ELSEVIER

Energy Policy 30 (2002) 477–499

ENERGY POLICY

www.elsevier.com/locate/enpol

Photovoltaic module quality in the Kenyan solar home systems market

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Abstract

As one of the largest unsubsidized markets for solar home systems (SHSs) in the world, Kenya represents a promising model for rural electrification based on private purchases of clean decentralized photovoltaic technologies. Small amorphous-silicon modules dominate the market and most brands provide high quality and affordable service. Product quality varies widely, however, and the public has limited capacity to distinguish among competing brands. This imposes direct hardships on households with the misfortune to purchase low-quality equipment, and it constrains sales as some customers refrain from purchasing solar equipment due to the associated performance uncertainty. This article analyzes market failure associated with photovoltaic module quality in the Kenyan SHS market and develops strategies to address the problem—emphasizing that similar quality problems may exist for other SHS components and in other markets. The principal conclusion is that domestic product testing with public disclosure represents an inexpensive low-risk strategy, but it may prove inadequate. Mandatory product quality standards based on international testing regimes (e.g. IEC standards), augmented with a basic domestic testing option, would provide stronger assurance, but the risks associated with this intervention suggest caution. An emerging multilateral SHS market support effort (PVMTI) should ensure quality for the credit-based sales it promotes in Kenya; however, the long-term impact of this approach is not yet clear and it is unlikely to address quality problems associated with the existing unsubsidized sales-based markets for SHSs. Finally, fee-for-service models would decisively address quality problems, but launching this model in the Kenyan market would likely require large subsidies.

Keywords: Product quality; Product standards; Solar home systems; Kenya

1. Introduction

There are approximately 2 billion people in the world who lack access to grid electricity. For this population, solar photovoltaic (PV) modules can deliver small amounts of electricity for high-value applications like lights, television, and radio without the need for expensive transmission and distribution networks. A typical solar home system (SHS) in a developing country context uses a 10–50 peak Watt (Wp) module to deliver from 50 to 250 Wh of power per day.[1]

Approximately 1.3 million SHSs have been installed throughout the developing world during the past two decades (Nieuwenhout et al., 2000). While substantial when measured in total sales, this represents a penetration rate of only about 0.1%, leaving a tremendous potential for expanded use of SHSs.

Motivated by the perceived development benefits, as well as a desire to promote this environmentally superior technology, a number of multilaterals, individual governments, and non-governmental organization (NGOs) have actively supported SHS dissemination

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[1] SHSs store power generated during the day in lead-acid batteries. Larger systems typically include a charge regulator that prevents the module from overcharging the battery and may also include a low voltage disconnect that discourages excessive discharging of the battery. This is an essential component for larger systems; however, charge regulators are of questionable value for the small (less than 20 Wp) systems that dominate the Kenyan market because they use a substantial share of the power generated, over-charging is rarely a problem with such small systems, and the money might be better spent towards purchasing a second PV module.

0301-4215/02/$ - see front matter
PII: S0301-4215(01)00108-2

Table 1
Retail price per Wp for small amorphous silicon (a-Si) and crystalline (x-Si) photovoltaic panels

Panel	Panel type	Wp	$/rated Wp	$/measured Wp
NAPS/FEE	a-Si	12	4.50	5.00
Koncar	a-Si	12	5.00	6.00
Intersolar "Phoenix Gold"	a-Si	14	5.00	9.00
Solarex MSX20	x-Si	20	8.00	9.00

(Duke and Kammen, 1999). Strategies have ranged from outright equipment donations to sophisticated programs to train SHSs technicians and provide credit to their customers. Direct subsidization has come under criticism for disrupting markets (Covell et al., 1995); nonetheless, even the programs that most aggressively seek "full-cost recovery" involve considerable indirect subsidies.[2] Most notably, NGO or multilateral staff and overhead costs are rarely recovered.

More recently, a number of countries, including South Africa and Argentina, have launched programs that provide private businesses with exclusive concessions to charge off-grid households within their defined region a fixed monthly fee for solar electricity. This fee-for-service approach helps to ensure on-going maintenance while spreading cost recovery over the entire system lifetime. It also allows governments to subsidize SHSs within a stable framework with less risk of disruptive variation in the subsidy level (Greene et al., 1999). South Africa hopes to reach hundreds of thousands of homes within the next few years using this non-grid solar approach, and some of the concessionaires, notably Shell Solar, plan to expand the model to other countries in Africa and beyond. The viability of the solar utility model remains to be seen, however, and may be limited by the high subsidy levels required (e.g. about US$400–500 per household in South Africa), competition from grid-based electrification, and associated regulatory challenges.

The Kenyan SHS market, in sharp contrast, has evolved largely without subsidization. Private entrepreneurs and individual homeowners have installed about 150,000 SHSs, with approximately 20,000 new systems purchased annually (Nieuwenhout et al., 2000). The lack of a central catalyzing institution means that Kenyan SHS owners and vendors make all technology selection decisions, and there is evidence that inadequate product quality information has caused serious market failure (Duke et al., 2000).[3]

The Kenyan market is globally important for a number of reasons. First, on a per capita basis it is the largest private sector dominated SHS market in a developing nation. Second, the Kenyan SHS market has now become a driver of regional SHS sales. Third, the Kenyan market represents a promising, though not unproblematic, model of private sector dominated diffusion of a clean energy technology. A full understanding of the Kenyan solar market is critical in order to evaluate the strengths and weaknesses of this approach for the provision of rural energy services in developing countries.

Most SHSs purchased in Kenya since the early 1990s use small 10–14 Wp amorphous silicon (a-Si) modules. Two of the three main a-Si brands marketed in Kenya perform adequately; however, a third brand with severe quality problems has maintained a substantial market share despite a far higher price per *delivered* Wp (Table 1). For more information on the performance of a-Si PV modules in Kenya, see Jacobson et al. (2000).

These quality problems impose a substantial hardship on those rural Kenyan families with the misfortune of buying the low quality brand. This is significant, because a solar panel is often one of their most valuable durable assets. In addition to this direct harm to system owners, module quality market failure may undermine consumer confidence in both a-Si and crystalline PV modules, and thereby constrain the overall Kenyan SHS market below the socially optimal level (Fig. 1).

This article analyzes possible policy interventions to address these dual concerns, ranging from laissez-faire strategies that encourage module suppliers to strengthen their warranties to mandatory standards.[4] Although no simple solution exists, there are approaches that can improve the situation with only minimal risk.[5] A low-cost program of domestic module testing and performance disclosure represents a promising option that should at least do no harm. Minimum quality standards

[2] For a discussion of indirect subsidies in appropriate technology dissemination efforts see Harper and Finnegan (1998).

[3] Inadequate information about system design and maintenance on the part of vendors and users is another significant concern.

[4] Various developing countries have tackled this problem, including efforts by Mexico and China to institute equipment standards. A comprehensive review of these programs would prove useful but lies beyond the scope of this analysis.

[5] Risk refers to the potential for negative unintended consequences in the market associated with particular policy options (e.g. a substantial increase in the price of PV modules due to a reduction in the number of brands of high quality modules that are available in the market). These risks are discussed in more detail in the "Corrective Actions" section.

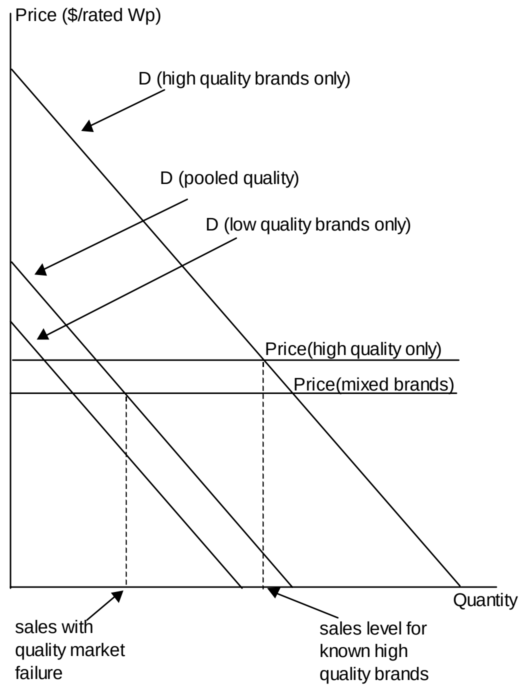

Fig. 1. Welfare Analysis of the Product Quality Market Failure. This figure illustrates that information market failure can cause both sales and quality levels to fall short of the social optimum. Assume that, on average, bad modules produce half of rated power while good modules produce at their rated levels. Given perfect information, in $/rated Wp terms, $D(\text{low}) = 0.5 \times D(\text{high})$. Given a 50% market share for low quality modules, perfect information about both market shares and the performance of high and low quality modules, but inability to distinguish which brand is high quality, then $D(\text{pooled}) = [D(\text{low}) + D(\text{high})]/2$. Adding risk-aversion, D(pooled) falls closer to D(low). Adding the "lemons" problem (Akerlof, 1970) ensures that demand falls still further as households suspect only low quality modules will come on the market. The market share of high quality modules will, in fact, fall as high quality modules are forced to overrate their product to compete with the prices offered by the low quality modules. With fully-informed customers, the incentive to overrate modules disappears and low quality modules disappear from the market. This puts upward pressure on prices in terms of $/rated Wp, though true prices in $/delivered Wp will fall as overrated modules are eliminated.

might prove highly effective if governments prefer stronger (and riskier) medicine.

The International Finance Corporation (IFC), the private-sector lending arm of the World Bank Group, has recently launched a major effort to catalyze SHS sales in Kenya. The photovoltaic market transformation initiative (PVMTI) leverages $30 million in Global Environment Facility funds with private sector investment in order to support photovoltaic markets in three countries: Kenya, India and Morocco. The program allocates $5 million for Kenya with a stated goal of leveraging a similar level of private funds, and it is just getting underway in 2001 after initial GEF approval in 1996 (WBG, 1998). PVMTI-Kenya focuses on establishing consumer finance programs to support SHSs sales and requires that all financed systems meet international equipment, design and installation quality standards.[6]

The impact of PMVTI-Kenya on module quality problems is, however, both limited and uncertain. First, PVMTI may not substantially affect sales of small a-Si and crystalline modules, which is where concerns about quality are greatest.[7] PVMTI-Kenya establishes consortia of large Nairobi-based equipment companies and banks that generally finance larger (e.g. 50 Wp) SHSs for credit union members and salaried rural employees (e.g. teachers and tea growers). PVMTI will displace some small (e.g. 12 Wp) off-the-shelf amorphous modules; however, sales of these modules will continue to the extent that: (1) many households are ineligible or otherwise unable to access PVMTI funds and (2) some households prefer to purchase low-cost amorphous modules rather than pay the extra equipment, installation and financing costs for PVMTI systems.

