# University-National Park Energy Partnership Program

# Installation of a Hybrid Solar Electric System at Espa Lagoon

Summer 2006

Prepared by
Matt Smith and Erin McDonald
Schatz Energy Research Center

Humboldt State University

Redwood National and Prairie Creek State Parks
Orick, California

# Table of Contents

# Executive Summary

The Redwood National and State Parks are the combination of several protected sections of parkland, stretching along the uppermost part of the Pacific Coast in Northern California. The protected ecosystem includes several varied features, such as coastlines, lagoons, prairies, streams and rivers, and, of course, forests of redwood trees. The 2006 University-National Park Energy Partnership Program (UNPEPP) project's goal was to design and install a hybrid solar electric system at a ranger residence on Espa Lagoon, in the Prairie Creek Redwoods State Park unit of Redwood National and State Parks. Two interns, Matt Smith and Erin McDonald, worked with Schatz Energy Research Center (SERC) engineers and Park staff to procure equipment and coordinate the design and installation of the system. The design and site analysis was based upon recommendations made by previous UNPEPP interns in 2000 (Grafman and Sorensen, 2000). Much of the equipment needed to complete the installation was inherited from previous park projects, including fourteen photovoltaic (PV) modules, an inverter, a charge controller, a generator, and an automatic transfer switch.

The equipment was performance tested, and an optimal placement on the site was decided upon. After construction and procurement of the balance of the system equipment, the installation went forward. Based on performance measurements and considering the available solar energy resource (corrected for shading), the PV system output is expected to be an annual average of 2.25 kWh per day. Including efficiency and transmission losses, the PV system is expected to provide an average of 1.49 kWh per day to the ranger residence, or 38% of the measured load.

The Schatz Energy Research Center (SERC), Prairie Creek Redwoods State Park and Redwood National Park provided support for the project.


**Figure 1: UNPEPP interns work with State and National Park Staff to mount module rack on poles.**

# Introduction

Espa Lagoon, which is located in the Prairie Creek Redwoods State Park (PCRSP), is an ecologically important interface between the Pacific Ocean and an upstream salmon-bearing watershed. Its coastal lagoon ecosystem has been negatively affected by large tree waste left by a 1963 tsunami, and the remediation of the site is a high priority for the State and Redwood National Parks System. In addition to naturally occurring disturbances to the ecosystem, there are two antiquated, 15 kW diesel generators adjacent to the lagoon that provide power to a year round ranger residence. The groundwater and noise pollution hazards to the lagoon from the generators necessitated their replacement. In 2000, UNPEPP interns Lonny Grafman and Angelique Sorensen performed a site analysis of the Espa Lagoon residence and made design recommendations for a renewable energy system. However, the park did not have the budget to implement their design. A windfall of used solar electric equipment within the Redwood National and State Parks was the impetus for revisiting the idea of replacing the diesel generators. The objective of the Summer 2006 UNPEPP project was to replace the generators with a hybrid solar electric system consisting of a photovoltaic array and a backup propane generator, along with the associated power handling equipment. The UNPEPP 2006 interns, Erin McDonald and Matt Smith, worked closely with Schatz Energy Research Center (SERC) and Park staff to review and update the 2000 design and to install the photovoltaic system.

**Figure 2: Existing diesel generators were part of a system that was just 7% fuel efficient overall (Grafman and Sorensen 2000).**

# Design Considerations

Since the main pieces of equipment for the project (Appendix A) were either donated or pre-existing on the site, the system's design focused on optimally incorporating the equipment in order to minimize additional purchases and maximize the output from the photovoltaic array. Significant expenditures such as more PV modules were not considered due to budget constraints. The PV system's power generation was limited by the capabilities of the equipment on hand and the shading at the site. The following are discussions of the design steps that were taken in order to balance system cost and the expected performance:

***Siting***

Important considerations for determining the array location at the site were shading, wiring distance, and wildlife land use patterns. The ranger residence was previously analyzed for array placement and a location was recommended (Grafman and Sorensen, 2000). Due to possible site changes during the intervening six years, the array site was reevaluated using a Solar Pathfinder, distance measurements, and an interview with the resident ranger about the use patterns around various potential sites. Based upon this investigation the UNPEPP 2000 recommendation was determined to still be optimal. The battery shed and propane tank are already located on site, which dictated the placement of the generator, batteries, charge controller, etc. These structures receive a significant amount of shading, which necessitates that a stand-alone array is installed somewhere that gets more direct sun. The selected site receives within 5% as much sun as other array locations considered, while being the closest to the battery bank. The reduction in wire cost, trenching and voltage drop outweigh the slightly lower amount of direct sun. The site also offers the additional benefit of being away from commonly used areas and elk traffic per discussion with the resident ranger.

