Field Performance Evaluation of Amorphous Silicon (a-Si) Photovoltaic Systems in Kenya: Methods and Measurements in Support of a Sustainable Commercial Solar Energy Industry

A PROJECT OF

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&
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Executive Summary

Kenya has an active market for photovoltaic (PV) solar home systems (SHSs), 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) modules dominate this market, largely due to their lower retail price relative to similar sizes of crystalline PV modules. Amorphous silicon modules sell for approximately US\$ 5.00 per rated peak Watt (Wp) in Kenya, while most brands of similarly sized crystalline modules sell for approximately US\$ 8.00 per rated Wp.

Despite this commercial success, there is substantial concern about the performance of single junction thin-film a-Si—both because of the technology's uneven quality record and the uncertainty introduced by short-term degradation which occurs when this type of PV module is initially exposed to the sun. To address these concerns, in 1999 an interdisciplinary research team from the Energy and Resources Group at the University of California at Berkeley, Princeton University, and Energy Alternatives Africa from Nairobi, Kenya, conducted a study of the long-term field performance of single junction a-Si PV modules in Kenya.

This study confirms that modules made by two of the three companies that dominate the Kenyan a-Si PV market offer long-term performance roughly comparable to crystalline PV. Thus, quality brands of single junction a-Si modules provide a highly cost-effective alternative to crystalline modules for SHSs—especially for households only willing or able to purchase a relatively small system.

There are, however, concerns about the susceptibility of available single junction a-Si modules to physical breakage. More importantly, one manufacturer has built a one-third share of the Kenyan a-Si market while selling modules with substantially inferior performance. The success of this brand despite its considerably higher price per *measured* Wp suggests that rural consumers are ill-equipped to compare the relative performance of different module brands. Some combination of public information, certification/labeling, standards (e.g. equipment quality requirements for accessing PV loan funds or government restrictions on uncertified modules), and new SHS business models (e.g. fee-for-service) may prove helpful in educating and protecting consumers, thereby ensuring that this market reaches its potential. There are, however, risks and limitations associated with each of these mechanisms that necessitate a cautious approach.

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Market Background

Kenya has an active solar home systems (SHSs) market, with cumulative sales in excess of 100,000 units and current sales of about 20,000 systems per year—all without any substantial subsidy and with only minimal programmatic support. There are more than 40 independent import and manufacturing companies, as well as hundreds of vendors, installers, and after-sales providers to serve this demand.

When the SHSs market emerged in the mid-1980s, typical systems used crystalline (x-Si) modules of 40 Wp (Acker and Kammen, 1996). In 1989, however, 10 Wp amorphous silicon (a-Si) modules entered the market, capturing the majority of SHSs sales within five years (van der Plas and Hankins, 1998). Since then, total a-Si sales in Kenya have increased dramatically, from 10 kWp in 1989 to 270 kWp in 1998 (Figure 1).

Figure 1. Sales of Amorphous Silicon and Crystalline Silicon PV Modules in Kenya
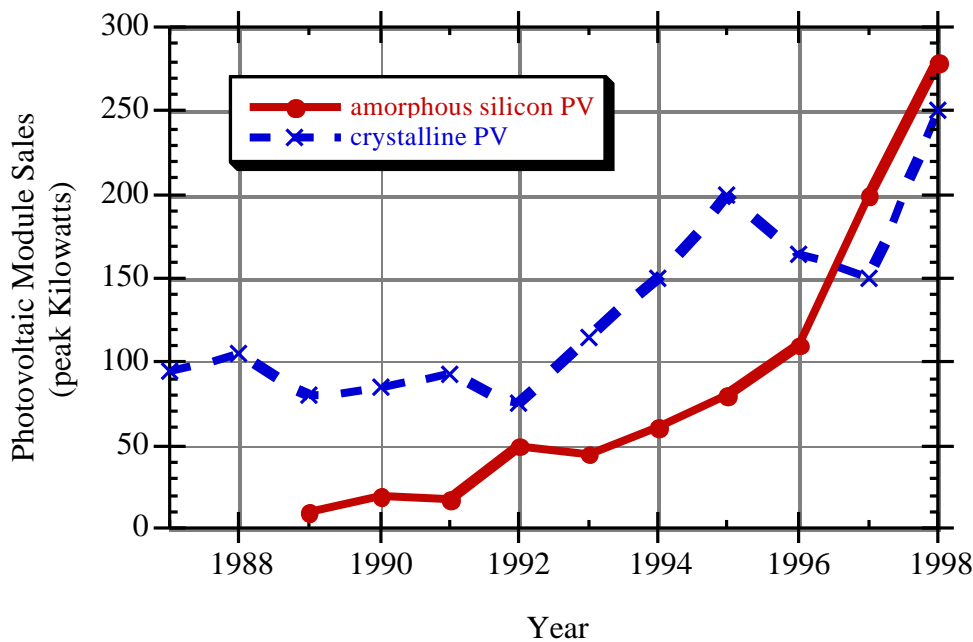
Data Source: Energy Alternatives AFRICA, 1999

Essentially all a-Si modules sold in Kenya go into SHSs, and a substantial majority of all household systems use a-Si modules. That said, most a-Si SHSs in Kenya hardly qualify as systems at all. In one typical pattern, families simply tie a module to their roof and directly wire it to a car battery that they already own and charge in town. Among other system design issues, the lack of a charge controller raises concerns about battery longevity; however, the critical advantage of this approach is that it reduces the incremental cost of "going solar" to as little as US$ 55. This

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has made PV generated electricity accessible on a fully commercial basis to thousands of Kenyan households that otherwise would not have been able to afford it.

On a global basis, the a-Si market was initially dominated by small single-junction cells used for calculators and other consumer applications. Annual production of these cells by Japanese firms has hovered in the vicinity of 5 MWp since 1987 (Nikkei Electronics, 1/25/99, No. 735). This market is generally considered distinct because producing very low output consumer cells is far easier than achieving uniform deposition of the active a-Si layers over substrate areas large enough to build conventional PV modules.

Single-junction a-Si modules are produced from a number of factories located in France, Croatia, China and the United Kingdom—all using production technology originally derived from the Chronar Corporation of the United States. Precise annual production figures for module-scale single junction a-Si are not available, but the total output of single-junction a-Si modules in 1999 probably did not exceed 5 MWp. In addition to Kenya, important markets for single-junction a-Si modules used in SHSs include China, Indonesia and Zimbabwe, among others.

As of 1997, cumulative production of multi-junction a-Si for modules had only reached about 3 MWp (Peterson, 1997); however, in 1997 BP Solarex (10 MWp dual junction) and United Solar Systems Corporation (5 MWp triple junction) both started production from a-Si plants.[1] Both of these manufacturers have announced major expansion plans, and Kaneka Solar Tech started production from a 20 MWp a-Si facility in late 1999, with plans to expand to 40 MWp of production capacity in 2000.[2]

These production figures suggest total a-Si production for 2000 of approximately 30 to 45 MWp (including consumer cells, single junction modules and multi-junction modules), or roughly one-fifth of global PV sales. If the new multi-junction a-Si production capacity comes on line as planned, a-Si may maintain or possibly increase its market share.

Quality Concerns

Despite their commercial success in Kenya there is substantial concern about the performance of single junction thin-film amorphous silicon (a-Si) PV modules. New a-Si panels suffer predictable light-induced efficiency degradation before stabilizing (Figure 2). Although manufacturers are supposed to rate panels at their post-degradation output levels, this "Staebler-Wronski" degradation (Staebler and Wronski, 1977) introduces performance measurement complexity that may add to the reputation problems of a-Si. Additionally, single-junction a-Si manufacturers have generally not been willing to match the warranty terms offered for crystalline panels, fueling doubts about the relative reliability of this PV technology.