Second, it is unclear whether the parallel SHS markets established by PVMTI will prove durable once the program ends in 2008. PVMTI-Kenya has spent a large share of project funds on temporary international consultants but, despite their efforts, the participating consortia have been slow to initiate SHS sales (Graham, 2001). This likely reflects the intrinsically high transaction costs involved with marketing systems and processing small loans for dispersed rural households with modest incomes. SHS financing efforts consequently offer thin profit margins.

The experience of other SHS financing efforts corroborates this conjecture. Enersol Associates, a non-governmental organization founded in 1984, pioneered financed SHSs sales in the Dominican Republic and Honduras. Enersol made important but slow market development gains and, in 1994, the organization began to shift its SHS efforts to a for-profit affiliate (Soluz) relying increasingly on a fee-for-service model (while Enersol focuses on non-SHS projects such as PV water pumping and schools electrification projects). The case of a GEF project in Zimbabwe further suggests that temporary heavy subsidization of SHS financing may do little to improve the long-term economics of this market development model. That project appears to have had little lasting impact on the market despite creating a

[6] A number of other existing and emerging multilateral and bilateral SHS programs also promote high-quality systems. Examples include a wide range of GEF projects (Martinot, 2000) such as the emerging IFC/GEF Solar Development Group that provides both business advisory support and private equity investments in SHS businesses.

[7] It is also important to note that quality concerns are not confined to a-Si modules. Preliminary testing by the authors indicates that modules from at least one crystalline module brand are overrated by approximately 25–30%, suggesting that high-quality amorphous modules offer considerably better performance than this particular crystalline brand.

substantial SHS investment "bubble" in the process of achieving its numerical installation goals during the project period (Mulugetta et al., 2000). Finally, even if PVMTI consortia prove profitable in the near-term, they may have difficulty penetrating beyond the best customers that they are initially targeting. In particular, only a small fraction of rural households have regular salaried wages that can be garnished for repayment.

This discussion suggests that PVMTI may not have a substantial lasting impact on the Kenyan SHS market.[8] Consequently, it remains important to improve quality in the underlying commercial sales market for small off-the-shelf PV modules, even as PVMTI makes parallel efforts to promote larger high-quality systems.

2. Background: photovoltaic technology and performance

There are two main categories of PV technology, crystalline and thin-film. The former includes panels built from both mono- and poly crystalline cells, while the latter include a wide range of different deposition technologies. At present the dominant thin-film technology is amorphous silicon (a-Si). The most basic a-Si structure has a single photo-electrical circuit, while more advanced modules layer two or more such "junctions" on top of each other which can, at additional manufacturing expense, be optimized to absorb different ranges of light frequencies. There are several important differences between crystalline and amorphous silicon PV technologies. Most notably, crystalline PV modules generally have a higher light to electricity conversion efficiency while a-Si modules, like most thin-films, can be mass-produced using continuous production lines that promise substantial long-term cost advantages through scale efficiencies and reduced material and energy inputs (Payne et al., 2001).

Another important difference between the technologies is related to their performance during the first few months of use. PV modules are rated according to their output under industry standard test conditions, defined as $1000\,\mathrm{W/m^2}$ of solar insolation and a module temperature of 25°C.[9] The primary measure of quality for a PV panel is the amount of power delivered at standard test conditions over the lifetime of the module. Unlike crystalline PV modules, it is difficult to predict the future output of amorphous silicon PV modules because they are subject to light-induced degradation (Staebler and Wronski, 1977) during the first few months of operation. After this initial degradation period the power output of high quality a-Si modules stabilizes. Consequently, reputable a-Si manufacturers that test their modules as they come off of the production line generally use a rejection threshold that exceeds rated power, expecting stabilization at their targeted performance level after light-soaking.

Field measurements suggest that even high quality a-Si manufacturers typically target less than 100% of rated power. The best quality manufacturer of the single junction a-Si modules sold in Kenya, for example, produces modules that stabilize at an average of only about 90% of rated power—though nearly all of their modules comply with their 10-year warranty that guarantees at least 85% of rated output (Jacobson et al., 2000). Average performance levels for crystalline modules are also often just above the warranty level, which is typically about 90% of rated power (Hester and Hoff, 1985; Jennings, 1987, Lehman and Chamberlin, 1987, Chamberlin, et al., 1995). Moreover, data from two sources appear to indicate that long term power output degradation for crystalline and amorphous silicon PV modules is roughly comparable (Jacobson et al., 2000; PVUSA, 1998).

Crystalline PV technologies are, however, free from the pronounced short term light-induced degradation that adds uncertainty about the initial performance levels for a-Si modules. Moreover, with some exceptions due to encapsulation problems and overrating, crystalline PV technologies have a proven track record of reliability dating back to their initial commercialization for terrestrial applications during the 1970s. This contrasts with a-Si modules that only became widely available in single-junction format during the late 1980s, and in multi-junction format during the 1990s. As detailed below, certain single-junction a-Si module brands have suffered from severe performance problems, including failure to de-rate sufficiently to account for initial light-induced degradation as well as water intrusion and breakage due to substandard encapsulation.

[8] It is possible that PVMTI will have useful spillover benefits to the extent that technicians trained by PVMTI consortia act as installers for non-PVMTI systems. Such spillovers may prove modest, however, given that more than one-third of small modules are self-installed and PVMTI may fail to achieve comprehensive geographic coverage. PVMTI may also prompt some equipment manufacturers to seek international certification. One of the high quality amorphous PV manufacturers is pursuing this strategy and PVMTI's efforts to test SHS batteries may also prompt quality improvements. The impact on non-PVMTI sales is limited, however, as these efforts do little to eliminate low-quality equipment manufacturers from the market (see Section 4).

[9] Module power is approximately one-to-one proportional to insolation levels while output voltage typically drops by about 0.3%/°C, and this yields an approximately proportionate decrease in power output (Green, 1982).

In sum, the higher quality a-Si brands sold in the Kenyan market offer similar performance to crystalline modules—often at a substantially lower cost per delivered peak watt. The difficult challenge for the end-user is knowing which brands to trust and which to avoid.

3. The Kenyan context

Photovoltaic systems were first used in Kenya in the late 1970s for government funded telecommunications projects. In the 1980s falling module prices led to an increase in the use of PV in Kenya. During this period international donor aid programs began to fund PV-powered projects such as water pumping and vaccine refrigeration for remote health clinics (Musinga, et al., 1997).

Up until the mid-1980s, Nairobi based PV import companies focused on government and donor aid projects in the East Africa region. In Kenya, groups ranging from Christian missionaries to the military installed photovoltaic systems for remote power in rural areas (Musinga et al., 1997). The conventional wisdom at the time was that rural Kenyans did not have enough money to buy photovoltaic systems (Hankins, 1992).

In 1984, Harold Burris, an ex-Peace Corps volunteer from the US, set up a small business in a coffee growing region near Mt. Kenya. This was the first solar dealership in Kenya located outside of the capital city of Nairobi, and by 1990 he had sold approximately 500 PV systems (Perlin, 1999). In 1985 Burris and another ex-Peace Corps volunteer, Mark Hankins, acquired funding from the US Agency for International Development (US-AID) for a workshop to train rural Kenyan technicians to install and maintain photovoltaic systems. Burris' hired a number of these trainees, and several of them later started successful photovoltaic businesses of their own (Perlin, 1999; Musinga, et al., 1997). Burris' business showed that it was possible to sell photovoltaic systems without donor aid by marketing directly to rural Kenyan families. He also demonstrated the advantages of regionally based sales and service. Burris' successes led other groups to set up dealerships in rural areas, including outlets for several of the Nairobi based import companies.

Typical systems sold to rural families during the period from 1984 to 1990 used crystalline modules of approximately 40 Wp (Acker and Kammen, 1996; Musinga et al., 1997). In 1989 small low cost photovoltaic amorphous silicon (a-Si) modules were introduced to the Kenyan PV market, making solar electricity an option for families with relatively low incomes. In 1990 a 12 Wp amorphous silicon PV module cost about US$90 (Musinga, et al., 1997), or about US$120 in current US dollars. It is now possible to buy a similar module for about $US50 (Table 1).

By 1990, families accounted for 40% of all PV sales in Kenya (Perlin, 1999; Musinga et al., 1997, Hankins, 1992), and by 1997 sales of amorphous PV exceeded those of crystalline PV in terms of total kilowatts (EAA, 1999). Most solar home systems in rural Kenya are now based on a 12 or 14 Wp amorphous silicon module, and virtually all of the amorphous silicon modules sold in Kenya are used in household systems. In contrast, crystalline PV modules are used in both household systems and other applications (such as donor aid and government funded projects).

The main reason for the high sales figures for amorphous silicon PV modules is their availability in low wattage sizes at a relatively low cost per watt. Kenyan government tariff and tax policies have also favored amorphous silicon modules over their crystalline PV competitors. Although the Kenyan government had removed all import duties on PV modules in 1986, tariffs were reintroduced in 1992. The 1992 policy placed a lower overall tax on amorphous silicon PV modules than on crystalline PV. In 1996 de facto duties and taxes were reduced to 5% on both module types (Soper, 1999/2000); and duties were again removed entirely for both a-Si and crystalline modules in June 2000 (Republic of Kenya, 2000). Nonetheless, as shown in Table 1, the price per rated Wp for small a-Si modules remains lower than for comparably sized crystalline modules due to underlying wholesale import price differences.

Today, intense competition among importers and vendors fuels rapid sales growth (over 20% annual growth during the 1990s). Cash sales of small a-Si modules used for household electricity in rural and peri-urban areas drive the majority of this growth. At the same time, sales of crystalline photovoltaic modules for government and donor aid funded projects remain an important source of income for some businesses.

There are more than 10 major PV import and manufacturing companies, and hundreds of rural vendors, many of which sell a range of brands.[10] Regional town vendors sell at least 50% of all a-Si modules while the remaining SHS customers purchase their modules directly from distributors in major cities (Musinga, et al., 1997).

To sum up, the use of household photovoltaic systems in Kenya grew out of what was initially a larger market for donor aid and government funded systems. By the mid-1990s, sales of PV modules for household systems had surpassed sales for other applications, and SHS sales continue to dominate the Kenyan PV market.

[10] Currently over a dozen brands of photovoltaic modules are sold in Kenya. These include three brands of single junction amorphous PV modules (Free Energy Europe, i.e. FEE, Intersolar's Phoenix Gold, and Koncar), one dual junction a-Si module (Millenia module by BP Solar), one triple junction a-Si module (Unisolar), and a number of poly-crystalline and single-crystalline module brands (BP Solar, Solarex, Helios, Kyocera, Eurosolare, and others).

