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Field Performance Measurements of Amorphous Silicon Photovoltaic Modules in Kenya

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ABSTRACT

Our research team measured the performance of 130 amorphous silicon (a-Si) photovoltaic (PV) modules and 17 crystalline PV modules at 145 homes in rural Kenya. We also purchased 14 a-Si modules in Nairobi that we tested at outdoor testing facilities in the US and Kenya. We used an outdoor IV test method that has an accuracy of ±5% and a repeatability of ±5% for clear sky conditions. The large majority of the a-Si PV modules sold in Kenya are made by three different manufacturers. Our results show that modules made by two of the a-Si PV module manufacturers are an effective, low cost alternative to crystalline PV. However, the poor performance of modules made by one manufacturer indicates a need for measures to ensure the high quality of all modules sold in the Kenyan PV market.

1. INTRODUCTION

Kenya has an active solar home systems market, with cumulative sales in excess of 100,000 units, and current sales of approximately 20,000 modules per year. Small, 10 to 14 Watt single junction amorphous silicon (a-Si) photovoltaic (PV) modules make up the majority of these sales. One key reason for the large market share enjoyed by a-Si PV is its low retail price relative to similar sizes of crystalline PV modules. Amorphous silicon modules sell for approximately $5.50 per rated peak Watt (Wp) in Kenya, while similar sizes of crystalline modules sell for approximately $9.00 per rated peak Watt. Despite their commercial success, there is substantial concern in Kenya about the quality of a-Si PV modules because of the technology's uneven performance record [Ochieng, 1999].

2. METHODS

Our group measured the performance of PV modules using an outdoor IV test method. The accuracy of the method is estimated at ±5% based on a comparison with solar simulator measurements made at the U.S. National Renewable Energy Laboratory (NREL). Additionally, multiple measurements of a crystalline module indicate a repeatability for the method of approximately ±5%.

2.1 IV Test Method

We tested modules using an outdoor IV curve measurement procedure. In designing the procedure we aimed to create a portable and rugged test kit that would provide accurate and repeatable results.

We collected three IV curves for each module tested in the field, and two curves each time that we tested a module at one of the outdoor testing facilities described in section 2.5. The curves were collected with a custom IV curve data logger. The data logger records current-voltage pairs at a rate of 10 Hz. The tests take 15 to 25 seconds each, which results in 150 to 250 current-voltage data pairs per curve. During the tests we varied the load on the PV module by manually adjusting a 100 ohm power rheostat.

We used a Licor 200SA silicon diode pyranometer to measure the average solar radiation on the PV module during the tests and a type-K thermocouple to measure the initial and final temperature on the back surface of the module. We used a portable test rack to orient the modules to be normal to the sun's beam during tests.

Prior to carrying out the tests, we cleaned each module with water to remove any accumulated dust. We then dried the modules and allowed them to sit in the sun for several minutes so that they reached thermal equilibrium.

2.2 Calibration of the IV Curve Test Method

In order to ensure the accuracy of our tests, we calibrated each of our instruments carefully. The pyranometer calibration is the most critical of these measurements.

2.2.1 Pyranometer Calibration: We calibrated each of the Licor 200SA pyranometers using an Eppley PSP pyranometer as the reference standard. The calibration procedure involved orienting both pyranometers so that they were normal to the sun's beam, then measuring the average output from each pyranometer over three separate one minute periods. We used the average from these three periods to determine the final calibration coefficient.

We carried out each of the pyranometer calibrations under clear sky conditions with an air mass between 1.0 and 1.5. The original calibration measurements were carried out at the University of California, Berkeley. We then cross-checked the calibrations with measurements at field sites in Kenya. The measurements for the Berkeley and Kenya sites differed by less than 2% in all cases.

In addition, we made calibration measurements to verify the accuracy of the IV curve testers' current and voltage measurements and the temperature measurements. We also measured the temperature-voltage correction coefficients for each brand of module that we tested.