Most of the a-Si modules sold in Kenya do include some sort of manufacturers' warranty:

- Free Energy Europe (FEE) offers a 10 year warranty;
- NAPS offered a 5 year warranty before their module factory was purchased by FEE;
- Koncar offers a 5 year warranty;
- Intersolar offers a 5 year warranty; and,

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[1]   www.nrel.gov/ncpv/pdfs/tf_united.pdf and www.nrel.gov/ncpv/pdfs/tf_solarex.pdf
[2]   www.nrel.gov/ncpv/pdfs/npcinc.pdf

- Uni-solar offers a 20 year warranty.

APS has no stated warranty in their literature. For those manufacturers that do offer a warranty, the terms include the usual protection against manufacturing defects and a drop in output below 85% or 90% of rated power depending upon the manufacturers specific terms.

The importing agents for all of the major a-Si brands sold in Kenya have historically been cooperative about replacing defective modules. Replacements have run less than 1% for all but the worst performing brand in our study (for which the importer reports returns of about 10% of modules sold). There are, however, serious concerns about the practical value of these warranties for rural Kenyan SHS owners.

First, rural households are unable to measure the output of modules, and the dealers are generally not well-equipped to help them and may prefer to discourage such testing to avoid having to process returns. Battery failure is the first sign of possible panel failure; however, batteries regularly fail even when used with a module that is functioning well. It is therefore hard for a rural household to know whether their module is performing within the warranty terms. As a result, only absolutely "dead" modules tend to come back for warranty replacement.

In addition, if a company is sold or goes bankrupt the Kenya representatives for the old brand may choose not to honor the defunct manufacturer's warranty. It is important to note, however, that Free Energy Europe purchased the NAPS a-Si manufacturing facilities in 1998 and has stated that they will honor warranties on modules sold by NAPS before the change in ownership.

Figure 2. I-V Curves Showing Staebler-Wronski Degradation for a "Brand B2" 12 Wp a-Si Photovoltaic Module
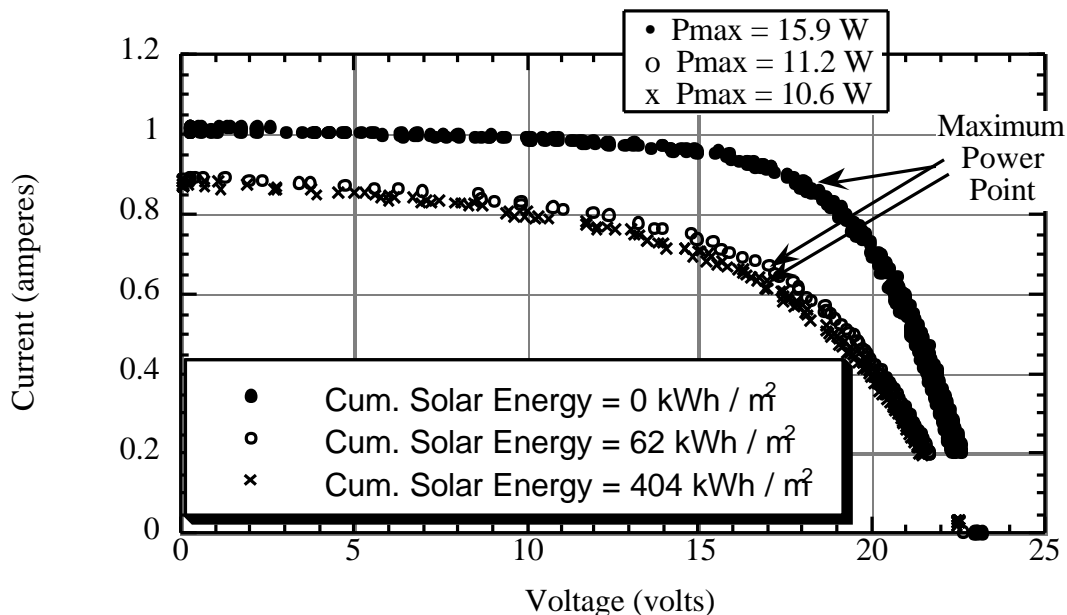
Project and Methodology Description

During the Spring of 1999, graduate students and staff from Energy Alternatives Africa (Nairobi, Kenya) the Renewable and Appropriate Energy Laboratory (RAEL) of the University of California Berkeley and the Science, Technology and Environmental Policy (STEP) program at Princeton University conducted a field and laboratory-based testing program with the primary purpose of assessing the performance and longevity of single-junction a-Si modules typically sold for SHSs in Kenya. In addition to module testing, we also interviewed the owners of each of the 145 SHSs in our sample and conducted a range of tests to assess overall system performance. Finally, we established a pair of outdoor test sites (in Nairobi and Berkeley) to closely track the initial Staebler-Wronski degradation (as well as any subsequent degradation over the time frame of our testing) in a set of new panels.

We developed a testing methodology able to estimate module output normalized to standard test conditions (25 degrees Celsius and insolation of 1000 W/m2). This involves a customized low-cost I-V tester that records current (I) and voltage (V) pairs as the resistance is varied using a potentiometer. The resulting I-V curve (e.g. Figures 2, 3 & 4) can be used to estimate module output at the maximum power point, or any other voltage, by multiplying voltage times the associated current.

Figure 3. I-V Curve Performance for a "Brand A" 12 Wp a-Si Module
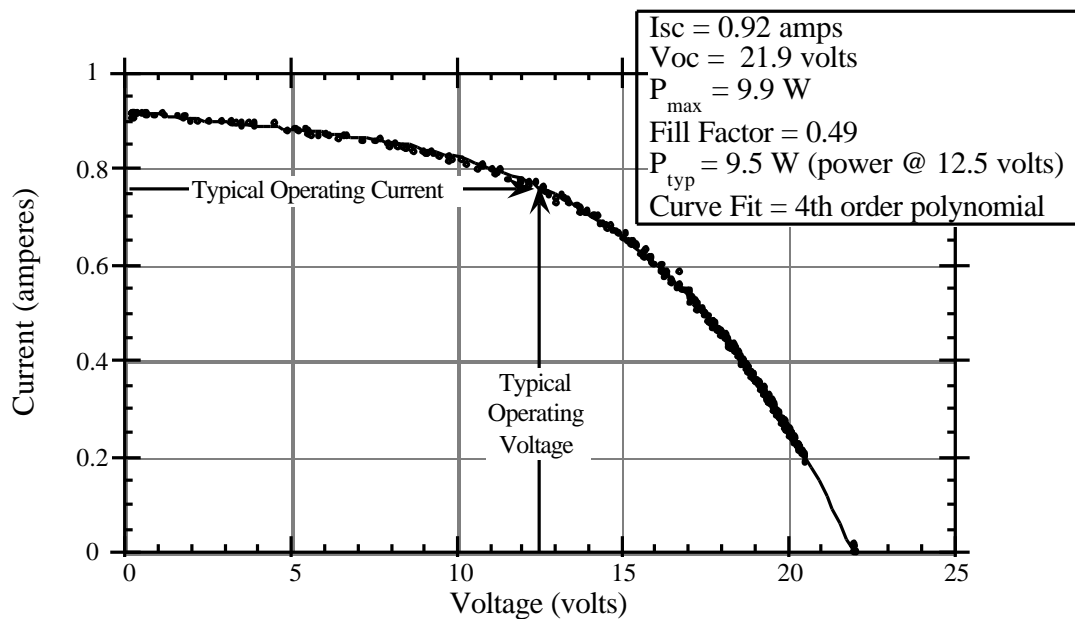
To account for module temperature variations, we measured the temperature on the back of the module with a Type-K thermocouple. We used an inexpensive but rugged and accurate Licor 200-SA pyranometer to measure solar radiation on the module surface. Finally, to standardize the test procedure, we designed a simple test rack that ensured that both the module and pyranometer were pointed directly at the sun during the test.