4. Information quality market failure

Duke et al. (2000) summarizes the results of a recent study of the long-term performance of the single-junction a-Si modules sold widely in Kenya. The research team used a customized field testing kit to measure the output of 130 a-Si modules with a mean age of 2.7 years (Jacobson et al., 2000). The performance among the modules sampled within each brand type was quite consistent; however, the relative performance across brands varied dramatically (Table 2). Two of the three a-Si brands performed well, suggesting that high quality single-junction a-Si modules are a cost-effective alternative to crystalline PV, especially for smaller module sizes.[11]

In addition to producing far less than rated power, the worst-performing a-Si brand sold in the Kenyan market appears to suffer from high breakage rates due to a combination of inadequate framing and encapsulation as well as user attempts to repair failed modules (Table 3). The other a-Si module brands appear to have less of a problem with breakage; however definitive data have not been collected since users dispose of an unknown percentage of broken modules (Duke et al., 2000).

Even if they also suffer from a substantial breakage rate not revealed by this data set, the higher quality single-junction a-Si modules may be a good choice for capital-constrained rural Kenyan households. A conservatively estimated annual breakage rate of 10% would translate into an expected module lifetime of approximately 9 years (assuming all modules last 20 years if they do not physically break). The relative importance of short-term (months) vs. long-term (years) performance will vary depending on the user. In order to weight near-term performance more heavily, an ideal metric would discount future performance at the system owners private rate of time preference. For a cash starved rural household with a real discount rate conservatively estimated at 20%, the electricity produced from their SHS in 10 years time is worth only about 15% of the electricity produced during the first year after purchase. The long-term trend towards declining PV prices further strengthens the case since the cost of replacing broken modules will likely decline steadily over time as well (Duke and Kammen, 1999).

That said, one of the three PV brands most commonly sold in Kenya (Intersolar's "Phoenix Gold"; see Table 2) has had significant quality problems,[12] yet its market share has risen from about 20% in 1996 to over one-third by the first quarter of 2000 (Soper, 1999/2000; Fanning, 1999/2000). In addition, this brand commands roughly the same price per *rated* Wp as other a-Si modules despite its far higher cost per *delivered* Wp (Table 1). The apparent inability of the market to discriminate between products of varying quality levels is a critical issue for the sustainability of the Kenyan market and similar SHS markets in other countries. It also reflects a broad product (and service) quality problem in immature developing country economies (World Bank Group, 1998/1999) and has important theoretical and practical implications for efforts aimed at aiding the dissemination of new technologies.

There are a number of possible explanations for how this knowledge gap can persist and allow a substandard brand to maintain a large market share without suffering a significant price penalty. First, substandard panel performance, or even outright failure, is generally not detectable until the battery loses enough of its charge that appliances no longer function. Even then, consumers expect frequent battery failure so they may replace their battery, seemingly fixing the problem until the daily energy deficit drains the new battery completely. To complicate matters further, even PV vendors and technicians are generally unable to measure module output with sufficient accuracy to distinguish between adequate and substandard performance. These difficulties associated with establishing the actual performance of PV modules contribute to the uncertainty associated with quality levels among the various brands.

Moreover, survey data indicate that the majority of SHS owners are ignorant of the brand of their module, let alone having knowledge of the severe quality variations across different brands (Duke et al., 2000).[13] SHS markets are diffuse, meaning that any quality information derived from user experience permeates slowly and imperfectly. The average SHS penetration rate is still only 3–4% among rural Kenyan households (Hankins, 2000), making it relatively easy for vendors of low-quality modules to find new uninformed customers.

The preceding discussion suggests that thousands of rural Kenyan households suffer major financial losses

[11] Small crystalline modules tend to be expensive because there are important scale economies in the process of soldering together individual solar cells into a single module. Also, a small module requires a certain number of cells connected in series to achieve the appropriate voltage, and for smaller crystalline modules this requires an expensive additional step of cutting individual solar cells.

[12] The results discussed in the paper are based on tests of modules carried out in 1999 and reported in Jacobson et al., 2000. Since these tests were carried out, Intersolar has made efforts to improve their products. Ongoing tests of the 14 Wp rated Phoenix Gold modules by the authors indicate that the newer modules are substantially better than the ones tested in 1999, but continue to perform below their warranty levels.

[13] It is possible that some households use brand proxies such as country of origin to compare the relative quality of different modules (Hong and Wyer, 1990).

Table 2
Summary of module performance for working a-Si modules[a]

Module Model	Rated max. power (W)	Average measured max. power (W)[b]	Percentage of rated output (%)	95% confidence interval (± % points)[c]	Average age of modules (years)	No. of modules tested
Koncar	12	10.0	83	±3	2.8	31
NAPS	11	9.7	88	±3	3.1	31
NAPS/FEE	12	10.6	89	±3	0.9	32
Intersolar "Phoenix"	11	6.8	61	±1	2.4	5
Intersolar "Phoenix Gold"	14	7.7	55	±9	1.5	12

[a] 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 Koncar modules, 2 NAPS/FEE modules, 3 FEE modules, and 6 Intersolar "Phoenix Gold" 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.

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

[c] The 95% confidence interval about 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 times the "Student's *t*" statistic value for the number of tests in the sample. The value is divided by the average to get a percentage range. This information tells us, for example, that we can be 95% confident that the mean output for NAPS/FEE modules is between 86% and 92% of their rated output.

Table 3
Failure rates for a-Si modules from field tests in Kenya[a]

Module Model	Failed modules (%)[b]	Cracked modules (%)[c]	No. modules encountered
Koncar	6	3	31
NAPS	0	6	32
NAPS/FEE	0	6	32
Intersolar "Phoenix"	46	29	13
Intersolar "Phoenix Gold"	40	0	10
APS	0	50	2
Chronar	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.

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

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

[c] 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.

simply because they have had the misfortune to purchase the wrong brand of PV module. In addition to this direct harm, the inability of consumers to discern the relative quality of different module brands reduces overall confidence in PV and creates an important market failure. "Pooled quality" assessments push public perception of module reliability towards the performance level of the worst brand sold, while unfair competition from low quality brands threatens to fulfill these pessimistic expectations by pressuring better performers to overrate their modules as well.[14] This perverse dynamic constrains the market for SHSs below the socially optimal level (Fig. 1). Akerlof (1970) describes an analogous market failure in his classic paper. People who own high quality cars, for example, will be reluctant to bring them to market because they know they cannot extract the full value of the vehicle given buyers' legitimate expectation that many of the used cars sold will in fact be "lemons."

The pooling of quality expectations may also operate among specialized audiences such as importers, retailers, installers, and international PV experts. Anecdotal evidence suggests that most such experts in Kenya and abroad are considerably better informed than end-users about the range of quality across different a-Si brands, but they also generally believe that single-junction amorphous modules are less reliable than the actual performance of the higher quality a-Si brands. This has important implications to the extent that domestic experts inform and influence SHS purchase decisions, while international experts determine the technology stipulations within international programs to promote SHSs.

[14] During recent years the manufacturer of one of the highest quality single junction a-Si brands sold in Kenya (NAPS/FEE) has had to reject approximately 20% of the modules it produces due to output shortfalls, suggesting that obtaining quality is expensive, but also indicating that the manufacturer expects some long-term gain from a high quality strategy—perhaps by qualifying for participation in multilateral and bilateral funded projects (see the Certification and Labeling section).

Fig. 2. Advertisement by Sollatek (source: Daily Nation, December 9, 1998). Advertisement for Intersolar photovoltaic modules claiming a relatively low cost per peak watt and offering a 10-year expected lifetime and a 5-year warranty. Table 1 shows that these modules are priced similarly to their competitors in terms of rated power, but they are significantly more expensive in terms of delivered power.

The primary incentive of vendors is to sell modules, not to provide their customers with the most value per dollar. This suggests that vendors who are informed about quality differences among brands may continue to market the lower quality modules if they are able to obtain them at a lower wholesale price, or if they simply find that (uninformed) customers prefer to purchase them. It is plausible, for example that Intersolar, the manufacturer of the lowest quality a-Si module (the 14 Wp Phoenix Gold) identified in Duke et al., 2000, has successfully marketed its troubled product in part by claiming a slightly higher *rated* power than its competitors (Fig. 2).[15]

Product quality information failure in the Kenyan SHS market probably indicates a broader international problem in other markets with significant sales of solar equipment directly to end users through scattered vendors and installers (e.g. China and much of Africa). User uncertainty about both a-Si and crystalline module quality may also constrain sales of all types of SHSs on a global basis. This, in turn, could hurt long-term efforts to commercialize PV because near-term sales help bring down the price of PV technology through learning by doing, learning by using, and manufacturing scale economies (Duke and Kammen, 1999).

5. Corrective options

SHS owners are only able to gauge PV module quality after purchase, and even then only if they degrade severely, making PV a classic candidate for quality information failure (Cooper, 1992). There is a range of possible corrective options, including:

1. Reputation Signaling through Advertising and Branding,
2. Warranties,
3. Performance Testing and Disclosure,
4. Certification & Labeling,
5. Minimum Quality Standards,
6. Alternative Business Models.

Each of the first four categories is purely voluntary; however, private companies could unilaterally implement the first two, while the third and fourth approaches require new private or public organizational structures. The fifth category is more intrusive in that it would involve direct government regulation of module importation based on quality considerations. The sixth option outlines various centralized SHS business models that would sharply to reduce or even largely eliminate quality problems in their market areas. Each of the six options has distinct expansion potential and entails different risks, as discussed below.

5.1. Reputation signaling through advertising and branding

High quality producers can signal their superiority over competitors using a number of strategies. These include advertising their own brand as well as marketing their goods under another brand name or via a retailer with a strong reputation for quality.

A number of PV manufactures and distributors do advertise in the Kenyan market and their methods include attempts at price and quality signaling. For example, Fig. 2 includes a claim by Sollatek that the 14 Wp a-Si modules they sell (made by Intersolar) have the "cheapest cost per watt." Likewise, in Fig. 3, Free Energy Europe claims that its modules are the "best tested in Kenya" based on research reported in Duke et al., 2000.

[15] That said, vendors have some incentive to sell high quality goods to encourage repeat sales and maximize the impact of word of mouth advertising. It is also unpleasant and potentially costly to deal with unsatisfied customers (e.g. processing returns to the manufacturer under warranty), providing another incentive to sell higher quality products when it is profitable to do so.

Fig. 3. Best Tested in Kenya Advertisement (*Source*: bumper sticker distributed in Kenya by Free Energy Europe, 2000). Advertisement from Free Energy Europe claiming that their modules are of superior quality based on testing results reported in (Duke et al., 2000).

In theory, a company that invests heavily in advertising its brand must actually deliver high quality goods or else the public will switch to other products rather than pay the price premium necessary to recoup the firm's sunk advertising costs. This strategy does not work well, however, when consumers cannot readily detect poor quality (Ping and Reitman, 1995). As noted above, it is extremely difficult for SHS owners to evaluate the quality of PV modules before or after purchase. Even when modules fail unambiguously, the dispersed nature of the SHS market limits communication of this information about quality among rural households. Rural geography also increases the cost of marketing to this audience. Collectively, these considerations suggest that advertising has limited capacity to signal high PV module quality in this context.[16]

Reputation signaling by associating high quality modules with a well-known and respected brand is another possibility. This strategy could, for example, prove useful for marketing BP Solar's Millenia a-Si modules. To the extent that rural households in Kenya or other relevant markets are familiar with the BP trademark (e.g. due to their petroleum products) they may have more faith in the quality of these modules than those from smaller less well known manufacturers.