2.2.2 Reference Module Tests: We purchased two polycrystalline modules in Kenya for testing. We used these as "reference modules" during a number our tests. These tests provided an estimate of the repeatability of our IV test procedure. We define repeatability based on a 95% prediction interval about the mean measured maximum power for a number of tests of each reference module. The prediction interval indicates a 95% probability that an individual measurement will fall within the specified range.

We completed 37 tests for one of the modules and 29 tests for the other. These measurements indicated a repeatability for clear sky test conditions of ±5.1% for one of the modules and ±4.2% for the other, respectively.

2.2.3 Solar Simulator Tests at NREL: Finally, we sent five of the a-Si modules and one of the polycrystalline reference modules to NREL, where they were tested in two different solar simulators.

The first set of tests were conducted in a "SPIRE 240A" pulsed solar simulator. This type of simulator is commonly used by PV manufacturer's for rating modules. The second set of tests were carried out in a "Large-Area Continuous Solar Simulator" (LACSS). This simulator is generally considered to be more accurate than the pulsed solar simulator [Emery, 2000].

These tests show that our maximum power estimates agree with results from both of NREL's solar simulator tests to within ±5% or better for four of the six modules tested. For these four modules (two brand A modules, one brand B2 module, and the polycrystalline reference module; see Section 2.4), our measurements agreed with the LACSS test results to within ±1%.

For the remaining two modules (brand C2) our maximum power estimates exceeded those from the LACSS tests by 4.8% and 6.2%. However, NREL cautioned that the simulator results for these two tests may have been inaccurate because they were not able to obtain reliable quantum efficiency data[1] for this module brand [Rummel, 2000]. We chose not to use the simulator tests for these two modules in evaluating our method due to the uncertainty in the accuracy of these measurements.

2.3 Data Analysis Methods

The IV curves for each module were analyzed in four steps. First, we normalized each of the IV curves to standard test conditions of 1000 W/m^2 and 25°C. Next, we combined the IV curves for each module test into a single data set. We then fit a polynomial model to the data set. Finally, we estimated the maximum power output for each module from the modeled IV curve.

We normalized the module current using:

$$I_n = I_m * \frac{1000\ \mathrm{W/m^2}}{E}$$

where: I_n = normalized current (amperes)
I_m = measured current (amperes)
E = mean measured solar radiation on the PV module (W/m^2)

We normalized the module voltage using

$$V_n = V_m * \{1 + b*(25°C - T)\}$$

where: V_n = normalized voltage (volts)
V_m = measured voltage (volts)
b = temperature coefficient (1/°C)
T = module temperature (°C)

[equations from Chamberlin, et al., 1995].

The temperature coefficient, b, is the fraction of voltage lost per degree temperature increase for the module.

We fit the normalized IV curves with a polynomial model. A fourth order model provided an adequate fit for most a-Si module curves, although a fifth order model was used in some cases. We used seventh to ninth order polynomials for crystalline module curves in order to conform to their higher fill factor IV curves. See Figure 1 for a typical a-Si module curve fit. The maximum power output was estimated from each modeled IV curve.

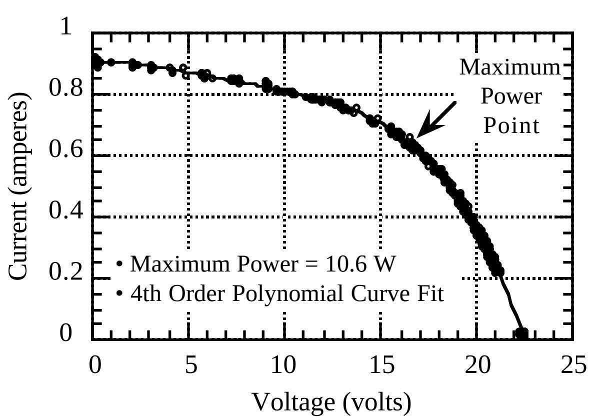

Fig. 1: IV Curve for a Brand B2 a-Si photovoltaic module (12 Wp rated power)

2.4 Field Testing of PV Modules in Kenya

We measured 130 a-Si modules and 17 crystalline modules in the field in Kenya. The crystalline modules were included for comparison purposes only. We used the tests to evaluate the performance of modules that are currently being used in Kenyan homes. Throughout the testing we had two fully equipped teams in the field.