**Figure 3: UNPEPP intern Matt Smith spacing the rack poles before pouring concrete.**

### *Module Performance Testing*

Each of the fourteen modules' performance was tested using a standard IV curve procedure (Reis et al 2002, Pauletto 1996). All modules were tested within two hours of solar noon on clear sky days. The test angle was maintained perpendicular to the sun using an angle indicator mounted on the solar module test rack. Temperature and insolation data were recorded over the duration of the test, which was approximately 30 seconds. The temperature was monitored using a thermocouple fixed to the back of each module. Irradiance data was collected using a rack-mounted pyranometer. A twist knob variable resistor was used to create a curve of current vs. voltage for each module. Two curves were constructed per module and an IV curve template was used to normalize the resultant curves to standard test conditions (Jacobson et al, 2000).

**Figure 4: UNPEPP interns Erin McDonald and Matt Smith conduct performance testing on solar modules.**

### *Array Design*

The array was designed in order to minimize the negative effects of mismatch. Mismatch occurs when modules with different performance curves are wired together or when an array is unevenly shaded. Modules wired in parallel must operate at the same voltage while those wired in series must operate at the same current level. Differences in performance curves force modules to work outside of their optimal operating levels, which can reduce efficiency and damage the equipment. When modules are all new, of the same type, and operating close to manufacturers specifications the effects of mismatch are generally considered negligible. When modules in an array are of different types, older, and degraded to different levels, the effects can become more significant (Chamberlin et al 1995).

Careful ordering of module placement within the array can minimize the effects of mismatch. The equipment obtained from the park service has two potential sources of mismatch: different types of modules and older modules. Wiring in series modules of the same type that have similar IV curves, particularly those with similar current over the operating voltage range, minimizes current variation where the voltage is additive. These same-type module series may then be wired in parallel with other types of module series pairs operating at the same voltage, where current is additive. This arrangement is thought to optimally match modules of similar type and of similar performance (Appendix B).

**Figure 5: Intern Matt Smith and SERC engineer Peter Johnstone mount modules.**

### *Wire Sizing*

Using the short circuit currents of the modules that were in parallel, the gauge size necessary to run wire from the array to the battery shed was determined. The procedure for sizing wire followed the instructions outlined in the National Electrical Code (N.E.C. 2001). Size 2 AWG was found to be appropriate for the maximum acceptable voltage drop of 3% over the transmission distance. Size 2 AWG also meets the requirements for the maximum short circuit current of the system with the required safety factor of 1.25, which is 38.5 Amps.

**Figure 6: UNPEPP intern Erin McDonald gluing conduit connections between the battery shed and the array combiner box.**

### *Rack Design*

Mounting the array involved unique design considerations. The roof of the residence appeared weathered and unable to support solar modules. The two different types of modules prevented the use of a prefabricated rack. Due to these constraints, the interns chose to construct a rack at the SERC machine shop. Scrap steel was acquired at a minimal cost and welded into a two-piece framework for easy transport and reassembly at the site. The framework was mounted on two recycled steel poles, which were set in rebar enforced concrete. The mounting bracket between the rack and poles is designed for three-phase seasonal adjustments. A pivot bolt allows the rack to move between the optimal angle orientation for summer, winter, and spring/fall. Two people can easily accomplish the seasonal adjustment.

**Figure 7: SERC machinist Ray Glover looks on as intern Erin McDonald uses an Oxyacetylene cutting torch during rack construction.**

# System Performance

### *Expected Array Output*

The nominal power output was estimated using local insolation data, shading losses, and the maximum power point calculated for the array. The insolation data was obtained from the 2000 UNPEPP report, which correlated data collected from Gold Bluffs Beach to that at Trinidad, CA and data sets developed by the National Renewable Energy Laboratory (NREL). Since the correlation indicates a 98% agreement with the conditions in Trinidad, an average of all three was used to evaluate the nominal system performance (Grafman, Sorensen, 2000).