The overall accuracy for this approach is approximately ±5%. This estimate of the accuracy is based on a calibration of our test method against a solar simulator at the United States Department of Energy's National Renewable Energy Laboratory (NREL). The repeatability of the test for clear sky conditions is ±5%. This means that, under clear sky conditions, 95% of repeated tests of the same module will yield maximum power estimates within ±5% of the average maximum power for that module. This methodology is generally not sufficient for testing individual modules for compliance with specified power ratings, though it can be used to this end if the module is severely under performing. It is, however, well suited to our primary objectives of assessing long-term degradation rates and comparing the *average* performance of different brands, models and vintages of a-Si modules under field conditions. See Jacobson, et al., (2000) for more information about the I-V test methodology.

Figure 4. I-V Curve Performance for a "Brand C2" 14 Wp a-Si Module

Isc = 0.90 amps
Voc = 22.9 volts
P_{max} = 7.2 W
Fill Factor = 0.35
P_{typ} = 7.0 W (power @ 12.5 volts)
Curve Fit = 4th order polynomial
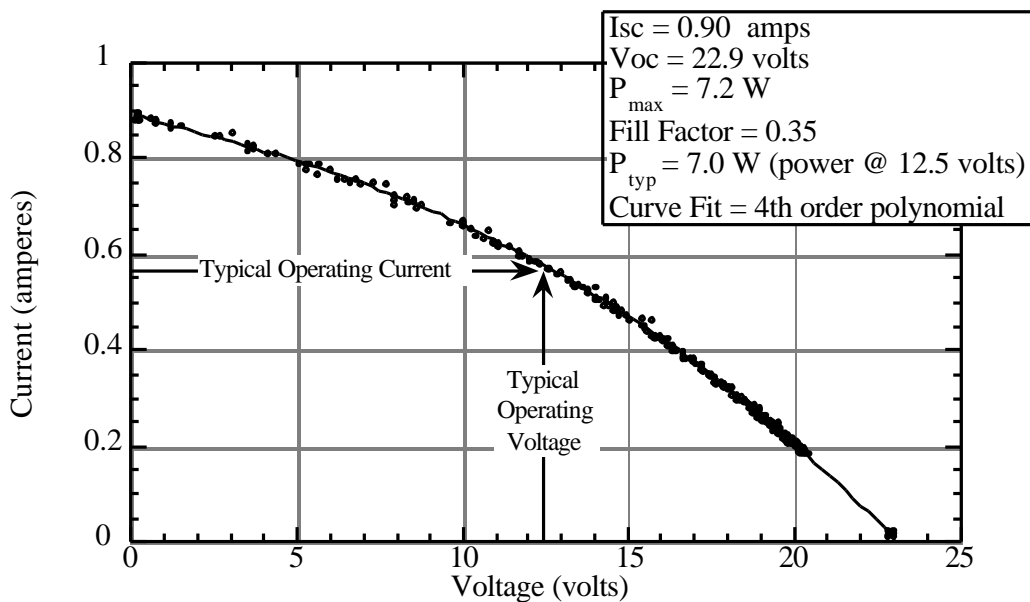
Sample Characterization

Figure 5 shows the geographic distribution of our field data collection sites. Seventeen of the 145 homes we visited had two modules, and two had three, yielding a total of 164 PV modules. Of these solar panels, approximately 85% were 10 to 14 Wp a-Si modules and the other 15% were crystalline panels ranging in size from 10 to 51 Wp. We intentionally sought out a-Si systems— testing crystalline systems only as convenient or if we encountered particularly old modules. Accordingly, the average age of the amorphous modules in our sample was 2.7 years vs. 3.7 years for crystalline modules.

Figure 5. Field Data Collection Sites In Kenya
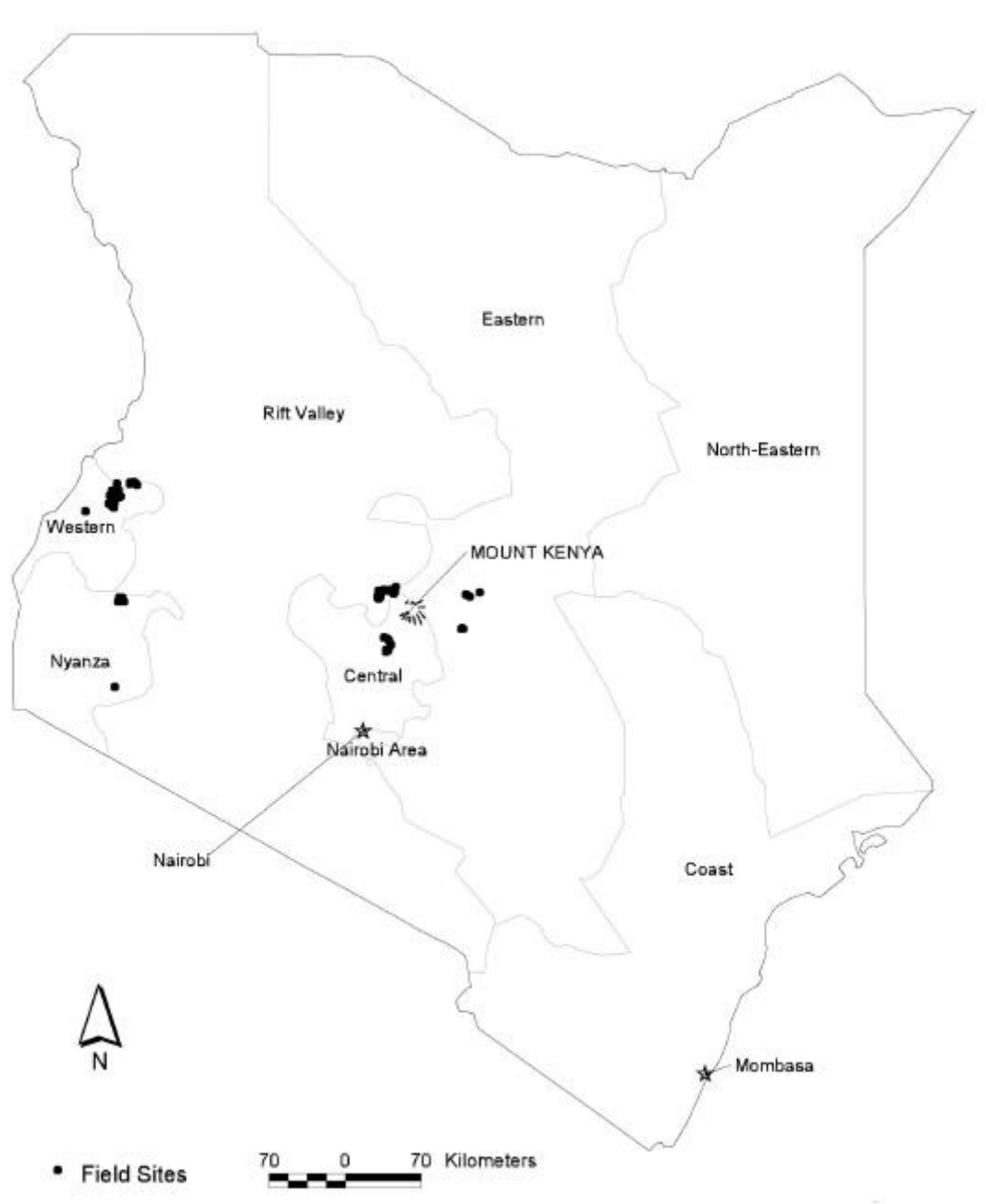
There are three principal manufacturers that have dominated the a-Si market in Kenya:

- Nesté Advanced Power Systems (NAPS) of France marketed two models in Kenya (an 11 Wp panel with model #A13R, and a 12 Wp panel introduced in 1997 with model #11601), and the factory was recently purchased by Free Energy Europe (www.free-energy.net);

- Koncar of Croatia which has marketed their 12 Wp module (model # KT1-3A) in Kenya since 1990 (www.koncar-solar.tel.hr); and,

- Intersolar of Wales which has marketed two models, the 11 Wp Phoenix (model # B107W) and the 14 Wp Phoenix Gold (B108D) (www.intersolar.com).

