']; end
    for k = 1:nmods, header=[header,' Mod',int2str(k),'_Wh_woScreen\t']; end
    for k = 1:nmods, header=[header,' Mod',int2str(k),'_Eff_wScreen\t']; end
    for k = 1:nmods, header=[header,' Mod',int2str(k),'_Eff_woScreen\t']; end
    header = [header,' Tamb_min\t Tamb_ave\t Tamb_max\t'];
    for k = 1:nmods, header=[header,' Mod',int2str(k),'_Tave\t']; end
    for k = 1:nmods, header=[header,' Mod',int2str(k),'_Tmax\t']; end
    header=[header,'
'];
    return

% This function constructs the header line for the daily output file.
% This header should be changed if the daily output layout is changed.
function header = DailyOutputHeader(nmods)
    header = 'Date\t Time\t DataBat\t DataTemp\t Pyro\t VSetpoint\t TOA\t';
    for k = 1:nmods,
        header = [header, ' VPV_',int2str(k),'	 IPV_...',
            int2str(k),'	 TC_\t',int2str(k),'	' ];
        end
    for k = 1:4,header=[header,' Shade',int2str(k),'	' ]; end
    header=[header,'Screen\t Shade_Ave\t'];
    for k = 1:4,header=[header, ' RelDif_Shade',int2str(k),'	' ]; end
    header=[header,'
'];
    return

% This function handles any error cases that arise within the algorithm.
function SDC_ERROR(string)
display(string)
display('Type "help SDC" for more information.')
return
APPENDIX F: DAILY MONTHLY SUMMARIES

The following are excerpts from the Daily Monthly Summaries spreadsheet.
<table>
<thead>
<tr>
<th>System Data</th>
<th>Jul-06</th>
<th>Aug-06</th>
<th>Sep-06</th>
<th>Oct-06</th>
<th>Nov-06</th>
<th>Dec-06</th>
<th>Jan-07</th>
<th>Feb-07</th>
<th>Mar-07</th>
<th>Apr-07</th>
<th>May-07</th>
<th>Jun-07</th>
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<tbody>
<tr>
<td>testing days</td>
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<td>30</td>
<td>30</td>
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<td>30</td>
<td>30</td>
<td>29</td>
<td>30</td>
<td>31</td>
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<tr>
<td>total solar radiation</td>
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<td>145,503</td>
<td>128,042</td>
<td>113,935</td>
<td>56,169</td>
<td>56,707</td>
<td>38,707</td>
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<td>51.3%</td>
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</table>

<table>
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<td>20.8</td>
<td>20.8</td>
<td>20.8</td>
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<td>avg daily WkWp (rated)</td>
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<td>10.8</td>
<td>10.8</td>
<td>10.8</td>
</tr>
</tbody>
</table>

annual avg           | 27.3     | 29.5     | 29.5   | 30.2     | 30.2   | 30.2       | 30.2  | 30.2      | 30.2      | 30.2        | 30.2        | 30.2        |

annual avg           | 2.0     | 2.0     | 2.0   | 2.0     | 2.0   | 2.0         | 2.0  | 2.0       | 2.0       | 2.0         | 2.0         | 2.0         |

average WkWp         | 3.8     | 3.8     | 3.8   | 3.8     | 3.8   | 3.8         | 3.8  | 3.8       | 3.8       | 3.8         | 3.8         | 3.8         |

average WkWp         | 2.4     | 2.4     | 2.4   | 2.4     | 2.4   | 2.4         | 2.4  | 2.4       | 2.4       | 2.4         | 2.4         | 2.4         |

average WkWp         | 0.1     | 0.1     | 0.1   | 0.1     | 0.1   | 0.1         | 0.1  | 0.1       | 0.1       | 0.1         | 0.1         | 0.1         |
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APPENDIX G: CLEARNESS INDEX SPREADSHEET 2007.05.30