The maximum power point obtained by performing I-V curves for each panel was used to determine the maximum power production of the entire array, 827 watts (Appendix A). This is the maximum amount of energy that could be produced by the array at standard test conditions

(25° C, 1000 Watts/m2). The nominal kWh per day is computed by multiplying the 827 watts by the number of peak sun hours corrected for shading at the particular site (Table 1).

**Table 1: Expected kWh/day accounting for local solar availability and system losses**

| Month | kWh/m2/day (peak sun hours) | % solar availability | kWh/m2/day (corrected peak sun hours) | Expected kWh/day | Expected kWh/day after system losses |
|---|---|---|---|---|---|
| Jan | 1.68 | 0.60 | 1.01 | 0.84 | 0.55 |
| Feb | 2.36 | 0.64 | 1.51 | 1.25 | 0.83 |
| Mar | 3.69 | 0.66 | 2.44 | 2.02 | 1.34 |
| Apr | 4.97 | 0.75 | 3.70 | 3.06 | 2.03 |
| May | 5.76 | 0.76 | 4.35 | 3.59 | 2.39 |
| Jun | 6.16 | 0.74 | 4.56 | 3.77 | 2.50 |
| Jul | 5.69 | 0.74 | 4.21 | 3.48 | 2.31 |
| Aug | 5.17 | 0.73 | 3.75 | 3.10 | 2.06 |
| Sep | 4.17 | 0.72 | 3.00 | 2.48 | 1.65 |
| Oct | 3.11 | 0.62 | 1.93 | 1.59 | 1.06 |
| Nov | 1.92 | 0.66 | 1.27 | 1.05 | 0.69 |
| Dec | 1.57 | 0.58 | 0.91 | 0.75 | 0.50 |

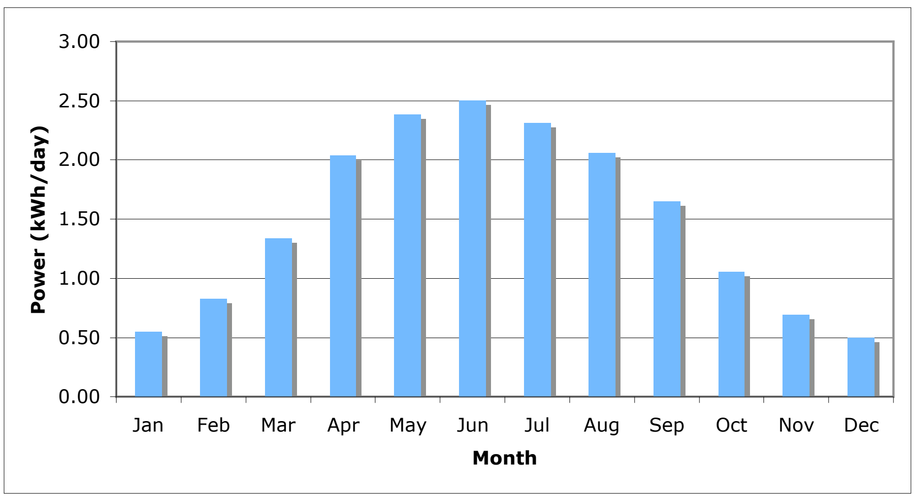



**Figure 8: Expected kWh/day accounting for local solar availability and system losses.**

To estimate the expected array output, system losses must be deducted from the nominal output. Losses through transmission, inverter conversion, and battery storage all contribute to total energy loss (Table 2). Cumulatively, these losses reduce the available power by approximately 33%.

**Table 2: System loss factors**

| Efficiency Correction Factors | |
|---|---|
| Wire loss | 0.97 |
| Inverter loss | 0.88 |
| Battery | 0.9 |
| Module temp. | 0.9 |
| Blocking diodes | 0.97 |

### *Generator Run Time*

The average daily load used by the residence was measured using a HOBO data logger. The data logger recorded the current leaving the control panel to the house in 30-second intervals. The data was recorded for 11.3 days and the average load was found to be 3.92 kWh/day. The difference between the residence demand and the number of kWh produced by the array is the load that must be met by the propane generator. On site there is also a tool shed with high peak power demand, which is infrequently used. The shed is currently run entirely off of the diesel generators, bypassing the battery bank, and will be switched over to the propane generator. The generator is estimated to be responsible for an annual average of 2.43 kWh/day or 62% of the residence load plus the power requirements of the tool shed.