Other a-Si manufacturers that lack an internationally recognized brand name could attempt to market their modules through well-respected retailers. For example, where they exist, it might prove possible to sell modules through retail chains with a strong reputation for quality. These strategies are complicated, however, because the manufacturer would have to convince the retailer that its modules would not tarnish the retailer's reputation. The retailer would also have to develop systems to provide users with information about SHS installation and use.

In general, then, reputation signaling through advertising and branding may be important, but its value is limited by consumers' ability to distinguish between high quality and low quality products. The next three sections discuss a range of alternative strategies that manufacturers may be able to voluntarily implement to signal their quality to consumers.

5.2. Warranties

Warranties perform an important function to the extent that they protect consumers who happen to purchase a "lemon" and strengthen the incentive for manufacturers to maintain quality. One of the most light-handed options for addressing quality concerns would be to improve the efficacy of warranties. As with reputation signaling, this option has the important virtue that individual PV companies, or their local distributors, may be able to address the quality market failure unilaterally without the need for complicated industry level cooperation or government action.

A typical 20-year warranty for a large crystalline module guarantees at least 90% of rated power (at standard test conditions) during the first 10 years, dropping to 80% of rated power for the next 15 years.[17] In principal, manufacturers rate a-Si modules at their stabilized output levels, such that their modules should initially produce 15–25% above rated power, then stabilize at 90–100% of rated power after light-soaking. In practice, however, even manufacturers intending to ship only modules that comply with their warranty terms must contend with variance in both the initial and stabilized output of any given a-Si module. This means that even testing each module before shipment leaves room for error. Available evidence suggests, however, that the performance variance of individual modules is not large within any given brand of high-quality single-junction module (Jacobson et al., 2000).

The main a-Si module brands sold in Kenya all include manufacturers' warranties:

- NAPS offered a 5-year warranty before their module factory was purchased by Free Energy Europe (FEE) in 1998;
- FEE honors the NAPS warranty and offers a 10-year warranty on current sales;
- Koncar offers a 6-year warranty (www.koncar-solar.tel.hr);

[16] It is important to note, however, that equipment importers and distributors do advertise substantially in the Kenyan market (largely through newspaper ads) indicating that they perceive it to be of some value at least for marketing to local equipment retailers. In fact, FEE has been aggressively promoting the results from Jacobson et al., 2000 suggesting that its modules outperform its principal competitors. See Fig. 3. It is too early to tell if this will have a substantial impact on the marketplace.

[17] This example is for a Siemens SM55 (www.solarpv.com/sm55_sm50.html). In another example, at the time of purchase Solarex (now BP Solar) guarantees about 97% of rated power for larger modules and 90% for smaller modules and at least 80% of rated power for 20 years for both small and large modules (www.bpsolarex.com).

- Intersolar offers a 6-year warranty (www.intersolar.com);
- BP Solar offers a 10-year warranty on the Millenia module (www.bpsolar.com); and,
- Uni-solar offers a 20-year warranty on its multi-junction a-Si modules, but they are relatively expensive and have a very small share of the Kenyan market (www.ovonic.com/unisolar.html).

Typical terms include protection against manufacturing defects and a drop in output below 90% of rated power; however, there are important differences from brand to brand. For example, FEE guarantees that its modules will not drop below 85% of rated output, while the Millenia module is guaranteed to produce its rated power at the time of sale, and no less than 80% of rated power for 10 years.

The relevant importers for the two best performing brands in our study report that less than 1% of the modules sold have been replaced under warranty. The relatively good performance of these modules (Table 2) is consistent with their low level of returns. For the best performing FEE modules, only 13% performed below the 85% warranty cutoff, while only 17% of the Koncar modules meet their higher 90% warranty standard, and 48% would meet an 85% standard (Duke et al., 2000).

It is, however, clear that warranties are not providing adequate consumer protection. Duke et al. (2000) reports that, for the worst quality brand, all of the modules in their sample were performing at less than 75% of rated power, and over 90% were still nominally under warranty. Despite apparently strong warranty terms, the total return rate for these modules has only been about 10%.[18] This raises serious concerns about the practical value of warranties for rural Kenyan SHS owners.

A number of factors limit the efficacy of warranties in Kenya including:[19]

1. rural households are unable to measure the output of modules;
2. PV buyers may not know their rights and may have little faith in stated warranties due to previous experience with merchants who refuse to honor them;
3. some module importers and vendors may not cooperate in honoring warranties;
4. if a company is sold or goes bankrupt, the Kenya representatives for that brand may refuse to honor the now defunct manufacturer's warranty.

Measurement issues are likely the most serious impediment to effective warranties. 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 extremely difficult for a rural household to know whether its module is producing less than rated power. As a result, only severely degraded modules come back for warranty replacement and, even then, most rural vendors lack the appropriate equipment or knowledge to accurately test a module.[20]

The second and third concerns listed above suggest the possibility of a self-reinforcing pattern in which warranties are not taken seriously by vendors or buyers. Some shops may resist processing warranty claims because of the associated transaction costs. This expected resistance, in turn, could discourage rural people from bothering to travel to the shop to make a claim. Further research is needed, but it is possible that a mutual tendency to disregard warranties may play a role in allowing severely substandard modules to persist in the marketplace. There is, however, little doubt that the inability of households (or most vendors) to reliably measure their module performance is a major factor behind this market failure.

The fourth concern about possible bankruptcy or buyouts is only relevant to the extent that the first three issues are addressed. Moreover, recent experience is encouraging. FEE purchased the NAPS a-Si manufacturing facilities in 1998 and has stated that it will honor the warranties on modules sold by NAPS before the change in ownership. Despite this favorable precedent, any given module manufacturer could be bought out by a company that refuses to honor its predecessor's warranties. It is also possible for a company to simply fail, in which case their outstanding warranties would be useless unless a local importer or vendor chose to honor them.

An importer or manufacturer committed to strengthening its warranty could consider:

1. issuing clear instructions to vendors that they expect warranties to be honored, cooperating fully in processing returns, and covering the cost of shipping modules to and from rural supply shops (ideally

[18] The importer for this low-performing brand reports that his company will pay full round-trip shipping costs for any module returned by a vendor. Personal communications with the authors, May 1999. Similar arrangements are offered by Free Energy Europe and possibly by other PV module manufacturers and importers (van der Vleuten, personal communication, 2001).

[19] Some of these concerns were articulated during a meeting of Kenyan SHS industry experts hosted by the Renewable and Appropriate Energy Laboratory (RAEL) of UC Berkeley and Energy Alternatives Africa (EAA) in Nairobi during January of 2000.

[20] Vendors could readily detect serious degradation by simply measuring the amperage of a panel charging a partially discharged battery in strong sunlight. This method is probably only accurate to within about $\pm 15\%$, however, and many vendors simply check the open circuit voltage (V_{oc}) and short circuit current (I_{sc}) of the panel. Neither of these is accurate since some severely degraded modules appear to offer acceptable performance in terms of these measurements (i.e. V_{oc} and I_{sc}).

including a handling fee to cover their time and incidental expenses)[21];
2. providing vendors with instructions and simple meters for basic module output tests sufficiently accurate to detect severe under-performance;
3. including a short version of the owner's warranty rights on the permanent module label;
4. increasing the length of their warranty;
5. offering customers a super-warranty (e.g. providing two replacement panels to any customer who returns a substandard module);
6. publicly disclosing the number of returns processed under warranty.

The first two suggestions directly facilitate vendor efforts to process warranty claims. The main suppliers of a-Si modules in Kenya indicate that they have traditionally covered shipping costs on returned modules, but it is unclear to what extent they actively support such returns. Adding a generous handling fee to cover the time and effort necessary to process warranty claims would encourage their vendors to cooperate fully with dissatisfied customers.[22]

Perhaps more important would be ensuring that vendors have the capacity to evaluate customers' modules with sufficient accuracy to identify moderately to severely degraded modules. This is achievable with a minimum of equipment; however, suppliers may be concerned that setting up vendors to test modules could unleash a slew of expensive warranty claims. Assuming a crude field test methodology that is only accurate to $\pm 15\%$, one approach might be to only process claims free of charge on modules performing at 75% of rated power or lower. Panel owners with modules in the range of 75–90% of rated power would have to pay for shipping themselves if they wanted to press their claim. Another concern with this approach is that some vendors have little or no technical knowledge (e.g. in some towns it is possible to buy PV panels at the local supermarket) and it would therefore be difficult to train them to reliably test modules.

A combined approach of ensuring that vendors receive adequate compensation for processing claims and equipping them to do crude field evaluations of module performance would likely allow people with severely degraded modules to exercise their warranty rights. Moreover, manufacturers and/or suppliers could tune the cutoffs and terms to avoid excessive warranty returns costs.

The third strategy is a low-cost and potentially important technique for strengthening customer awareness of their warranties, and there is a broad consensus in favor of this approach among principle stakeholders in the Kenyan market (RAEL/EAA Conference, January 2000). At present no a-Si manufacturer puts comprehensive warranty information directly on a permanent label attached to the back of their modules. This simple change would make sure that customers have access to this information even if the local dealer does not tell them or if they lose the explanatory sheets of paper that come with some modules.

Finally, higher quality module manufacturers could draw on the last three warranty strategies listed above as part of a confidence building campaign to convince potential buyers that their product is reliable. That said, high consumer discount rates and declining module price suggest that protecting buyers from severe near-term degradation is a higher priority than extending the duration of coverage. Moreover, care would be necessary in implementing any sort of "super warranty" to avoid possible gaming of the system (e.g. by users who intentionally harm their module in the hopes of obtaining two replacements under warranty). There is also a risk that this approach would increase supplier, vendor and/or manufacturer resistance to processing claims. Public disclosure of the number of returns under warranty might also prove useful, but it would be difficult to prevent companies from misrepresenting their statistics without complicated and expensive audits.

In sum, the first three strategies listed above offer the best prospects for strengthening the practical value of warranties for rural SHS owners. Collectively, these would be a useful way for certain manufacturers to signal that they sell high quality goods and ensure customer satisfaction, but low quality manufacturers have little incentive to improve their warranty terms and may nonetheless be able to compete successfully.

5.3. Performance testing and disclosure

The next most aggressive strategy for addressing information failure in the Kenyan market for PV modules (or other similar markets) would be to establish a system for periodic local testing of all the major brands of modules sold in Kenya. A basic outdoor testing kit can be assembled for less than \$10,000 (Jacobson et al., 2000). There are about ten major brands of modules sold in Kenya, half of which are a-Si while the rest are crystalline. Even for the lowest quality modules with the highest performance variance, it should be possible to obtain average performance estimates with $\pm 10\%$ accuracy by testing ten modules from each brand annually. The authors estimate that a basic testing regime could be developed and sustained

[21] Several PV module manufacturers and importers have made such arrangements with vendors. See footnote 18, above.