As noted above, all three of these are derivative of the single-junction a-Si technology originally commercialized by Chronar Corporation of New Jersey, USA during the late 1970s and 1980s.

In reporting results we do not list PV module manufacturers by name. Rather, we refer to each brand using a letter, and number different models in chronological order. The three module types currently sold on a large scale in Kenya are, in no particular order, Brand A, Brand B2 and Brand C2. Of the 143 amorphous panels in our sample, Brand B2 and Brand A each accounted for 24% of the total. Brand B1 accounted for another 22%, followed by Brand C1, Brand C2 and Brand E, all with shares of 10% or lower.

Module Testing Results

We found substantial variation in the average quality of different module brands (Table 1; see also Figure 6 for a graphic comparison of module performance) with Brand B2 panels performing best, Brand A panels performing a close second, and Brand C1 and Brand C2 modules trailing substantially. Including panels from our outdoor testing facility, 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. Moreover, we are 95% confident that the average performance for Brand B2 modules in Kenya is between 86% and 92% of their rated output. Brand B1 modules performed similarly with a mean output of 88% of rated power and a 95% confidence interval ranging from 85% to 91% of rated output.

Table 1. Summary of Module Performance for Working a-Si Modules[3]

Module Model	Rated Max. Power (Watts)	Average Measured Max. Power (Watts)	Percentage of Rated Output	95% Confidence Interval (± % points)[4]	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

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 6). On average, none of the

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3   In addition to the 130 modules tested in the field, the information in Table 1 includes the results from modules tested at the University of California, Berkeley and at Energy Alternative Africa's offices in Nairobi. 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.

4   The 95% confidence interval around the percentage of rated output is given in percentage points. The interval spans the range that is plus or minus two standard errors from the average power times the "Student's t" statistic value for the number of tests in the sample. The value is divided by the average power to get a range in percentage points. This information tells us, for example, that we can be 95% confident that the mean output for brand B2 modules is between 86% and 92% of their rated output.

modules in our sample performed at their rated output levels, however, this is not unexpected. A number of researchers have reported results from field performance tests indicating that crystalline and amorphous 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 A modules produced, on average, 83% of their 12 Wp rating, and we are 95% confident that the average performance of Brand A modules in Kenya is between 80% and 86% of their rated power. While the quantitative difference in performance between Brand B2 and Brand A is modest, we have large enough samples of each to be 95% confident that there is a real difference in the average performance of these two module brands. That is, it is unlikely that the reported performance differential is just the result of an unusual sample of modules.

Figure 6. Average Measured Power Output for Five Brands of a-Si Modules in Kenya; Performance of Crystalline (x-Si) Modules is Included for Comparison
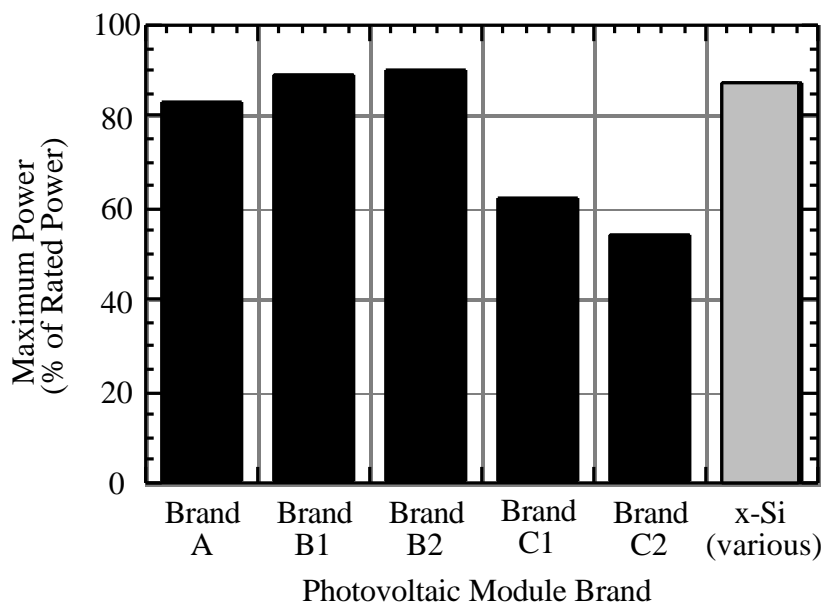
Brand C1 and Brand C2 products performed notably worse than the others. The older 11 Wp Brand C1 modules averaged 61% of rated output with a 95% confidence interval ranging from 47% to 75% with the relatively wide range resulting from the relatively small number of Brand C1 modules in our sample. Their current 14 Wp Brand C2 modules produce only 55% of rated output on average, with a 95% confidence interval ranging from 46% to 64%.

At least some brands of a-Si modules also appear to suffer from high levels of failure due to encapsulation problems. We also found some modules that had failed due to cracked glass plates. Defining module failure as producing less than 10% of rated power, 54% 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 (Table 2). These modules were excluded from our mean performance estimates because our sample may have missed some failed modules that had been removed from customers' rooftops. Nonetheless, accounting for failed modules would widen the performance gap substantially if the true failure rates for each brand are similar to what we encountered.

Table 2. Failure Rates for a-Si Modules from Field Tests in Kenya[5]

Module Model	Failed Modules (%)[6]	Cracked Modules (%)[7]	# Modules Encountered
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 may discard failed units.			

It should be noted that over the past decade all three of the companies have made modifications aimed at improving module quality. Moreover, a senior company representative from the manufacturer for Brand C1 and Brand C2 has reported that he is aware of quality problems and expects improvements to the manufacturing process instituted during 1999 and 2000 to substantially ameliorate the problem. Preliminary testing of the newly released brand C2 modules by RAEL does suggest improved performance; however, more testing is needed in order to confirm these results.

In addition to comparing performance across different brands we also considered module degradation as a function of age. Figure 7 is consistent with degradation of 1% per year for Brand A and Brand B1 modules.[8] It is possible, however, that incremental improvements in manufacturing techniques explain this difference in performance for the differently aged modules.[9]

Testing over an eight year period by PVUSA indicated a 1-5% per year degradation rate for arrays of both a-Si and crystalline modules.[10] Our analysis is therefore broadly consistent with PVUSA's data, tending to confirm their result that a-Si and crystalline panels have similar long-term degradation rates.

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[5]   This table includes only those modules (130) that we encountered in the field.

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

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

[8]   Brand B2 modules were not included because they have not been available long enough to show a clear long-term degradation trend. Other brands were not included due to small sample sizes.

[9]   Such an improvement would be consistent with learning curve theory for manufacturing processes as discussed in Argote and Epple (1990), Neij (1997), and Duke and Kammen (1999).

[10]   The Photovoltaics for Utility Scale Applications (PVUSA) research facility is located in Davis, California, USA. Note, however, that *array* degradation may be due in part to increased voltage losses in the interconnections and other array level effects rather than the degradation of individual PV modules. PVUSA (1998) and Townsend, *et al.* (1998).