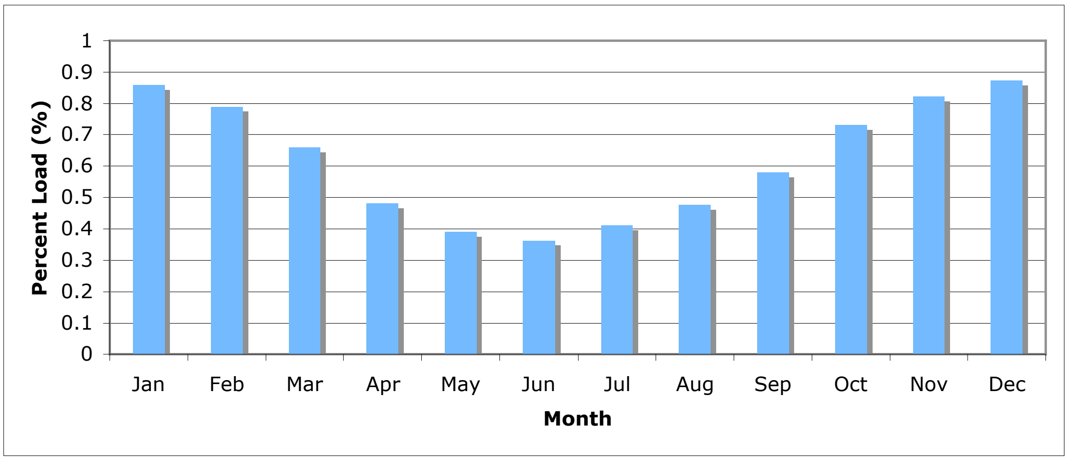



**Figure 9: The portion of the residence load to be met by the propane generator varies widely throughout the year.**

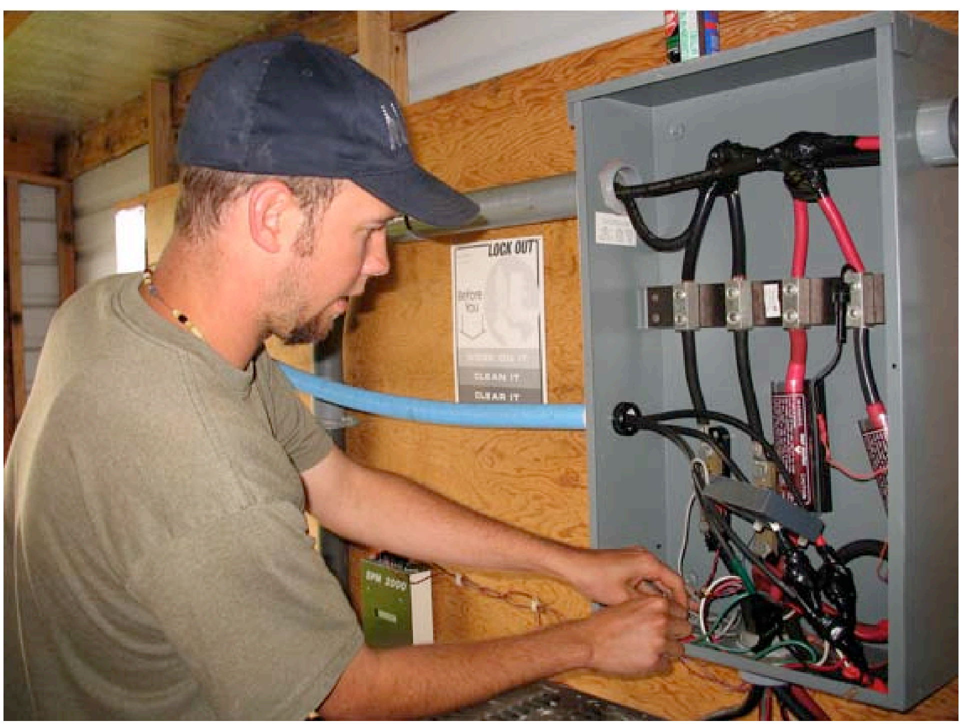



**Figure 10 UNPEPP intern Matt Smith installs a HOBO data logger to measure residence power use.**

*Observed Performance*

At the time of project completion all photovoltaic system components were installed and operating as expected. Park staff were in the process of connecting portions of the generator system, so follow up visits by SERC staff are recommended to determine the overall system performance. A maintenance guide and observation sheet were left with the resident ranger. The observation sheet is for the ranger to record daily weather conditions, cumulative amp hours, instantaneous wattage of the PV system and estimated generator run time. These data will be used to analyze system operating conditions.

**Figure 11: Intern Erin McDonald adjusts rack to the summer setting.**

**Figure 12: Renewable energy puts a smile on everybody's face.**

# Summary

The Redwood National and State Parks sponsored the UNPEPP 2006 project, with the goal of installing a hybrid solar/propane power system at the Espa Lagoon Ranger residence. An initial site assessment and design ideas were presented by the 2000 UNPEPP project, and formed a basis for the system's layout and design. The main equipment for the project was donated from within the National and State Parks system, so the focus of the project was aimed towards optimal placement of equipment, obtaining the balance of the system, and installing. After considering efficiency and transmission losses, the PV portion of the system is expected to provide an average of 1.49 kWh per day, which is 38% of the measured residence load. At the time of project completion all components were operating as expected and a monitoring program was implemented with the resident ranger to provide system operation information.

# References


Grafman, Lonny and Angelique Sorensen. (2000). *UNPEPP 2000 - Prairie Creek Final Report.* Available from Schatz Energy Research Center