[22] A range of participants at the January, 2000 RAEL/EAA conference indicated that vendors and importers of the lower quality brands were resistant to honoring their warranties; however, most vendors state that they are willing to process return claims and anecdotal evidence suggests that many vendors and importers do, in fact, honor warranties.

for approximately $20,000 per year.[23] Any group implementing a domestic testing program could also consider an indoor testing lab; however, this would more than quintuple equipment costs while only improving accuracy marginally. If improved accuracy is deemed necessary, a better investment would be to simply test a larger number of light-soaked a-Si modules using outdoor testing (Jacobson et al., 2000).

The entire program could be funded with less than 1% of the revenue from modules sold for SHSs in Kenya. This suggests that the industry could potentially shoulder the entire cost, though it is likely that the lowest quality brands might choose not to participate.[24] In any case, it would be necessary to have the actual testing done by an independent industry, non-governmental or government group to ensure credibility. To reduce the risk of manipulation or corruption it would also be essential to allow participating manufacturers reciprocal rights to monitor and challenge the entire testing process. This would, for example, help to ensure that modules were sampled randomly.

While some level of financial buy-in from industry would be useful, complementary or full public support for this market-enabling program would be readily justifiable. In addition to the national government, possible sources include the Global Environment Facility or bilateral development aid; however, it could prove difficult to attract even the modest funding levels required because a performance testing and disclosure program has intangible benefits. There is also a risk that a donor would have an agenda (e.g. ensuring that modules from their country receive positive treatment in the process) and donor involvement adds a layer of bureaucratic complexity that might slow implementation.

Regardless of the exact funding and testing strategy used, there are two key distinctions between this approach and international certification such as that proposed by PVGAP (see the next section). First, most certification programs involve a broad range of tests beyond just measuring output performance. Comprehensive certification has the virtue of offering consumers information about a wide range of quality attributes, but it also substantially raises costs.

Second, most international certification programs impose binary pass or fail judgements. This may simplify consumer education, but at the expense of limiting consumer information. One alternative would use a simple domestic testing procedure of the sort described in this section, but rather than reporting the average output level of each brand, give a "seal of approval" to those above a certain cutoff. This strategy has the virtues of low cost and simplicity, but it is subject to the same generic concerns about certification programs detailed in the next section. Moreover, while certification condenses complex information from a range of different tests into one easily understandable indicator, it is arguably easier to convey the concept of average performance for each brand rather than educating the public about the meaning of an abstract seal of approval.

This is all the more likely given that lower quality manufacturers could actively disrupt any quality certification program by making confusing quality claims. Intersolar, for example, advertises its modules as offering "Quality Design to ISO 9001. " This indicates that the manufacturing facility voluntarily commits to adhere to a set of management practice standards compiled by the International Organization for Standardization (www.iso.ch) to help ensure consistency in its production process. It does not, however, indicate that there is any independent auditing, or that Intersolar products will achieve any given level of performance.

Manufacturers can also label their products with a range of official looking "quality seals" of their own design. In India, for example, some domestically produced electronic goods are labeled "made as JAPAN" with the first two words in small type (Malghan, 2000). This sleight of hand circumvents laws against false country of origin claims while associating the product with the strong quality reputation of Japanese electronic goods. Similarly, Chinese manufacturers have labeled their refrigerators with official energy efficiency certification logos from the United States government's Energy Star program without actually undergoing any testing to verify compliance (Borg and Waide, 1999).

Intentional obfuscation is less of a concern for the domestic performance testing and disclosure option because a manufacturer falsely labeling its modules with a specific testing result would be subject to legal challenge and harsh criticism among industry stakeholders. In contrast, it would be far more difficult to successfully criticize or litigate against a manufacturer that labels its panels with a vague "quality approved" sticker.

[23] Note that these costs may vary depending on the agency that is carrying out the work. Also, it is assumed here that the various crystalline module importers and/or manufacturers would lend modules to the testing agency. These modules would then be returned to the appropriate parties at the end of the test period. For crystalline modules the tests can be carried out quite quickly (less than a week). Amorphous modules would have to be retained for 3 – 6 months, and we have assumed here that they would be purchased and later resold at a substantial discount.

[24] In that case, the higher quality manufacturers could pay the extra cost required to purchase from the non-participating manufacturers. This would raise the cost for participating manufacturers and also increase the risk of legal action against the testing group itself or the participating manufacturers. An alternative would be to test only those brands willing to pay for the service and sign a legal waiver.

Disclosure of information associated with the testing can occur at three different levels. These include (a) the manufacturers, (b) the domestic solar industry (i.e. PV importers, vendors, installers, etc.), and (c) the public at large (i.e. potential consumers). These three groups have different, though sometimes overlapping, sets of interests with respect to SHS quality and sales. Testing agencies will have varying degrees of difficulty communicating key information to each respective group, but comprehensive disclosure can play an important role in improving quality in SHS markets.

Disclosure of detailed test information to manufacturers, and particularly to the manufacturers of the low performing brands, can encourage performance improvements. While most low-performing manufacturers are presumably aware of the main problems with their products, in some cases testing and disclosure can provide new information to manufacturers. Moreover, constructive communication between the testing agency and the businesses in question may help encourage investment in quality improvements. However, it is important not to overestimate the effectiveness of this approach, especially in the absence of stronger measures that penalize low quality (or at least threaten to do so).

Members of domestic solar industries are a somewhat more diffuse group to reach than manufacturers. In Kenya, for example, while it is relatively easy to distribute information to the 10 odd major import companies, there are also hundreds of PV vendors and more than 1000 installers. Providing product quality information to these people may reduce the use of low quality equipment as vendors, for example, choose to avoid the potential hassles and reputation penalties associated with dissatisfied customers. Some vendors may continue to sell low quality goods if they find that such sales remain profitable. Nonetheless, information campaigns that target vendors may be worthwhile, if only because they are much easier to reach than their even more diffuse customer base.

Finally, information about quality can be disclosed to the public at large in an attempt to reach the PV customers themselves. While this is the group that has the greatest interest in acting on the information, it is also the most difficult to reach. For further discussion of this issue, see Section 5.4 below.

5.4. Certification & labeling

International and domestic organizations have developed a number of standards meant to ensure the quality of PV modules and systems. The most current were developed by the International Electrotechnical Commission (IEC) and the Institute of Electrical and Electronics Engineers (IEEE):[25]

- IEC 1215–1993 Crystalline silicon terrestrial photovoltaic (PV) modules—Design qualification and type approval;
- IEC 1646–1996 Thin-film terrestrial photovoltaic (PV) modules—Design qualification and type approval;
- IEEE 1262–1995 IEEE Recommended Practice for Qualification of Photovoltaic (PV) Modules (applies to both crystalline and a-Si and closely resembles the IEC standards).

Under all of these standards, manufacturers are able to maintain certification indefinitely unless they make substantial changes to module design, materials, components or processing.

Manufacturers can, however, strengthen their quality credentials by participating in one of two international testing *programs:*

- the Photovoltaics Global Approval Program (PVGAP) based in Geneva; and,
- PowerMark.

PowerMark is the "sole US agent for [PVGAP] and the only US PV testing and certification program meeting the requirements for international reciprocity (www.powermark.org)." Both PVGAP and PowerMark encompass the full range of balance of system components used in solar installations and require that the manufacturer itself receive certification in accordance with ISO 9000 guidelines. PVGAP differs marginally from PowerMark in that it requires more frequent testing and addresses system design as well as components (see Table 4):[26] Finally, the IEC is currently formulating its own PV certification program. PowerMark has committed to following their recommendations and

[25] During the late 1970s through the mid 1980s JPL Block V was the dominant standard but it has been displaced by the others listed here (www.asu.edu/east/ptl/asuptlquestions.html). CEC 503 and CEC 701 closely parallel IEC 61215 and IEC 61646, respectively, and the European Union testing laboratory at Ispra, Italy developed them and continues to use them; however, both PowerMark and PVGAP (introduced in the text below) cite the IEC and IEEE standards as the primary basis for their international module testing programs. There are also a number of standards meant to ensure the safety of PV modules and balance of systems components (e.g. ANSI Z97.1 and Underwriters Laboratories UL 1703); however, these are beyond the scope of our analysis, especially since the developing country SHS market relies on small 12 volt systems that involve little risk to installers or users.

[26] The specific re-testing requirements for amorphous silicon modules under PVGAP are laid out in PVGAP Recommended Standard 3. PVGAP promulgates Recommended Standards with the intent that the IEC will ultimately adopt them with only minor modifications. See www.pvgap.org/f-mission.html for a current listing of the full range of PVGAP Recommended Standards for various components and systems.

Table 4
Quality assurance programs

	PVGAP	Powermark
Applicable standards	IEC 1215—1993 Crystalline silicon terrestrial photovoltaic (PV) modules—design qualification and type approval IEC 1646—1996 Thin-film terrestrial photovoltaic (PV) modules—design qualification and type approval ISO 9000	IEC 1215—1993 Crystalline silicon terrestrial photovoltaic (PV) modules—design qualification and type approval IEC 1646–1996 Thin-film terrestrial photovoltaic (PV) modules—design qualification and type approval IEEE 1262–1995 IEEE recommended practice for qualification of photovoltaic (PV) modules (applies to both crystalline and a-Si and closely resembles the IEC standards) ISO 9000
Renewal terms	Any modification that may affect quality requires retesting Certified on-site output testing of 100% of production Re-testing of all IEC requirements every 1–2 years	Any modification that may affect quality requires retesting Retest modules every 2–3 years
Present Scope	PV modules Balance of systems equipment System design Installers	PV modules Balance of systems equipment

PVGAP may ultimately conform their program to the IEC guidelines as well (Chalmers, 2001).

IEC 1646 requires that 7 modules be tested (plus one control unless temperature coefficients are already known). These are broken into three pairs plus a single module, and each of these four sets is subjected to a different sequence of tests before a final light soaking.[27] The modules are then required to pass a final visual inspection, insulation resistance test, and produce at least 90% of rated power normalized to standard test conditions. If two or more modules fails then the model does not obtain certification. If one fails, the manufacturer is allowed to repeat the relevant test on two more randomly selected modules, both of which must pass to obtain certification. For PVGAP, there are no failures allowed.

It is useful to consider the minimum average module performance rating consistent with a high probability of achieving PVGAP certification on the first attempt. Assuming a normal distribution of performance with a standard deviation of 3%, obtaining a 90% chance of successful certification requires average module performance (post test sequence and final light-soaking) of 97% of rated power. Assuming a standard deviation of 2%, the required average module performance drops to 94% of rated power; nonetheless, obtaining PVGAP certification requires average module performance well in excess of the 90% minimum standard for any given module.