**Figure 7. Linear Regression of Module Output vs. Age for "Brand A" and "Brand B1"
a-Si Modules (consistent with a 1% per year decrease in performance)**
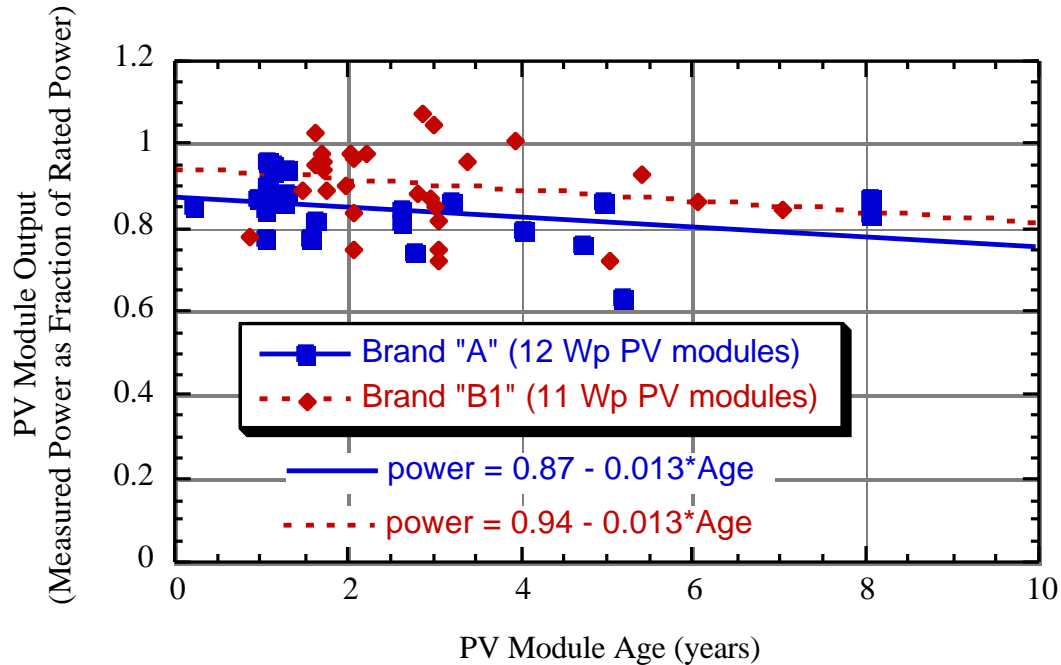
Customer Knowledge

Despite the stark quality variations described above, our survey indicates that only about 9% of respondents thought they knew the brand of the module they owned, and 15% of these respondents answered incorrectly. In addition, over 40% of respondents would not even hazard a guess about how long their panel would last, less than 3% of respondents knew whether they had an amorphous or crystalline solar module, and only about 6% of respondents had an opinion about whether amorphous or crystalline panels last longer.

Customers who do not even know the brand of their panel, let alone having any specific knowledge of that model or manufacturer's track record, cannot distinguish high quality modules from inferior goods. However, there may be other proxies for brand names such as country of origin or distinctive visual aspects (Hong and Wyer, 1990). Our survey would not have detected these possible quality signals, and our results may therefore overstate the level of ignorance among rural Kenyan purchasers of a-Si modules. Additionally, the highest performing a-Si module in our study, brand B2, enjoys a market share that is approximately twice that of its nearest competitor. This may suggest that at least some rural customers are differentiating between brands.

Nonetheless, C2 modules appear to have made modest gains in market share during 1999 and the first half of 2000 despite their substantially higher average cost per *effective* Wp.[11] Table 3 shows that, at about $US 5.00 per rated Wp, C2 modules are among the lowest priced modules sold in Kenya; however, adjusting for their lower average performance, C2 modules are easily the most

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[11] Sales figures based on personal communications of the authors with the relevant distributors in July and December of 1999 as well as February of 2000.

expensive a-Si module in the market (and this holds even without accounting for the much higher breakage and failure rate observed in our sample for this type of module). This suggests that many customers are ignorant of the relative quality of the different module types—a conjecture that is supported by our survey data indicating minimal knowledge of brand and type even for users' own modules.

Table 3. Retail Price per Rated Wp for Small Amorphous Silicon and Crystalline Photovoltaic Modules

Panel	Panel Type	Wp	$/rated Wp	$/measured Wp
Brand B2	a-Si	12	4.50	5.00
Brand A	a-Si	12	5.00	6.00
Brand C2	a-Si	14	5.00	9.00
Polycrystalline	x-Si	20	8.00	9.00

Finally, with regard to security concerns, it is interesting to note that only 15 percent of respondents indicated that they personally knew someone whose solar panel had been stolen. This suggests that module theft may not be a major problem in the regions from which we drew our sample—perhaps in part because of the considerable care taken by many owners to protect their modules.

Outdoor Testing Facility

As noted above, we also tested 9 new a-Si modules at Energy Alternatives Africa's outdoor testing facility in Nairobi, Kenya and 5 new a-Si modules at the Renewable and Appropriate Energy Laboratory (RAEL) of the University of California, Berkeley. Figure 2 shows the Staebler-Wronski degradation for a Brand B2 module. Initially, the I-V curve indicates a fairly high fill factor but the curve quickly flattens, with the majority of the degradation occurring in just 14 days (the 62 kWh/m^2 of cumulative solar exposure corresponds to 14 days for this measurement)[12].

As expected, this testing has confirmed average Staebler-Wronski degradation of 25%-30%, with most of the losses occurring during the first month. These results vary considerably by manufacturer, however, with Brand C2 modules suffering losses as high as 42%. The final stabilized power output for the three brands tested at our outdoor facility are similar to the results collected during our field tests.

System Design

In addition to testing module performance we also gathered considerable data pertinent to system configuration. The factors considered include module tilt, orientation, and shading; battery size; wire size; use of battery terminals; and the role of charge controllers.

Regarding module tilt, an analysis using seasonal insolation data and standard solar incidence equations indicates that, throughout Kenya, mounting modules horizontally generally maximizes both annual energy production as well as output in the worst month of the year.[13] Based on the

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[12] Fill factor is defined as the ratio of the actual power output to the product of the short circuit current and the open circuit voltage. Numerically, it is calculated by Pmax ÷ (Isc * Voc).

[13] It is, however, advisable to mount modules with a slight tilt (*e.g.* 5 to 10 degrees) to ensure that water efficiently drips off the panel.

observed tilts for the SHSs in our sample (and assuming effectively random orientation determined by rooflines) over 95% of the panels in our sample are positioned such that they lose no more than 10% of total possible annual solar energy. Similarly, shading accounts for a less than 10% loss in annual solar energy for over 85% of the panels in our study. Finally, we estimate that 65% of the panels in our sample lose less than 10% of available solar energy due to the combined effects of non-ideal tilt, orientation, and shading (Figure 8). Note that this analysis assumes that there are no seasonal patterns in daily cloud cover (e.g. always cloudy in the morning, but sunny in the afternoon). This assumption may result in small errors in our analysis.

With regard to balance of system components, our data indicate that batteries are generally oversized. Most 12 W_p modules in our sample used 50 Ah batteries. Substituting a 20 Ah battery would save the owners about $US 20, or 12% of initial system cost, and the systems would likely perform better. At an 80% depth of discharge, a 50 Ah battery represents over 10 days of storage for a 12 Wp module. Given that most users' demand chronically outstrips the supply from these small modules, they are likely to drain a 50 Ah battery to an extremely low state of charge and then keep it there indefinitely.

In contrast, with a 20 Ah battery, if the owners use only half of their daily energy production for a little over a week they could fully recharge from an 80% discharge state. In practice, 20 Ah batteries are likely to remain in a chronically low state of charge as well, but there is more likelihood that they will periodically reach higher charge states—and, most importantly, they are less expensive to purchase and replace.[14]

Fewer than one in ten of the systems in our sample included a charge controller, though most of those with a controller did have a low voltage disconnect (75%) and a battery voltage indicator (92%). A low voltage disconnect, if properly set and not by-passed, protects the battery from overly deep discharge, which is almost certainly the most common cause of shortened battery life for typical Kenyan SHSs. It is, however, essential to consider the parasitic load from charge regulators (which can consume as much as one third of the output from a 12 Wp module) as well as the relative benefits of foregoing a regulator and applying the savings to the cost of a second panel.[15]

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[14] It is also important to point out that a 12 Wp module provides a maximum output of only about one amp. The risk of overcharging is therefore minimal even for a 20 Ah battery in a system that lacks a charge regulator.

[15] van der Plas and Hankins, 1998.