Chamberlin, Charles E., Peter Lehman, James Zoellick and Gian Pauletto. (1995). *Effects of Mismatch Losses in Photovoltaic Arrays.* Solar Energy. Vol. 54, No. 3, pp 165-171.

Pauletto, Gian. (1996). *Power Loss in the Photovoltaic Array Electrolyzer System of the Schatz Solar Hydrogen Project.* Senior Project presented to Dept. of Environmental Resources Engineering at Humboldt State University.

Jacobson, Arne, Richard Duke, Daniel Kammen, and Mark Hankins. (2000). *Field Performance Measurements of Amorphous Silicon Photovoltaic Modules in Kenya.* From Proceedings of The American Solar Energy Society (ASES) Madison, Wisconsin.

Reis, A. M., N.T Coleman, M.W. Marshall, P.A. Lehman, and C.E. Chamberlin. (2002). *Comparison of PV Module Performance Before and After 11-years of Field Exposure.* From Proceeding os 29$^{th}$ IEEE Photovoltaics Specialists Conference.

Schwartz, Joe. (August and September 2005). *How to Install a Pole-Mounted Solar-Electric Array: Part 1.* Home Power. pg 108.

Schwartz, Joe. (October and November 2005). *How to Install a Pole-Mounted Solar-Electric Array: Part 2.* Home Power. pg 109.

Earley, Mark W. (2001). *National Electrical Code Handbook.* Article 690

Sandia National Laboratories, *Maintenance and Operation of Stand-Alone Photovoltaic Systems*. Pg. C-3 (1991)

# Appendix A: System Components

**Solar Modules –** *(8) Siemens SP75, 4.4 amp, 17 volt, 75-watt modules*, *(6) Solarex, 3.56 amp, 16.8 volt, 60 watt modules*

**Batteries –** *(20) Interstate Workaholic Deep cycle batteries, 6-volt, 375 amp hr*. The battery storage was in place before the 2006 project began. The batteries are wired with 5 parallel strings of 4 batteries in series. This creates a 24-volt system with 1875 amp-hr max capacity.

**Charge Controller-** *Xantrex C40, 40 amp controller* - The charge controller is used to regulate the voltage from the array and maintains the battery charge.

**Inverter –** *Xantrex Prosine 2.5 inverter* – The inverter is a 2500-Watt true Sine Wave inverter with 50-amp surge capability. Besides converting stored DC power to AC, the inverter also protects batteries from damage associated with over-discharge by shutting down when battery voltage drops below a critical level (usually 20 volts for a 24 volt system).