The age of the a-Si modules in the field ranged from a few months to 10 years. The average age was 2.7 years, and 85% of the modules were less than 5 years old. All but 2 of the 130 modules had been in the field for more than 3 months and had completed their initial Staebler-Wronski degradation period [Staebler and Wronski, 1977].

The majority of the a-Si modules that we encountered were made by three manufacturers, which we designate here by the letters A, B, and C. We refer to the modules made by the three respective manufacturers in this report as "brand A", "brand B1", "brand B2", "brand C1" and "brand C2" modules. The B1 and C1 modules are earlier models that have now been discontinued. The A, B2, and C2 modules are currently available in the Kenyan market. We also found a small number of modules made by two additional a-Si module manufacturers. We refer to these as "brand D" and "brand E" modules.

Brands B1 and B2 each contributed 25% of the 130 modules encountered, while brand A modules made up 24% of the total. Brand C2 had a share of 10%, followed by brand C1 (8%), brand E (6%), and brand D (2%).

2.5 Outdoor Testing of New Modules Over Time

We purchased 14 a-Si modules in order to test their performance over the first few months of operation. Nine of the modules were tested at Energy Alternatives Africa’s compound in Nairobi, Kenya, while an additional 5 modules were tested at an outdoor testing laboratory at the University of California, Berkeley. We used these tests to confirm the Staebler-Wronski degradation of the modules. After the modules’ power output had stabilized, we were also able to compare their performance with the results from our field tests.

3. RESULTS

3.1 Average Module Performance

We found substantial variation in the average quality of different module brands (Table 1 and Figure 2) with brand B1 and B2 panels performing best, brand A panels performing a close second, and brand C1 and C2 modules trailing substantially.

Including modules from the outdoor testing facilities, but excluding cracked or failed modules (*i.e.* those producing less than 10% of rated capacity), the average brand B2 module in our sample produced 89% of rated output, with a 95% confidence interval of ±3%. Brand B1 modules performed similarly with a mean output of 88% (±3%).

Brand A modules produced, on average, 83% (±3%) of their 12 Wp rating. While the quantitative performance difference between brand B2 and brand A is modest, a t-test indicates that it is statistically significant ($p = 0.04$).

The narrow confidence interval bands indicate consistent performance among the brand A and brand B modules. That is, while there is substantial variation in performance between brands, the performance of the better brands is relatively consistent from module to module.

It is somewhat troubling that, on average, none of the module brands in our sample performed at their rated output levels. Nonetheless, the brand B1 and B2 modules compare favorably with the 17 crystalline (x-Si) modules of various vintages and brands that we tested in the field (see Figure 2). Moreover, this result is consistent with previously reported field performance tests that indicated that both crystalline and a-Si PV modules often perform 5-15% below their rated power output [Hester and Hoff, 1985; Jennings, 1987; Lehman and Chamberlin, 1987; Chamberlin, et al., 1995].

Brand C1 and C2 products performed notably worse than the others. The older 11 Wp brand C1 modules averaged 61% (±14%) of rated output. The currently available 14 Wp brand C2 modules that we tested produced only 55% (±9%) of rated output on average. The larger confidence intervals for brand C modules are due both to smaller sample sizes and to greater variations among the modules.

Measurements of Staebler-Wronski degradation for 6 brand C2 modules indicate that power output is initially high, but that it quickly drops to well below the rated output of 14 Wp. The mean stabilized maximum power for the 6 C2 modules was 8.4 Wp. See Figure 3 for a representative C2 module. Performance of a brand B2 module is included for comparison. These results indicate that much of the low performance of the brand C2 modules can be attributed to Staebler-Wronski losses.