Figure 8. Combined Effects of Non-Ideal Tilts and Shading on Actual Solar Energy Collected
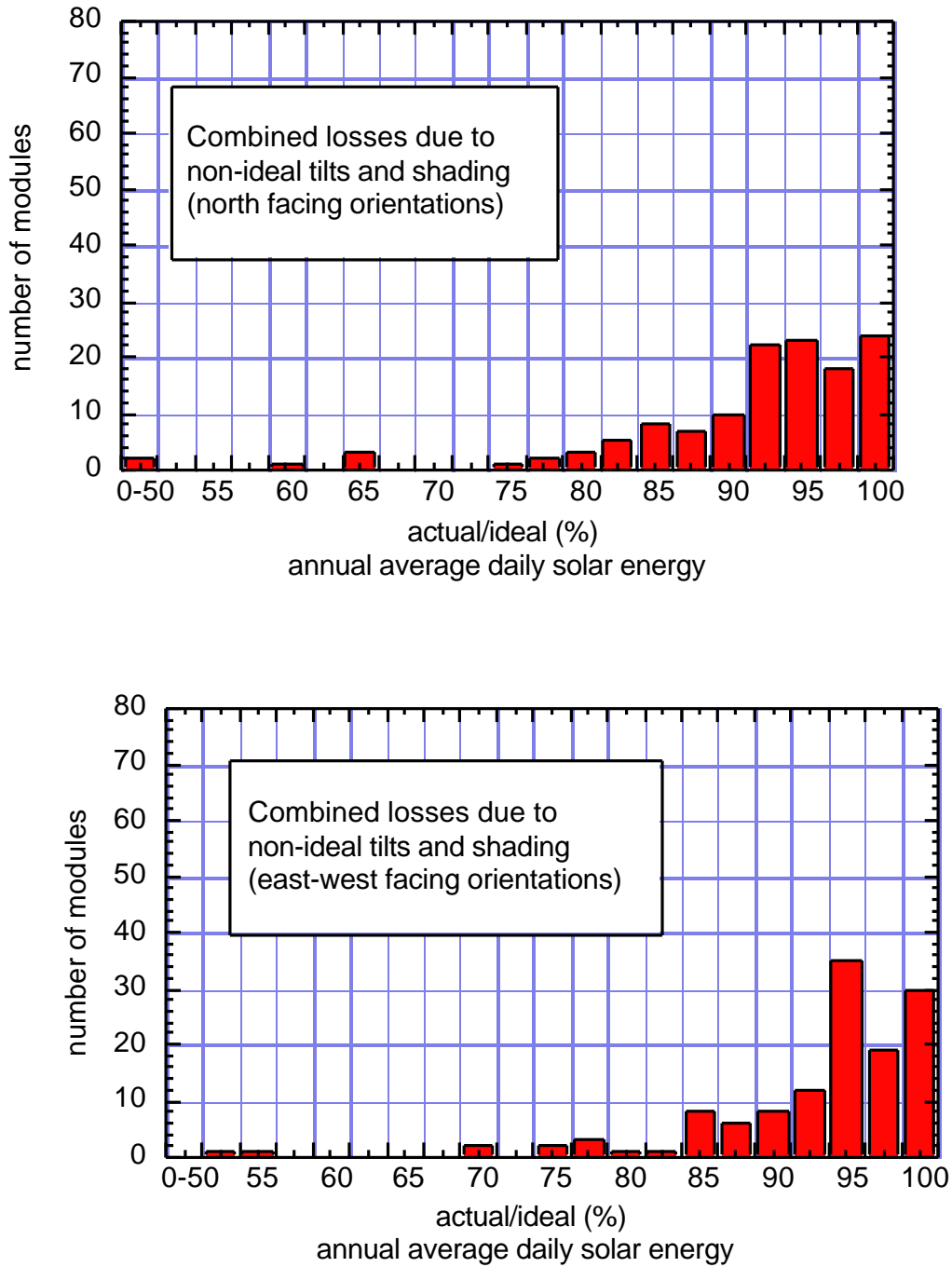
Actual annual average daily solar energy collected at each panel is expressed as a percentage of the total possible annual solar energy available at the site. North facing orientations present the worst case scenario and east-west facing orientations are the best case.

Voltage losses due to wire sizing never exceeded 2.5% for any of the systems in our sample; however, only 34% had battery terminals, with the remainder using alligator style clips or simply wrapping exposed wires around their battery terminals. We also found that all of the systems that used battery terminals had tight connections vs. only 20% of the batteries without terminals, and 36% of the batteries had corrosion on or near the wiring connections. These are important correctable design and maintenance issues because significant voltage losses can occur from loose or corroded connections.

Balance of System Equipment

Batteries made by Associated Battery Manufacturers (ABM) made up the largest share of our survey sample with 71% of the batteries identified. ABM batteries trade under various names including Chloride Exide, Thomas White, and Dagenite. Automotive and Industrial Battery Manufacturers (AIBM) made up the next largest share of our sample, with 18% of the batteries identified, all from their Jua Tosha and Voltmaster lines.

Low electrolyte levels were generally not a major problem for batteries tested in our survey, probably because the low charging currents from the 10 to 14 Wp a-Si solar modules relative to the average size of the batteries will rarely result in out-gassing of the batteries' electrolyte.

It is possible to make a rough estimate of state of charge (SOC) by measuring the specific gravity of the electrolyte in the cells. These data indicate that 39% of the batteries in the sample had a very low state of charge, 21% had a medium state of charge, and 35% had a high state of charge.[16]

Our data on battery ages and battery replacement intervals suggest that many families that use 10-14 Wp solar home systems will replace their batteries every one to two years. This replacement interval may be longer than the useful battery life since some families may not be able to afford to replace their battery even though it is no longer performing well.

There also appears to be a high level of familiarity with basic lead-acid battery maintenance among users. There is, however, no clear correlation between average battery life and respondents' answers to various questions about their maintenance habits.

Finally, about two-thirds of respondents indicated that they had not yet replaced their original fluorescent tubes and, on average, respondents who had replaced their bulbs did so only once every 3.5 years.

Economic Analysis

Based in part on our measurements of actual module output, this section compares the lifecycle cost per kWh for the three principal off-grid electricity options available to rural Kenyan households: battery charging without any panel, battery charging using a crystalline panel, and battery charging using an a-Si panel.

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[16] These specific gravity data may overestimate the state of charge since, in some of the cases, high specific gravity readings were likely due to the addition of acid by users unaware that they should only add distilled water to battery cells. On the other hand, the batteries in our sample rarely receive equalization charges so electrolyte stratification is likely to be common and specific gravity readings taken near the top of battery cells will tend to yield incorrectly low state of charge estimates. It is not clear which of these potential sources of errors is likely to dominate, so it is unclear whether our results overstate or understate the average battery state of charge.

For the base case analysis we make the following assumptions:
- 20 year system lifetime;
- 2 year average battery life;
- 20 year crystalline module life and 10 year a-Si module life;
- US$ 1.00 cost per battery charge;[17]
- panel owners do not bring their batteries to charging stations for supplemental charges;
- system efficiency losses of about 20% for panel based systems and 0% for battery-only systems;
- the labor cost associated with installing panel based systems is US$ 12.00 on the assumption that it requires one day of a skilled technician's time while battery-only systems are self-installed at no cost;
- wiring costs US$ 5.00 for panel based systems, half that for battery-only systems, and it must be replaced after 10 years; and,
- users spend US$ 0.60 annually on distilled water for their batteries.

For the battery-only case we make the further assumptions that users take their batteries for 40 charges per year and are able to obtain a charge worth 80% of the batteries capacity each time.

Prices for all system components are based on informal surveys of distributors conducted by the authors during July of 2000, and delivered module amperage is calculated based on our measurements for each module type, assuming an average charging voltage of 12.5 volts. For panel-based systems we use a 20 Ah "Jua Tosha" battery while the battery charging systems use 50 Ah "Chloride Exide" batteries. Both are locally manufactured batteries partially optimized for deep discharge cycles in rural household applications. The former is more than twice as expensive on a per Ah basis, but nonetheless better suited for 12 Wp SHSs because of its 25% lower unit cost and more appropriate size.

We further assume a 12 Wp NAPS module for the a-Si case, but estimate the amperage and cost of a 12 Wp crystalline module by simply scaling down the price and output of a 20 Wp crystalline Solarex module, which is one of the most commonly available small crystalline panels.