**Generator –** *Winco PSS8B4W 7.2 kW propane generator*

# Appendix B : Module Pairing

Module performance was evaluated using IV curves. To reduce scatter the IV curve data was fit to a five parameter lumped equivalent circuit model given as (Chamberlin et al 1995):

$$I = I_L - \left[ \frac{I_L - \frac{V_{OC}}{R_P}}{\exp(ekt \cdot V_{OC}) - 1} \right] \times \left\{ \exp\left[ ekt(V + R_S I) \right] - 1 \right\} - \frac{(V + R_S I)}{R_P}$$

Where,

| | |
|---|---|
| I | = module output current (A) |
| V | = module voltage (V) |
| $I_L$ | = light induced module current (A) |
| $V_{OC}$ | = open circuit module voltage (V) |
| $R_S$ | = module series resistance (Ω) |
| $R_P$ | = module parallel or shunt resistance (Ω) |
| ekt | = f(q,n,k,T) ($V^{-1}$) |

The parameters were derived by minimizing the sum of the squared residuals between the amp values from the two IV curve tests and the amperage produced by the model for a given voltage. This methodology changes the model such that the difference between the model and the data set is as small as possible. The model becomes a better description of the way each module behaves in the real world under different operating conditions. Microsoft Excel's Solver function was used to perform the minimization. The number of IV curve data points used for the model fitting varied between 643 and 399 among the modules, which is a sufficiently large data set for model fitting (Figure 13). In all cases the routine converged upon an accurate parameter set (Figure 14).

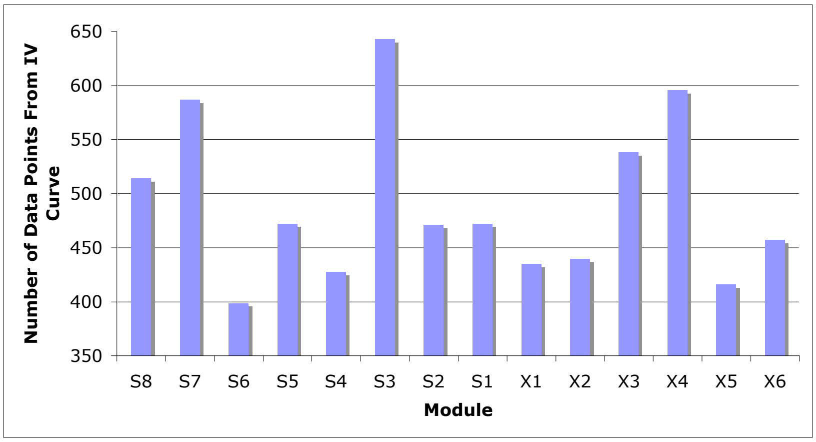



**Figure 13: Number of IV curve data points obtained for each module during performance evaluation.**

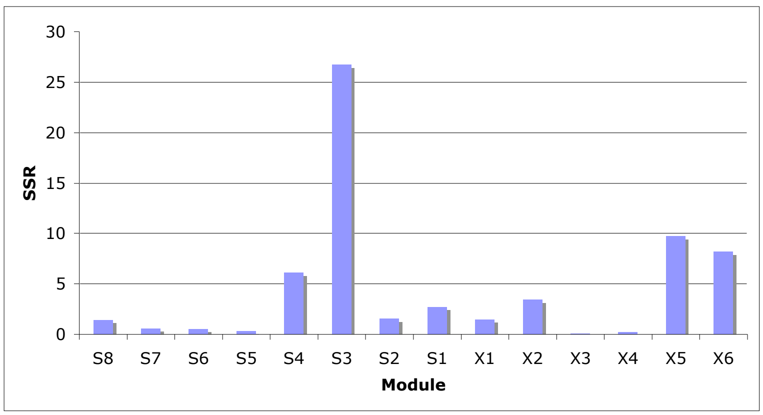
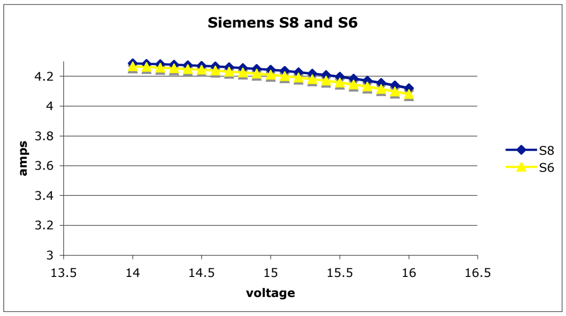