[27] The stress and durability tests include a wet leakage current test, measurement of output at normal operating conditions, measurement of output at low irradiance levels, hot spot endurance, UV exposure, thermal cycling, humidity freeze, robustness of terminations, resistance to breakage from twisting, mechanical load and a hail impact test.

The IEC standards are substantively equivalent to each other, except that IEC 1646 incorporates a range of light soaking and thermal annealing tests necessary to accurately measure a-Si modules. Moreover, IEEE 1262 is similar to the IEC standards, though IEC 1646 requires that modules produce 90% of rated power *after* light-soaking, while IEEE 1262 requires 100% of rated power *prior* to light-soaking (or after high temperature annealing to reverse the effect of any light-soaking during the testing process). These criteria would be roughly equivalent if light soaking reliably caused 10% degradation from initial output levels; however, single junction a-Si modules generally exhibit considerably greater levels of light-induced degradation (Jacobson et al., 2000). This suggests that IEC 1646 may be more appropriate for testing single junction a-Si modules and, in fact, it has become the dominant testing standard for all a-Si modules.

There are at least two laboratories that have been accredited to test compliance with the IEC standards, the Photovoltaic Testing Laboratory (PTL) at Arizona State University (www. asu-ptl. org) and the Energy Systems Testing Unit (ESTI) of the Joint Research Centre of the European Commission located in Ispra, Italy (iamest.jrc.it/est/est.htm).[28] There is de facto

[28] ESTI conforms to ISO/IEC Guide 25 (General Requirements for the Competence of Calibration and Testing Laboratories) as well as the European standard EN 45001, General Criterion for the Operation of Testing Laboratories, and it has been formally accredited by the Comite Francais d'Accreditation (COFRAC). Similarly, "ASU-PTL meets the requirements of A2LA (American Association for Laboratory Accreditation) and PMC (PowerMark Corporation), including:

- PV-1. Criteria for a Model Quality System for Laboratories Engaged in Testing Photovoltaic Modules.

reciprocity between these labs; however, formal written confirmation of this arrangement has not been achieved.[29] As of February 2000, fifteen different module manufacturers had obtained certification to both IEEE 1262 and IEC 61215/IEC 61646 from PTL—including three different a-Si module manufacturers and one cadmium Telluride thin-film module. As of May 2000, ESTI had certified 32 separate manufacturers to CEC Spec. 503 and/or IEC 61215 Standards.[30]

The economics literature highlights the risk that certifying labs and programs will use their exclusive franchise to extract excessive fees (Cave, 1985). In the case of PV module certification programs there is some indication that PowerMark was launched to ensure that US PV manufacturers would not be forced by European laws to obtain testing from ESTI, thereby putting that lab in a position to charge monopoly testing fees.[31] PowerMark is also negotiating with PVGAP over a range of issues (e.g. which institutions will be allowed to accredit certifying agencies) and the two programs may eventually merge (Chalmers, 2000).

Both PowerMark and PVGAP should eventually allow testing by a wide enough range of labs to preclude excessive fees. As of May 2000, PTL was the only laboratory to have received accreditation from the International Electrotechnical Commission Quality Assessment System for Electronic Components (IECQ) to serve as a testing laboratory for the PVGAP program. ESTI should, however, be accredited shortly (Varadi, 2000). Moreover, the Florida Solar Energy Center is in the process of obtaining international accreditation for their testing laboratory (Chalmers, 2001). PVGAP also allows for the possibility that manufacturers develop their own on-site laboratories where they could obtain and maintain PVGAP certification for their products under the supervision of PVGAP—but no manufacturer has such facilities at this time (Kay, 2000).

Regardless of the exact form that it takes, certification is likely to have minimal effect on private solar purchase decisions in the Kenyan context because the target audience will have little reason to trust any given quality seal. Public information campaigns represent a possible strategy to address this problem; however, the success of such a public information campaign would depend critically on financing by an institution that is trusted by the public and able to carry out an effective public awareness effort to reach this dispersed population. Finally, as noted at the end of the last section, low quality manufacturers could confuse the public with false or misleading quality claims that would be difficult to prevent without clear laws prohibiting such obfuscation abetted by a fully functional judicial system.

In conformity with these considerations, several manufacturers indicated to the authors that they view formal certification as largely superfluous for selling modules to private customers in Kenya—though one of these is pursuing certification anyhow, largely in order to qualify for participation in donor aid projects.

None of the single-junction a-Si modules tested in the study by Duke et al. (2000) has yet been quality certified.[32] As noted above, however, one single-junction a-Si manufacturer is pursuing IEC 1646 certification with the stated rationale that it must do so in order to sell its modules to internationally sponsored projects. Thus, despite the limited benefits of certification for increasing sales in private SHS markets, international organizations may have prompted at least one small module manufacturer to seek certification by imposing minimum quality standards in their SHS programs.

In addition to concerns that it may not increase sales substantially in private markets, certification is also costly relative to the profits of small module producers. A typical fee for initial IEC certification of a given module exceeds \$25,000.[33] Under the IEC standards, modules must be re-certified any time there is a substantial manufacturing process change, and even if the modules are unchanged, they must be regularly re-certified to maintain eligibility under PVGAP.

In present value terms, IEC 1646 certification would likely be cost effective for a small a-Si manufacturer (e.g. with output of about 0.5 MWp) only if certification boosted sales by at least 4%. If such a manufacturer were to pursue ongoing PVGAP certification, it would need to see sales growth on the order of 12% to justify the present value of the investment.[34] The cost of certification for firms with larger ex ante sales volumes is

(footnote continued)

- PV-1.1. Calibration, Traceability and Statistical Requirements of Testing by Accredited Laboratories in Support of the Photovoltaic Module Certification Program.

These two documents were developed under the National Renewable Energy Laboratory program for Photovoltaic Module Certification/Laboratory Accreditation Criteria Development and meet the requirements of ISO/IEC Guide 25 as well as the relevant requirements of the ISO 9000 series of quality standards." www.asu.edu/east/ptl/asuptlquality.html. Note also that TUV Rheinland in Germany has certified modules to CEC 503 standards (www.solarpv.com/sm55_sm50.html and www.tuev-rheinland.de/engpages/umw.htm).

[29] www.asu.edu/east/ptl/asuptlquestions.html

[30] iamest.jrc.it/esti/certific/aaindex.htm

[31] www.asu.edu/east/ptl/asuptlquestions.html

[32] Solarex introduced its CEC 701 and IEC61646 compliant Millennia a-Si modules to the Kenyan market during early 2000.

[33] Personal communications with Bob Hammond of PowerMark during May, 2000.

[34] It is assumed that modules have to be re-certified once during a 10-year time frame for the IEC case and every 1–2 years for the PVGAP case. For both cases, the discount rate is 15%, the profit margin is 15%, and the cost of management oversight of the certification process is 25% of the associated lab fees. It is further assumed that manufacturers must invest \$10,000 to help their distributors take advantage of the certified status in marketing modules and that process improvement investments necessary to obtain certification are exactly offset by associated cost savings (e.g. a lower discard rate).

proportionately lower. For example, Uni-Solar has 5 MWp of triple-junction a-Si production capacity. Assuming an 80% capacity factor, PVGAP certification would be cost effective if it boosted Uni-Solar sales by 2%.[35] There is, therefore, some risk that certification along the lines of PVGAP would disadvantage high quality manufacturers that are too small to afford the testing and re-testing requirements. For example, the highest-performing single-junction a-Si brand identified in Duke et al., 2000 is produced by a small firm for whom PVGAP requirements might prove prohibitively expensive. This is of particular significance for mandatory minimum quality standards as discussed in the next section.

In light of these concerns, the next section discusses the benefits and costs of stronger measures to compel quality certification when quality labels alone do not increase free market module sales sufficiently to motivate all manufacturers to seek certification.

5.5. *Minimum quality standards*

The core problem with certification and labeling is that it does little to protect consumers buying panels outside the context of internationally funded SHS programs. Moreover, certified modules may flow into formal programs, leaving the residual supply of uncertified modules for free market sales in countries like Kenya and China.

In principle, national governments could address this by legally prohibiting the sale of modules that fail to meet minimum quality standards. There are, however, reasons for concern. First, there is a risk that the process of enacting legislation or promulgating regulations prohibiting substandard modules could be subverted. Domestic manufacturers might, for example, take advantage of the process to increase barriers to imported solar equipment.[36] In addition to this legislative risk, certain government officials (e.g. customs officials) might use ambiguities in minimum quality standards to extract "rents" from importers and vendors. Corruption aside, minimum quality standards might simply lead to bureaucratic delays during the importation process.

It is also important to note that, as part of developing minimum quality standards, some governments may wish to exercise more direct control over the certification testing process. The Kenya Bureau of Standards (KBS), for example, has convened on-going discussions with industry stakeholders to develop national standards related to SHSs. As part of this effort, the KBS has discussed the possibility of selectively adopting different components of international PV module certification standards and performing the testing domestically. This approach has the modest potential advantage of allowing local governments to customize certification standards to better fit local conditions; however, it's costs are far more certain and significant. Developing domestic facilities to carry out testing that is similar in scope to that proposed by the international standards is likely to prove costly, and international manufacturers would have little incentive to pay for testing that is only valid for access to the Kenyan market.[37]

Finally, minimum standards may also set the bar too high, especially since high quality manufacturers have a strong incentive to exclude lower quality rivals. Requiring that modules produce their rated power, or nearly so, is undoubtedly helpful since companies can and should simply de-rate their modules in order to comply. The stress test components of the standard certification programs described in the previous section are, however, less unambiguously beneficial for markets such as Kenya. The hail and twist tests, for example, ensure rugged and durable encapsulation but, as noted, reducing the long-term risk of breakage is a relatively low priority in markets characterized by high personal discount rates and declining module prices. Excessively restrictive standards also risk increasing market concentration by driving out firms that are too small or technically constrained to afford testing and compliance costs.[38]

There are five a-Si brands currently sold in Kenya, but two of these have trivial market shares. This suggests that the departure of even a single brand of small a-Si modules from the Kenyan market might significantly reduce price competition for this market segment. Thus, it is important to target quality measures so that they do not eliminate high quality firms. Nonetheless, quality measures that drive out seriously overrated brands

[35] This assumes that Uni-Solar could obtain certification for an entire group of modules by testing one representative model. In fact, they would have to redo the mechanical load, dynamic load and twist tests (and possibly a few others) for each module size (PVGAP Draft Retest Requirements 09/07/99). Note, however, that Uni-solar plans expansion to the 25 MWp scale, suggesting that the certification cost per specific module model will be considerably smaller as a percentage of revenue in the future (www.ovonic.com/news/Apr11_2000.html).

[36] Although all PV modules are imported, a number of BOS components are manufactured in Kenya, including batteries, lamps, and other electronic BOS equipment.