Estimating discount rates for rural Kenyan households is an inexact science and we therefore consider the cost per kWh of each possible system option as a function of a wide range of discount rates. Assuming a discount rate of 25% for our base case, the per kWh life-cycle cost of delivered electricity from an a-Si SHS is about US$ 0.73 versus US$ 0.91 for a crystalline SHS and US$ 0.92 for the battery charging only case.[18] These results are sensitive to parameter choices.

Figure 9 illustrates the importance of the assumed discount rate. Similarly, if we assume that SHS owners use 50 Ah batteries with their 12 Wp panels, as many in fact do, then the associated per kWh costs at the 25% discount rate increase to $US 0.88 for a-Si and $US 1.06 for crystalline, and battery charging emerges as the cheapest option for discount rates any higher than 30%.

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[17] This breaks down as US$ 0.60 in charging fees; $US 0.30 in transport and $US 0.14 for the cost of time and inconvenience. The latter component is equivalent to one hour of foregone wages using 2000 annual work hours and an average rural income of $US 289 in 1995 from Nyang (1999).

[18] The crystalline case is more expensive, particularly for lower discount rates, because of the higher per Wp cost of these modules. Moreover, our analysis is generous to crystalline in that we assume that 12 Wp crystalline modules would sell for only 60% of the cost of a 20 Wp module. In fact, the per Wp cost of crystalline modules typically increases significantly as they are scaled down below 20 Wp due to higher circuitry and framing costs as well as the need to cut individual crystalline cells in half.

The assumed frequency of battery charging is also an important parameter choice. A family that uses a 50 Ahr battery to provide electricity for three hours of television and lighting will completely drain their battery approximately once per week. For our base case, however, we assume only 40 charges per year because financial constraints may induce some families to conserve on battery usage and capital constraints and inconvenience often prevent families from maintaining their batteries in a useable state at all times. If we increase the charging frequency to 52 charges per year, the cost of the no-panel battery charging option drops below the crystalline cost for discount rates exceeding 19%, and it beats the a-Si option for discount rates over 34%. Similarly, if we eliminate the estimated per-charge inconvenience and time factor, then the cost of the battery-only option beats crystalline for discount rates exceeding 22%, and a-Si for discount rates in excess of 40%. Changing both parameters to favor the battery case allows the no-panel case to beat a-Si for discount rates exceeding 28%.

Note, however, that our base case is generous to battery charging in assuming that customers drain their battery to the 20% charge level and obtain a full charge every cycle.[19] In fact, consistent deep discharges reduce a battery's ability to accept a full charge and battery stations may not always give their customers the fullest possible charge. There is, moreover, a substantial hassle factor involved with lugging a battery to and from the charging station on a regular basis and our estimates only imperfectly capture this cost.

On the other hand, the base case results are quite robust to some parameter choices. For example, we assume that a-Si single junction modules last only 10 years in our base case in order to account for the fact that they are typically more vulnerable to breakage given their more fragile framing and encapsulation design. This is consistent with an annual breakage rate of about 8%. If annual a-Si module breakage rates are assumed to be 0% then the cost per kWh for an a-Si system drops by only about four cents for a discount rate of 10% and only one cent for discounts rates in excess of 25%.

Similarly, changing the average battery lifetime does not notably affect the relative costs of the different systems—though assuming a shorter battery life raises the cost of all three options considerably. For example, a one year battery life implies that the a-Si option costs US$ 1.10 per kWh for a discount rate of 25% (as opposed to US$ 0.78 in the base case). It is important to note that battery life is a function of system type and design; however, there are insufficient data available to assess the relative average battery lifetimes for the different cases we consider.

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[19] This concern also negatively affects the performance of low wattage SHSs since our data suggest that many SHS batteries are chronically in a low state of charge; however, we partially account for this by assuming a 20% charging inefficiency for the SHS case.

Figure 9. Cost of Off-Grid Electricity Options as a Function of Household Discount Rate
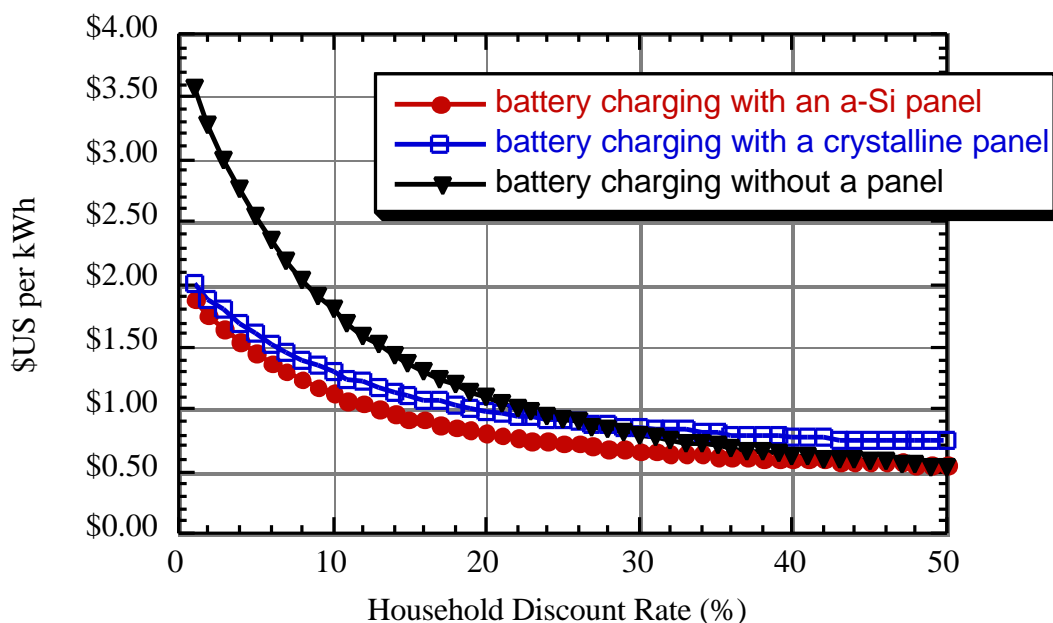
Implications for Market Development

This study presents evidence that the best quality a-Si modules available in Kenya provide excellent long-term service of comparable reliability to crystalline modules. There is, however, evidence of dramatic and largely undetected quality variation across brands.

This has two critical implications for development of the Kenyan market for SHSs. First, thousands of rural Kenyan households unfortunate enough to select the seriously under-performing a-Si brand have lost most or all of their investment in what is often the most expensive durable good they own. This is a substantial economic and social cost in its own right.

Second, widespread consumer ignorance about the relative quality of different brands, may discourage potential SHS customers. This occurs both because consumers face uncertainty about the performance of the particular module brand they buy and because they may base their performance expectations on a pooled quality estimate roughly derived from the average performance of all the installed modules (including both high- and low-performing brands) in their region (Duke et al, 2000).

This is also one plausible factor helping to explain why so many rural Kenyan households continue to rely on battery-only systems despite the relatively high life-cycle cost of this approach. Approximately 300,000 rural Kenyan households have lead-acid batteries that they regularly bring to charging stations, while more than 100,000 additional Kenyan families have opted to use a solar panel to charge their batteries (Hankins et al, 1997). As shown in Figure 9, battery charging is not competitive with SHS on a life-cycle basis except for very high real discount rates.

The prevalence of battery-only systems despite the relatively high cost of this approach is also consistent with the fact that rural Kenyans households typically have very little savings and little opportunity to borrow at non-usurious rates (*i.e.* high household discount rates). Despite this, even at a monthly fee of just US$ 3.00, only about 38 percent of the SHS owners we interviewed responded that they would have preferred to rent rather than buy the system they currently own. If these figures reflect true demand, then fee-for-service is unlikely to emerge as a major SHS delivery mode in Kenya unless substantial subsidies become available.