**Figure 14: The low values of the sum of the squared residuals between the model and the IV curves for each panel show a good fit.**

Once parameters were obtained for each module's IV curve, the model was used to compare the expected amperage at the operating voltage range and the short circuit current for pairs of modules. (figures 15-18) The operating voltage range is between 14 and 16 volts and the module pairs were matched to yield the smallest average difference in amperage over this range. Six out of the seven pairs were well matched with an average of less than 0.05 amp difference in current over the operating voltage.(Figure 19) One pair was mismatched with an average of 0.21 amps difference in current over the operating range.(Figure 20) This may prove to have negligible effect on system performance, but provides impetus to use diodes as additional protection against reverse current.



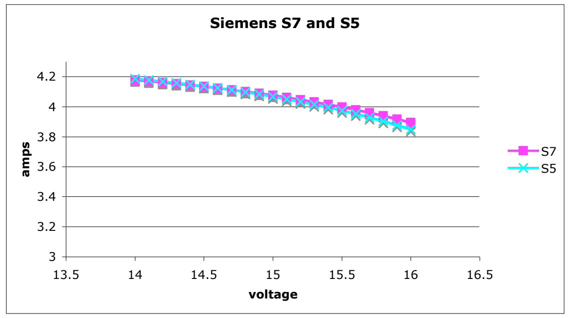
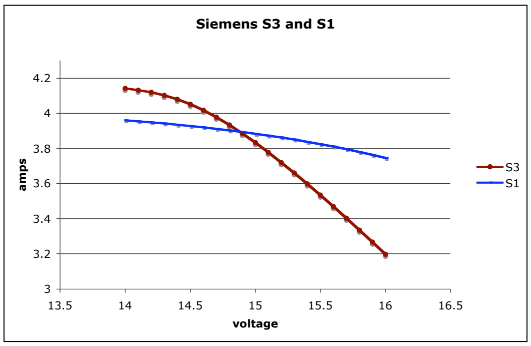



**Figure 15: Pairs S8S6 and S7S5 appear to be well matched.**



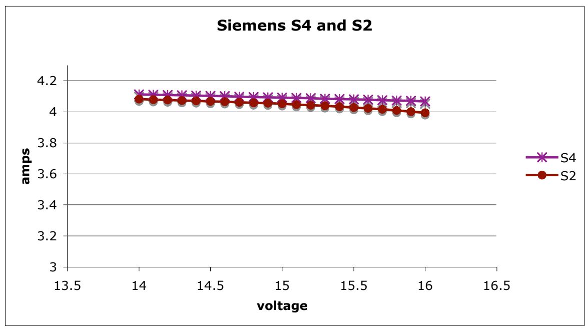
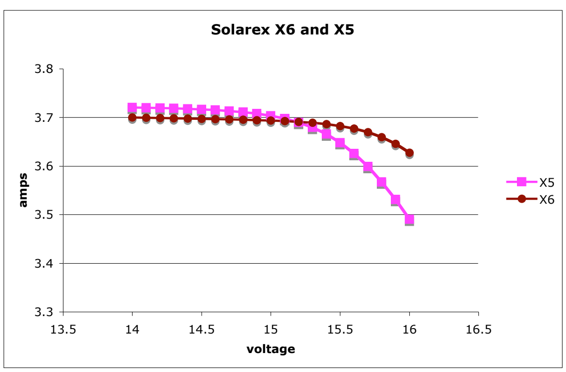