[37] Domestic testing that uses a completely different set of testing requirements may make sense. See "Discussion—Building Sustainable Clean Energy Markets," for a proposed strategy for domestic testing. Moreover, some of the concerns expressed here are moot if the Kenyan Government covers the cost of the testing through general revenues or a (moderate) industry wide tax.

[38] With a binary cutoff there is also little incentive for any manufacturer to beat the standard, so they may trim quality control expenditures to the point that they are just able to meet the cutoff point.

would likely improve the average price per *delivered* peak watt, and are therefore clearly desirable.

5.6. Alternative business models

Each of the five categories of remedies above address quality problems within the competitive structure that currently dominates in the Kenyan SHS market. There are a number of alternative SHSs dissemination options that could address quality problems by centralizing equipment procurement decisions and, in some cases, on-going maintenance responsibility as well. A comprehensive discussion is beyond the scope of this analysis, but all the options fall into two broad categories: financed SHS sales and fee-for-service.

SHS financing programs, such as the PV Market Transformation Initiative discussed above, are typically administered by a local financial institution partnered with an NGO or business. International donors often cover overhead costs and provide incremental subsidies. This approach has the potential to increase accessibility by lowering the "first-cost barrier" (Cabraal et al., 1996).

It introduces distortions by giving potential cash sale customers incentive to hold out for finance once they learn that it may become available. SHS loan funds also favor certain installers and equipment. This modifies free market patterns, but in so doing it can promote quality. The implementing partners for any SHS loan fund have considerable incentive to ensure that they only finance quality equipment and installations given that (1) NGOs and international partners often list public benefits as their chief objective, and (2) the program is likely to suffer lower repayment rates to the extent that users experience quality problems. SHSs loan funds therefore often require their customers to use certified equipment and installers that have been assessed and registered by the program.

Despite these advantages, financing has generally failed to achieve rapid SHSs sales growth. This is largely due to the high transactions costs of managing relationships with a large network of small-scale installers and arranging micro-credit for each remote and dispersed SHS customer. In addition, while they may improve initial system quality, equipment and installation quality stipulations accompanying financing do not guarantee on-going maintenance. Some programs address this by adding a maintenance contract to the SHS sale, but this raises monthly payments and is therefore difficult to sell to customers.

Under the fee-for-service business model, a "solar utility" (public or private) owns and maintains SHSs for its customers who pay a monthly fee to amortize the initial equipment and cover on-going operations and maintenance costs. A number of countries (notably South Africa) are developing rural energy concessions structured to attract large-scale private companies to act as solar utilities within regulated rural territories (Banks et al., 2000). This approach gives the government direct authority to regulate prices, offers some protection against the risk that grid extension will displace the fee-for-service systems, and provides a relatively stable regulatory framework in which to provide subsidies to attract well-financed corporations and increase penetration levels (Greene et al., 1999).

6. Discussion—building sustainable clean energy markets

The fundamental objective of any corrective measures undertaken in Kenya (or other similar private SHS markets) should be to improve consumer welfare. This requires balancing the benefits of reducing the information quality market failure with the costs of the corrective measures undertaken towards that end. For example, the costs of minimum quality standards would largely be passed on to consumers.[39] Fig. 4 shows this graphically as an upward shift in price that reduces consumer surplus by the amount labeled B. To the extent that minimum standards solve the product quality information failure, this is offset by an outward shift in demand that increases consumer surplus by the amount labeled A. Thus, minimum quality standards would produce net social benefits as long as $A - B > 0$. A similar theoretical framework applies to the other quality policy options.

The first four corrective options described above are all voluntary mechanisms that give PV module buyers information about quality. *Signal facilitation* of this sort offers potential advantages over legal mandates to the extent that private companies are better able to weigh the relative costs and benefits (Cooper, 1992). For example, if performance testing proves too expensive relative to its marketing value, then even high quality manufacturers might choose to compete on the basis of lower price or stronger warranties rather than participating in a voluntary performance testing and disclosure scheme.

Voluntary signal facilitation measures also allow manufacturers flexibility to sell lower quality modules at a lower price if the market demands them. As noted, this is important given that most SHS buyers have high personal discount rates that put a premium on initial performance rather than longevity. The long-term trend toward lower module prices also reduces the expected

[39] This is true to the degree that companies pay the costs associated with the quality assurance strategies through investments or taxes. It is also possible that some strategies could be funded using general government revenues or international donor aid.

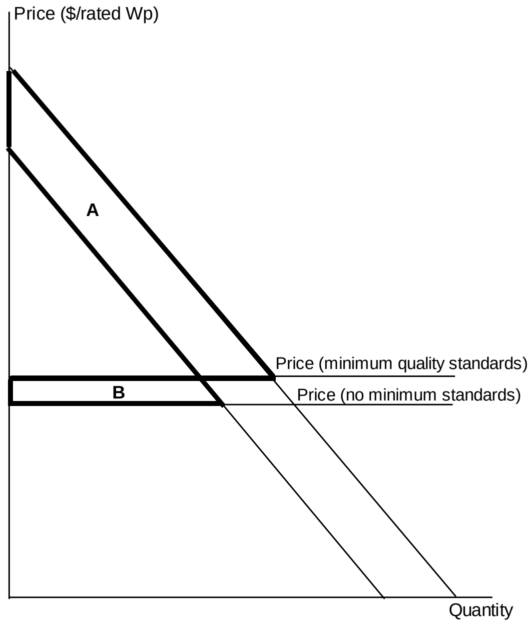

Fig. 4. Welfare Analysis of Minimum Quality Standards. To simplify presentation, this figure assumes constant returns to scale so that the long-run marginal cost (i.e. supply) is flat and equal to the market-clearing price. Minimum quality standards should shift demand outward to the extent that they resolve the PV module quality market failure, generating a partial equilibrium gain in consumer welfare labeled A. Standards would tend to push the long-run marginal cost upward (e.g. standards may force companies to reject a higher share of modules for sub-standard performance), causing a partial equilibrium drop in welfare equal to the area labeled B. Manufacturing upgrades necessary to comply with quality standards could push the long-run marginal cost up or down depending on the cost efficiency of the required process investments. In any case, welfare increases if $A > B$.

cost of replacing future module failures or augmenting the performance of a faltering module by adding another panel. In this context, SHS customers may well benefit by trading some long-term performance for a lower initial price. The IEC certification process, for example, may require modules to meet a longevity standard that is too rigorous for developing country markets. An obvious example of a test that is not always applicable to tropical developing country markets is the humidity freeze test. One might also question whether the normal operating cell temperature (NOCT) test is necessary since NOCT is unlikely to vary significantly across different module brands within the same PV technology (though it will be affected by module color as well as thermal properties and thickness of the sub and superstrates).

In contrast to international certification, the voluntary domestic the simple performance rating system described in Section 5.3 "Performance Testing and Disclosure" matches local conditions and preferences well. Providing an estimate of module output after 6 months does not give consumers as much information about long-term module performance as IEC certification (e.g. this performance rating system does not include twist or hail tests that indicate resistance to breakage). Nonetheless, the performance rating system gives capital-constrained buyers good information about the single metric that matters most to them—the amount of power they are likely to get from their module during the first few years after purchase. If enough consumers get this message and believe the results, it should drive convergence towards the same price per *delivered* Wp across different brands. To the extent that consumers lack information about module resistance to breakage or long-term degradation, differences in the life-cycle price of delivered power will remain. It may, however, prove possible to address these long-term performance concerns using the voluntary warranty strengthening mechanisms outlined above.[40]

While offering substantial potential benefits at low cost and risk, voluntary approaches like performance testing and warranty strengthening may fail to provide rural consumers with sufficient protection against inferior quality PV modules. It is, for example, unlikely that low quality producers will make it substantially easier for buyers to exercise their warranty rights. Moreover, it is not clear that any performance testing scheme would be sufficiently successful in getting information about relative module quality to the rural PV market.

These concerns argue for considering the stronger medicine of minimum quality regulations based on some combination of domestic and international certification standards and programs. International organizations such as the World Bank may also be able to substantially improve quality by imposing standards as a condition of participating in their SHS programs; however, as noted, government action may prove necessary for countries like Kenya where free market sales dominate.

That said, the associated risks argue for a cautious approach regardless of whether national governments or international organizations are imposing minimum standards. It might, for example, prove useful to first address the problem through local performance testing and strengthened warranties, proceeding to minimum quality standards only if module prices per *delivered* Wp fail to converge. If minimum quality standards are used, the authors recommend a "hybrid" approach that combines the use of international performance standards and programs) with a simple and inexpensive

[40] It is also worth noting that Jacobson et al. (2000) found substantial correlation between high near-term performance in terms of delivered Wp and other long-term performance factors such as susceptibility to water intrusion of breakage. This suggests that a simple output based performance metric may be a reasonably good indicator of broader module quality.

domestic testing regime. A program for photovoltaic modules could work as follows:

(1) PV panel brands that are IEC, PowerMark, or PVGAP certified receive a "Grade A" label exempting them from any domestic testing.
(2) PV panel brands that are not IEC or PVGAP certified can apply to be tested domestically by an appropriate agency (e.g. the KBS in Kenya). Modules that pass this domestic test receive a "Grade B" approved label.
   - The domestic testing regime should be simple and inexpensive (e.g. the approach outlined in the "Performance Testing and Disclosure" section and described in Jacobson et al., 2000).
   - The modules to be tested under the domestic program should be selected at random from vendors in the domestic market. A sample size of approximately 10 modules should give reasonable levels of accuracy. The applicant company should cover the cost of the testing.
   - No module in the sample should perform at below 90% of its rated power level. If a module does perform at below 90% of rated, the manufacturer/importer has two options:
     (i) De-rate the modules to the average output from the sample of 10 and sell them at this lower power rating, or
     (ii) Secure IEC or PVGAP certification through an international testing program.
(3) PV panels that do not have either a "Grade A" or a "Grade B" label cannot be sold domestically.
(4) Applicant companies should renew the label status of their panels every 3 years.
(5) To ensure the integrity of the process:
   - Manufacturers whose panels perform poorly should be able to "contest" the domestic test by paying to have a random sample of their modules' power output tested by an internationally certified and neutral testing lab such as NREL in the USA;
   - Manufacturers can also pay to "contest" the results of tests on competing brands (i.e. if Brand X passes the test, but the manufacturer or importer of Brand Y thinks that the modules perform below the level of the test results, then they can contest the outcome by paying for the cost of international testing).

This hybrid testing regime has several benefits. First, companies that have already received international certification will bypass the domestic testing entirely and receive a "Grade A" label. This prevents duplication of testing efforts, reduces bureaucratic hassles, and rewards those manufacturers who have undergone the stricter and more comprehensive international testing regime. Second, small companies that cannot afford IEC, PowerMark, or PVGAP testing will still have access to the domestic market, provided that they are able to pass the domestic testing regime. This domestic testing regime will only result in minor costs to the applicant companies, with correspondingly small panel price increases. At the same time, low performing panels will be excluded or de-rated. This protects domestic consumers without increasing the price of products significantly, and without limiting their options to buy high quality goods from small manufacturers or to purchase lower quality goods (e.g. more prone to breakage) at a discounted price. Finally, the provision for contesting results serves to protect companies from the possibility of an inaccurate test by giving them an institutionalized mechanism to appeal for an outside test.