3.2 Module Failures

In addition to their low measured performance, the brand C1 and C2 a-Si modules appear to suffer from high levels of failure due to breakage and encapsulation problems. See Table 2. Defining module failure as producing less than 10% of rated power, 46% of Brand C1 and 40% of Brand C2 modules in our sample had failed vs. only 6% of Brand A modules and 0% of Brand B1 or B2 modules. These failed modules were excluded from our mean performance estimates because field sampling at homes is likely to systematically miss failed modules that have been discarded. Nonetheless, if the true failure rates for each brand are similar to what we encountered, accounting for failed modules widens the performance gap further.

It should be noted that, over the past decade, all three a-Si companies have made modifications to attempt to address concerns about encapsulation and breakage, and the manufacturer of brands B1 and B2 appears to have achieved substantial progress in this regard [Van der Vleuten and Guillardeau]. A senior representative from the manufacturer for brands C1 and C2 has reported that he is aware of quality control problems with their modules. This manufacturer has taken steps to improve their modules; they recently released a new version of the brand C2 module. Our group is in the process of evaluating four units of this newly released module. We will present these results in a subsequent publication.

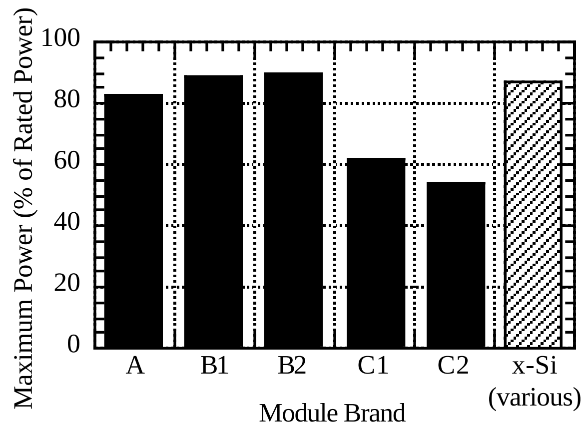

Fig. 2: Average Measured Power Output for Five Brands of a-Si Modules in Kenya; Performance of crystalline (x-Si) modules is included for comparison.

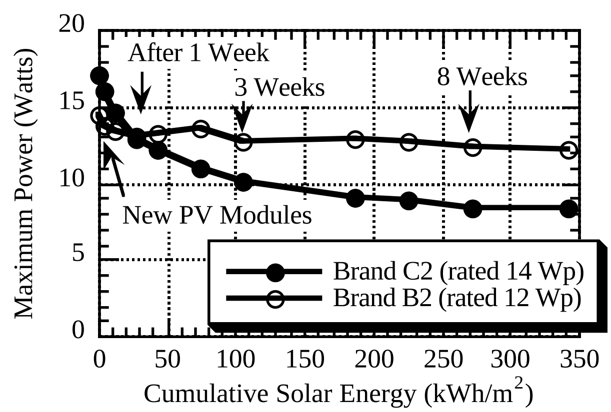

Fig. 3: Maximum Power vs. Cumulative Solar Energy for Brand B2 and C2 a-Si PV Modules. The result shows Staebler-Wronski degradation over two months.

TABLE 1. SUMMARY OF MODULE PERFORMANCE FOR WORKING A-SI MODULES[2]

Module Model	Rated Max. Power (Watts)	Average Measured Max. Power (Watts)[3]	Percentage of Rated Output	95% Confidence Interval (± % points)	Average Age of Modules (years)	# Modules Tested
Brand A	12	10.0	83%	±3 %	2.8	31
Brand B1	11	9.7	88%	±3%	3.1	31
Brand B2	12	10.6	89%	±3%	0.9	32
Brand C1	11	6.8	61%	±14%	2.4	5
Brand C2	14	7.7	55%	±9%	1.5	12
Brand D	25	22.5	90%	n/a	5.0	1
Brand E	10	7.2	72%	±11%	5.9	4

TABLE 2. FAILURE RATES FOR A-SI MODULES FROM FIELD TESTS IN KENYA

Module Brand	Failed Modules (%)[4]	Cracked Modules (%)[5]	# Modules in Sample
Brand A	6%	3%	31
Brand B1	0%	6%	32
Brand B2	0%	6%	32
Brand C1	46%	29%	13
Brand C2	40%	0%	10
Brand D	0%	50%	2
Brand E	38%	20%	8
Other (unknown)	50%	0%	2
These failure and cracking rates are for our data set only. They may underestimate failure and cracking rates for a-Si modules in Kenya, as people are likely to discard failed units.			