Policy Recommendations

As detailed in a forthcoming manuscript by the authors (Duke et al, 2000), there are a range of potential mechanisms available to address the quality variation and user ignorance problems outlined above. These include testing and certification, associated quality seals of approval or importation restrictions, user education and more centralized SHS delivery modalities.

The International Electrotechnical Commission (IEC) issued an international standard (IEC1646) for thin-film PV modules in 1996; however, at present none of the a-Si modules with a substantial market share in Kenya comply with this standard.[20] The PV Global Approval Program (PVGAP, www.pvgap.org), an organization supported by various multilaterals and PV industry groups, has a stated priority of focusing on quality problems in developing countries. In particular, they are working to:

- ensure that available IEC standards are universally recognized;
- develop "recommended standards" in cases where the IEC has yet to act; and,
- develop a PVGAP quality "mark" for PV components and a PVGAP quality "seal" for whole systems.

PVGAP expects a quality mark for modules to come into use shortly; however, it is unclear how quickly the a-Si module manufacturers that sell into the Kenyan market will seek or receive approval under this program. Moreover, absent considerable user education, a "seal of approval" may have little impact on the Kenyan market. This sort of public education campaign may prove difficult and expensive given the dispersed and remote nature of the target audience.

Another possibility is that the Kenyan government could ban the sale of modules that do not meet quality standards. This approach would, however, risk excluding relatively high quality and uniquely affordable small a-Si modules from the Kenyan market place until and unless their manufacturers are able to obtain certification. It could also create opportunities for excessive or corrupt government interference in the SHS market place.

One alternative to government mandated standards would be to encourage more centralized SHS delivery mechanisms that ensure quality components. Revolving credit mechanisms for SHSs, for example, often restrict loans to systems using certified components.

Similarly, a fee-for-service approach may have the potential to provide high quality systems to a broad range of rural Kenyan households. Fee-for-service companies can only be profitable if the systems they rent function well, so they have strong incentives to select high quality components. Moreover, this mechanism may be embedded in a stable regulatory framework that allows for the

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[20]   Uni-solar modules are IEC1646 compliant, however, they are considerably more expensive than other a-Si modules and have a trivial market share. Free Energy Europe expects to achieve IEC1646 compliance for its modules by the end of 2000.

provision of subsidies without destructive variability, thereby increasing SHS penetration levels (Greene *et al*, 1999). More careful survey work to assess the potential demand would provide useful background for policy makers and companies considering fee-for-service options for Kenya.

Conclusions

Single junction amorphous-silicon PV modules have suffered from a reputation for poor quality since they entered the marketplace. This study presents evidence that this reputation is partially deserved. One of the top selling a-Si modules in the Kenyan market falls far short of acceptable quality standards and thousands of rural households have suffered substantial economic hardship from investing in these products. Despite these sobering facts, it appears that this manufacturer is taking substantial steps to improve the quality of its modules.

Importantly, this study also clearly demonstrates that the other single junction a-Si modules commonly sold in Kenya deliver long-term performance that is comparable to that available from crystalline modules—but at a substantially lower retail price. There are legitimate concerns that even the best quality single junction a-Si modules may be subject to significant breakage risk; however, in the context of high household discount rates and falling module prices, the practical economic difference between a 20 and 10 year expected module lifetime due to breakage may be trivial.

In conclusion, quality amorphous silicon PV modules can provide a highly cost-effective alternative to crystalline modules for SHSs—especially for households only willing or able to purchase a 12-20 Wp system. There are, however, severe quality variations among the existing manufacturers, and many consumers appear to be unable to reliably discern these differences.

Some combination of public information, certification/labeling, standards (e.g. restrictions on uncertified modules by the government or PV loan funds) or new SHS business models (e.g. fee-for-service) may prove helpful in educating and protecting consumers, thereby ensuring that this market reaches its potential. There are, however, risks and limitations associated with each of these mechanisms that necessitate a cautious approach.

References

Acker, R. and Kammen, D. M. (1996) "The quiet (Energy) revolution: the diffusion of photovoltaic power systems in Kenya," *Energy Policy*, **24**, 81-111.

Akerlof, G. A. (1970) "The Market for 'Lemons': Quality uncertainty and the market mechanism" *Quarterly Journal of Economics*, **84**, 488-500.

Argote, L. and D. Epple (1990) "Learning curves in manufacturing," *Science* **247**, 920 - 924.

Chamberlin, C. E., Lehman, P., Zoellick, J., and Pauletto, G. (1995) "Effects of Mismatch Losses in Photovoltaic Arrays", *Solar Energy*, **54**(3), 165-171.

Chamberlin, C. E. (1998) Personal communication (Humboldt State University: Arcata, California, USA).

Duffie, J. A., and Beckman, W. A., (1991). *Solar Engineering of Thermal Processes, 2nd Edition*, (John Wiley & Sons, New York, USA).

Duke, R. D., Jacobson, A., Kammen D. M., and Hankins, M. (2000). "Mechanisms to Ensure Product Quality in the Markets for Photovoltaics" draft to be submitted to The Energy Journal.

Duke, R. and Kammen, D. M. (1999) "The economics of energy market transformation programs," *The Energy Journal*, **20**(4), 15 - 64.

Greene, N., Duke, R. and Bryk, D. (1999) "Regulating for Renewable Rural Electrification," Natural Resources Defense Council Report.

Hankins, M., Ochieng F. Omondi, and Scherpenzeel J. (1997) "PV Electrification in Kenya: A Survey of 410 Solar Home Systems in 12 Districts", submitted to The World Bank, ESMAP, Washington, DC, USA.

Hankins, M. and van der Plas, R. J. (1998) "Solar energy in Africa: a reality", *Energy Policy*, **26**, 295 – 305.

Hester, S. and Hoff, T. (1985) "Long-Term PV Module Performance", 18th IEEE Photovoltaic Specialists Conference, Las Vegas, USA.

Hong, S. and Wyer, R. (1990) "Determinants of Product Evaluation: Effects of the Time Interval between Knowledge of a Product's Country of Origin and Information about its Specific Attributes," Journal of Consumer Research, **17**, 277-288.

Jacobson, A., Duke, R., Kammen, D. M., and Hankins, M. (2000) "Field Performance Measurements of Amorphous Silicon Photovoltaic Modules in Kenya", Conference Proceedings, American Solar Energy Society (ASES), Madison, Wisconsin, USA, June 16-21, 2000.

Jennings, C. (1987) "Outdoor Versus Rated Photovoltaic Module Performance", 19th IEEE Photovoltaic Specialists Conference, New Orleans, USA.

Lehman, P. A. and Chamberlin, C. E. (1987) "Field Measurements of Flat Plate Module Performance in Humboldt County, California," 19th IEEE Photovoltaic Specialists Conference, New Orleans, USA.

Li-Cor (1994) "Radiation Measurement Instruments" (product literature), Li-Cor, Inc., Lincoln, Nebraska, USA.

Neij L. (1997) "Use of experience curves to analyze the prospects for diffusion and adoption of renewable energy technology," *Energy Policy* **25**(13), 1099-1107.

Nyang, Frederick Oloo (1999). *Household Energy Demand and Environmental Management in Kenya*, (Doctoral Dissertation, University of Amsterdam, Netherlands).

Peterson, T. (1997) "Making photovoltaics economical for electric utilities," Electric Power Research Institute Strategic R&D Report, Fall.

PVUSA (1998) "1997 PVUSA Progress Report", submitted to the California Energy Commission (CEC) and the Sacramento Municipal Utility District (SMUD).

Staebler, D.L. and C.R. Wronski (1977) "Reversible conductivity changes in discharge-produced amorphous Si," *Applied Physics Letters*, **31**(4): 292-294.

Townsend Timothy U., Reyes Antonio B., Newmiller Jeffrey D., Hutchinson Paul A., Seki Art, Whitney Daniel D. (1998) "PVUSA's Maui Host Site PV System: A Revamping Case Study", ASES Solar 98 Conference, Albuquerque, NM, USA.