**Figure 16: Pair S4S2 appear to be well matched. S3S1 show some discrepancy in operating conditions.**



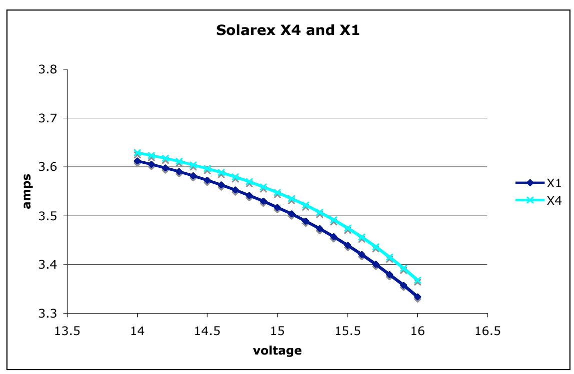



**Figure 17: Pairs X4X1 and X6X5 appear to be well matched.**

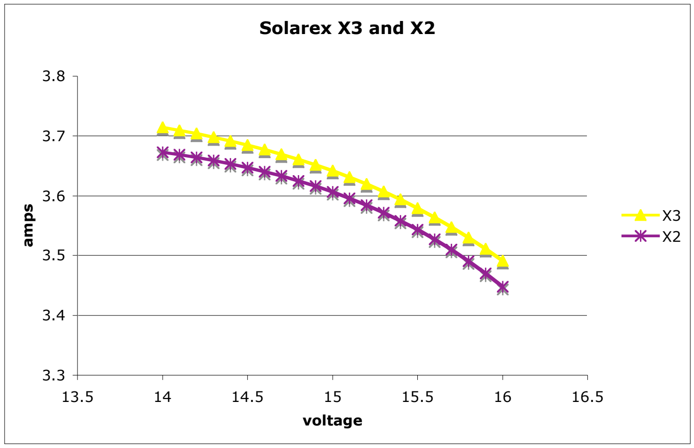



**Figure 18: Pairs X3X2 are well matched**

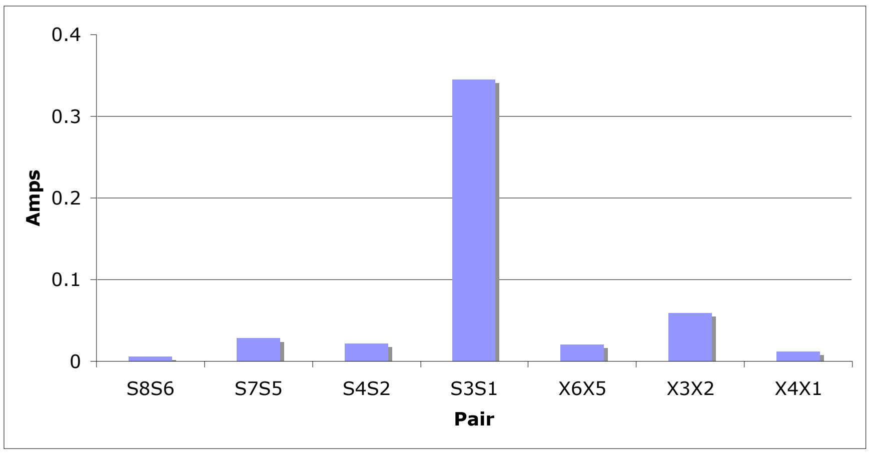



**Figure 19: Difference in short circuit current between module pairs.**

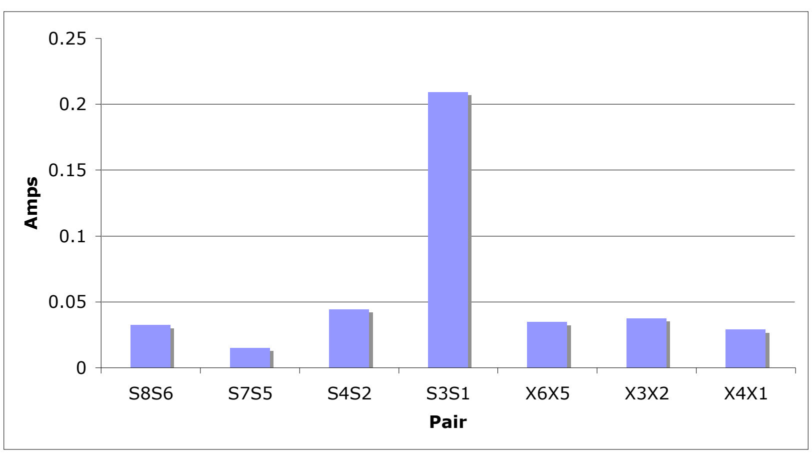



**Figure 20: Average difference in current between modules in a pair over the operating range of 14-16 volts.**