6.1. Quality measures for balance of systems equipment and installations

In addition to modules, the quality of balance of systems components (e.g. batteries) and installations (e.g. system design and installer quality) has a major impact on SHS performance. Non-module costs already represent more half of life-cycle costs (Banks, 1998) and their relative importance is likely to increase. In particular, module prices are likely to trend downward more quickly than prices for relatively mature system components such as lead-acid batteries (Duke and Kammen, 1999).

Any international organization or national government using PVGAP as the basis for their module standard should take care in extending the rule's scope. As noted, PVGAP has begun to issue standards for the full range of balance of system components as well as system designs. The guiding principles for deciding whether to adopt PVGAP minimum standards for additional components should be the same as those outlined above for the case of modules.

As an alternative, some combination of voluntary warranty strengthening and domestic performance testing with disclosure might, for example, prove most useful for SHS lights since they are often domestically produced by small companies that could ill afford investing in international certification.

Batteries represent a uniquely important and difficult case. Banks (1998) suggests that batteries represent about one-third of life-cycle system cost for a well-designed 50 Wp SHS. For the 12 Wp a-Si SHS found in Kenya, battery costs are closer to 70% of life-cycle costs because users want more power than these small systems can provide and thus chronically maintain their batteries in a low state of charge that causes premature failure. To the extent that consumers have difficulty assessing the quality of batteries, this suggests the potential for a significant market failure.

The shorter expected life cycle and transparent failure mode of batteries make it easier for consumers to assess battery quality. There is, however, still room for confusion since customers cause a large but uncertain share of battery failure by excessively discharging their systems. This also makes warranties problematic as the possibility of a free replacement may encourage users to abuse their batteries (i.e. the perverse incentive problem that economists call moral hazard). The possibility of substandard PV modules or battery charging stations further complicates the situation. Overall, this suggests a need to provide consumers with improved battery quality information.

Assessing battery quality is, however, inherently complex, time consuming, and expensive. Accurately testing the remaining storage capacity of a battery requires a full recharge followed by a load test. This is difficult to do in the field. Lab testing of new batteries is an alternative, but it requires expensive cycling (e.g. hundreds of full charges and discharges) that does not accurately replicate field usage patterns, though it can give important information for comparing the relative quality of brands (Duke et al., 2000).

Despite the associated complexity and cost, a mandatory performance labeling program based on lab testing could provide consumers with the knowledge they need to make informed purchasing decisions. The label might provide basic information about battery performance, such as the number of cycles the battery endures under a standardized set of laboratory conditions before its capacity drops to a predetermined fraction of its original capacity (this is sometimes referred to as the "useful lifetime" of the battery). Although this number will not necessarily tell consumers how long the battery will last for their particular application (since the lab test conditions are unlikely to be the same as their usage patterns), it can give important and easily understandable information for comparing battery brands. A performance labeling program will allow lower performing batteries to remain in the market, but it should force them to sell batteries at a price that is proportional to the quality of the battery for deep cycle applications.

For this program to work, however, performance labels should be mandatory for all solar-type batteries in the market. Otherwise, low performing brands are unlikely to participate, and consumer information would be reduced considerably. Of course, such a labeling program would face some of the difficulties associated with trust and public awareness that a solar panel labeling program would face (see Section 4 on "Certification and Labeling", above). However, the fact that a single number can capture relative battery quality for solar applications (i.e. the number of cycles in the battery's "useful lifetime") makes this task somewhat easier than in case of solar modules.

The testing and labeling could be carried out at a national (e.g. by the Kenya Bureau of Standards) or international level (e.g. through a PVGAP program). However, international testing may tend to favor large-scale international manufacturers for which the associated cost would impose less of a burden. Local manufacturers play an important role in some domestic markets, including Kenya. This highlights the need to keep the price of testing low, either by offering lower cost domestic testing or by keeping the cost of international testing within reasonable bounds.

Regarding system design, the potential for successful corrective action to address quality concerns in free markets for SHS is relatively limited. Certifying installers and/or their SHS designs according to PVGAP standards might give high-quality SHS businesses a modest edge in the market; however, as with modules, customers will have difficulty evaluating the significance of PVGAP certification. International organizations could insist on PVGAP certification for any installers working in SHS programs that they sponsor, and use system designs certified by PVGAP. This might prove useful, though sponsored SHS programs generally have other mechanisms for ensuring quality installations, and it would do nothing to address installation quality in free markets for SHSs.

6.2. Fee-for-service as a quality measure

The fee-for-service business model described in Section 5.6 squarely transfers responsibility for on-going maintenance to the solar utility. This approach is complex, however, and generally requires large subsidies that may not be available or sustainable.

In addition to addressing component quality concerns, this model allows large corporate solar utilities to purchase equipment in volume and use low-cost finance to spread customer costs over the lifetime of the equipment. It may also promote innovation since solar utilities are large enough to have substantial negotiating power with suppliers as well as the capacity to directly undertake targeted research and development. Moreover, solar utilities succeed or fail largely based on their ability to contain costs through technological and managerial innovation.

It is possible for a solar utility to emerge largely without government facilitation, as in the case of Soluz, operating in the Dominican Republic and Honduras. If a private company were to successfully launch a competitive unsubsidized fee-for-service model in Kenya there would be no cause for concern since it would simply provide customers with another option. The unsubsidized route has, however, proven arduous because capital is hard to access and margins are tight. Soluz needed years of ground work and investment in the Dominican Republic just to reach the point where revenues from roughly 2000 fee-for-service households and direct system sales covered direct operations costs (Martinot et al., 2000). Achieving a large impact on the relatively poor and dispersed Kenyan market would therefore be hard without substantial subsidies that would be difficult to obtain and sustain.[41] Moreover, a heavily subsidized fee-for-service effort could substantially displace existing PV markets. This would be acceptable as long as the fee-for-service approach remained viable over time, but there is a risk that subsidies would be withdrawn prematurely, leaving the sales market damaged with no clear alternative in place.

7. Conclusion

The quality information failure documented in the Kenyan market for SHSs is a small problem when measured by international standards of megawatts or money. The issue is, however, of fundamental importance to the tens of thousands of rural families that have had the misfortune to purchase a severely under-performing module. Relative to prevailing income levels in these markets this financial loss is similar to that suffered by a family in the United States that buys a car only to have the engine explode.[42]

Moreover, this problem is not limited to PV module sales in Kenya, but rather it potentially affects all the countries with active private markets for SHSs, and includes the full range of balance of system components. To the extent that there are serious quality information market failures in other countries, and for other components, broader remedies may prove necessary (e.g. encouraging all developing nations to adopt an international quality assurance program such as PVGAP).

Care must be taken at each step, however, to consider the particular risks and potential benefits of the available corrective options for each case. Establishing additional domestic performance testing and disclosure regimes and/or expanding their scope to cover balance of system technologies should generally be a low risk remedy; however, it may also fail to substantially address the problem if consumers remain confused about the relative quality of the options before them.

International certification regimes such as PVGAP or PowerMark would provide a substantially more rigorous (and costly) approach. These certification programs may prove especially helpful for donor aid and government projects—and should give private investors in SHS markets more confidence when selecting technologies. They are, however, unlikely to have a major impact on private markets like the one for SHS in Kenya in the absence of massive public awareness campaigns.

In contrast, mandatory minimum standards have the potential to solve quality market failures across a range of technologies and countries. This strategy does, however, involve significant risks of subversion by political lobbyists and bureaucrats. Moreover, the barriers to entry associated with testing may drive smaller players out of the market. Policy makers must therefore balance sometimes competing goals when determining whether and how to impose standards. For this reason, the authors recommend that if minimum quality standards are to be used, they should be based on a hybrid domestic and international approach (see section 6, Discussion—Building Sustainable Clean Energy Markets) that balances issues of quality, cost, economic development and consumer choice. Similarly, when deciding whether to promote alternative business models one must consider the risks of disrupting commercial markets, and the opportunity cost of any associated investment of public funds.

Despite such complexities, quality information market failure deserves serious attention in order to protect rural SHS purchasers and thereby encourage potential PV technology adopters. There are broader international implications as well. Duke and Kammen (in press) estimates that SHS sales accounted for roughly 10% of global PV sales in 1999. The total market for a-Si modules in SHSs is a small fraction of this, and most of the a-Si modules sold are of reasonably high quality. Nonetheless, anytime a customer suffers a bad experience with a substandard module, or other system component, it damages the overall reputation of SHS. The potential market for SHSs might be considerably higher if international equipment quality market failures were solved. This, in turn, would aid global market transformation efforts by reducing international PV module prices (Duke and Kammen, 1999).

The Kenyan case has special relevance in the current climate of strong multinational interest in private-sector led development based on clean energy technologies. Analysis of emerging markets like Kenya is critical to develop new understandings of the strengths and weaknesses of market based approaches to environmentally sustainable development. The driving issue in much of this work is that clean energy markets are still ‘unprofessionalized’ in that many key players are part timers, and customers are operating with a huge

[41] South Africa with its relatively prosperous rural populations (largely due to substantial government pensions for the elderly and remittances from relatives) has opted for a heavily subsidized approach in order to allow fee-for-service companies to achieve penetration rates in excess of 50%.

[42] The ratio of US to Kenyan per capita GDP was about 93 : 1 in 1995 (World Resources Institute, 1998) and the current price of a small SHS in Kenya is about $110, yielding a relative income scaled value of about $10,000.

information deficit. This is to be expected in the informal economic situation in rural areas of developing nations (WBG, 1998/1999). This manuscript explores strategies for catalyzing private provision of clean energy services using minimalist regulatory oversight and information provision. This goes beyond the 1990s idea of "public-private partnerships" to provide a new model for facilitated free market dissemination of economically beneficial and environmentally favored technologies.

Acknowledgements

The authors would like to thank an anonymous reviewer, Steve Chalmers, Claas Helmke, Eric Johnson, Shannon Graham, Bob Hammond, Liang Ji, Metod Jurisic, Chris Soper, Jim Fanning, the National Renewable Energy Laboratory (NREL), Tim Townsend, Frank van der Vleuten, Peter Varadi, and Dana Younger for generous assistance. Additionally the authors acknowledge Mark Hankins and the entire staff at Energy Alternatives Africa, Ltd. in Nairobi, Kenya for their efforts and insights over the past three years of collaborative work. This work was supported by a Link Energy Fellowship (to A.J.), a STAR Fellowship from the US Environmental Protection Agency (to R.D.D.), and a grant from the Energy Foundation.

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