The following is an excerpt from the Clearness Index spreadsheet for May 30, 2007.
| Date       | City of Year (%) | CA CDF (%) | Area Surveys | Enlarged | 0.900000 | 0.850000 | 0.800000 | 0.750000 | 0.700000 | 0.650000 | 0.600000 | 0.550000 | 0.500000 | 0.450000 | 0.400000 | 0.350000 | 0.300000 | 0.250000 | 0.200000 | 0.150000 | 0.100000 | 0.050000 | 0.000000 |
|------------|------------------|------------|--------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| 5/10/2023  | 500               | 1084       | 3.05 - 3.50  | 3.05      | 3.42     | 3.79     | 4.16     | 4.53     | 4.90     | 5.26     | 5.63     | 5.99     | 6.36     | 6.73     | 7.10     | 7.47     | 7.84     | 8.21     | 8.58     | 8.95     | 9.32     | 9.69     | 10.06   |
| 5/12/2023  | 502               | 1086       | 3.05 - 3.50  | 3.05      | 3.42     | 3.79     | 4.16     | 4.53     | 4.90     | 5.26     | 5.63     | 5.99     | 6.36     | 6.73     | 7.10     | 7.47     | 7.84     | 8.21     | 8.58     | 8.95     | 9.32     | 9.69     | 10.06   |
| 5/13/2023  | 503               | 1087       | 3.05 - 3.50  | 3.05      | 3.42     | 3.79     | 4.16     | 4.53     | 4.90     | 5.26     | 5.63     | 5.99     | 6.36     | 6.73     | 7.10     | 7.47     | 7.84     | 8.21     | 8.58     | 8.95     | 9.32     | 9.69     | 10.06   |
| 5/14/2023  | 504               | 1088       | 3.05 - 3.50  | 3.05      | 3.42     | 3.79     | 4.16     | 4.53     | 4.90     | 5.26     | 5.63     | 5.99     | 6.36     | 6.73     | 7.10     | 7.47     | 7.84     | 8.21     | 8.58     | 8.95     | 9.32     | 9.69     | 10.06   |
| 5/15/2023  | 505               | 1089       | 3.05 - 3.50  | 3.05      | 3.42     | 3.79     | 4.16     | 4.53     | 4.90     | 5.26     | 5.63     | 5.99     | 6.36     | 6.73     | 7.10     | 7.47     | 7.84     | 8.21     | 8.58     | 8.95     | 9.32     | 9.69     | 10.06   |
| 5/16/2023  | 506               | 1090       | 3.05 - 3.50  | 3.05      | 3.42     | 3.79     | 4.16     | 4.53     | 4.90     | 5.26     | 5.63     | 5.99     | 6.36     | 6.73     | 7.10     | 7.47     | 7.84     | 8.21     | 8.58     | 8.95     | 9.32     | 9.69     | 10.06   |
| 5/17/2023  | 507               | 1091       | 3.05 - 3.50  | 3.05      | 3.42     | 3.79     | 4.16     | 4.53     | 4.90     | 5.26     | 5.63     | 5.99     | 6.36     | 6.73     | 7.10     | 7.47     | 7.84     | 8.21     | 8.58     | 8.95     | 9.32     | 9.69     | 10.06   |
| 5/18/2023  | 508               | 1092       | 3.05 - 3.50  | 3.05      | 3.42     | 3.79     | 4.16     | 4.53     | 4.90     | 5.26     | 5.63     | 5.99     | 6.36     | 6.73     | 7.10     | 7.47     | 7.84     | 8.21     | 8.58     | 8.95     | 9.32     | 9.69     | 10.06   |
| 5/19/2023  | 509               | 1093       | 3.05 - 3.50  | 3.05      | 3.42     | 3.79     | 4.16     | 4.53     | 4.90     | 5.26     | 5.63     | 5.99     | 6.36     | 6.73     | 7.10     | 7.47     | 7.84     | 8.21     | 8.58     | 8.95     | 9.32     | 9.69     | 10.06   |
| 5/20/2023  | 510               | 1094       | 3.05 - 3.50  | 3.05      | 3.42     | 3.79     | 4.16     | 4.53     | 4.90     | 5.26     | 5.63     | 5.99     | 6.36     | 6.73     | 7.10     | 7.47     | 7.84     | 8.21     | 8.58     | 8.95     | 9.32     | 9.69     | 10.06   |
| 5/21/2023  | 511               | 1095       | 3.05 - 3.50  | 3.05      | 3.42     | 3.79     | 4.16     | 4.53     | 4.90     | 5.26     | 5.63     | 5.99     | 6.36     | 6.73     | 7.10     | 7.47     | 7.84     | 8.21     | 8.58     | 8.95     | 9.32     | 9.69     | 10.06   |
| 5/22/2023  | 512               | 1096       | 3.05 - 3.50  | 3.05      | 3.42     | 3.79     | 4.16     | 4.53     | 4.90     | 5.26     | 5.63     | 5.99     | 6.36     | 6.73     | 7.10     | 7.47     | 7.84     | 8.21     | 8.58     | 8.95     | 9.32     | 9.69     | 10.06   |

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APPENDIX H: 4X4 MATRIX REGRESSION SPREADSHEET

The following is an excerpt from the 4x4 regression spreadsheet.