TABLE 3: RETAIL PRICE FOR SMALL PHOTOVOLTAIC MODULES IN KENYA

Module Brand	Module Type	Rated Power (Watts)	$/rated Wp	$/measured Wp[6]
Brand B2	a-Si	12	5.60	6.29
Brand A	a-Si	12	5.40	6.50
Brand C2	a-Si	14	5.25	9.72
Polycrystalline	x-Si	20	8.96	10.29

3.3 Long Term Module Performance

In addition to comparing performance across different brands, we also considered module performance as a function of age. We had sufficient data to evaluate the long term performance of brands A and B1. Our data are consistent with a possible module degradation rate of 1% per year for these brands. Testing over an eight year period by PVUSA indicated a 1-5% per year degradation for arrays of both a-Si and crystalline modules [PVUSA, 1998]. Our analysis is therefore broadly consistent with PVUSA's data, tending to confirm the result that a-Si and crystalline modules have similar long-term degradation rates. This suggests that higher quality a-Si modules hold their performance levels adequately over time. The authors will present a detailed analysis of this issue in a forthcoming publication.

3.4 Module Price:

Our group collected retail price information in an informal survey of PV module dealers in Kenya. The results indicate that a-Si modules are sold for prices that range from $5.00 to $6.00 per rated Wp, while most crystalline modules of 30 Wp or smaller sell for $8.00 to $10.00 per rated Wp. We combined performance data with this price information to estimate the average cost per measured Wp for several brands of small PV modules in Kenya. See

Table 3. These data indicate that brands A and B2 are much less expensive than crystalline modules on a per Watt basis. However the low power output of brand C2 modules raises their effective price to the level of the small-module crystalline technology.

4. CONCLUSIONS

In this paper we report performance results for a-Si PV module performance from field testing in rural Kenya. The IV test method that we employed has an estimated accuracy of ±5% and a repeatability of ±5%. The method allowed us to make accurate measurements in rugged field conditions. These tests are critical for documenting the level of service that PV technologies are providing to rural end users.

Our results indicate that two of the three brands of single junction a-Si modules available in Kenya perform adequately. The low retail price per measured peak Watt, the small number of failed modules identified in the field, and the long term performance of these modules all indicate that they provide a cost-effective alternative to crystalline PV modules for low wattage applications.

However, the poor performance of modules made by one manufacturer indicates that standards, quality certification programs, consumer education, or other mechanisms are needed to ensure the high quality of all of the modules sold in the market. The authors will address the issue of quality in the Kenyan PV market in a forthcoming publication.

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[1] Quantum efficiency data are used to "tune" the spectral output of the solar simulator to match the PV module's spectral response. This tuning is necessary to ensure an accurate measurement of module performance.

[2] The information in Table 1 includes the results from modules tested at the University of California, Berkeley and at Energy Alternative Africa's compound in Nairobi Kenya in addition to the 130 modules tested in the field. The additional modules tested include 3 brand A modules, 2 brand B1 modules, 3 brand B2 modules, and 6 brand C2 modules. These statistics all exclude failed modules, defined as those producing less than 10% of rated capacity. Cracked modules and modules performing at pre-stabilized power output levels are also excluded.

[3] The average measured maximum power, 95% confidence interval, and # of modules in sample are calculated for non-cracked, functioning modules only. Modules performing at pre-stabilized output levels are also ignored.

[4] Failed modules are defined as modules that have an output that is less than 10% of the rated output.

[5] This category includes only those cracked modules that were operational. Cracked modules that had failed are listed as failed modules. Note that percentage listed is the fraction of the total functioning modules that are cracked.

[6] Note that these data exclude cracked and failed modules.