

Field Performance of Amorphous Silicon (a-Si) Laminate Photovoltaic Installations at SMUD and other Large Scale Deployments

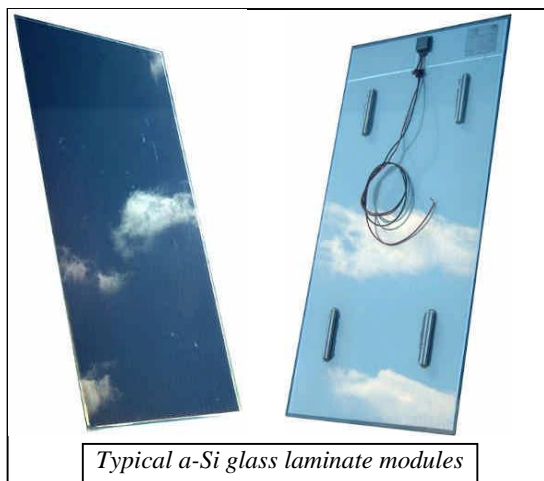
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November 2008

I.) Abstract/Introduction

In 2002 this author presented the first comprehensive report on the long-term field performance of amorphous silicon (a-Si) glass laminate thin-film PV modules based on large scale system deployments^{1,2}. The original report reflected on the extensive installation experiences at the Sacramento Municipal Utility District (SMUD) with the SMUD Solar Program, which at the time had the world's only large base of experience with fielded a-Si laminate modules. While thin-film PV modules today account for a small but rapidly growing share of the cumulative global module market, they account for about 20% of the SMUD PV fleet (3 MW out of a current 14 MW) with over 14 years of field experience. Worldwide, the total 43.8 MW of thin film production in 2002 has dramatically increased to 1000 MW in 2008³. Today, a-Si laminate module systems are deployed worldwide and make up a growing segment of the PV market. In Europe multi-MW systems are deployed and project development announcements in the US and Canada forecast substantial a-Si system installations (largely utility scale) in the coming years. Coupled with increasing interest in the deployment of utility scale a-Si systems is a necessity to demonstrate long-term performance, reliability, and durability data for long-fielded systems. This report serves to update the original in evaluating performance and juxtapose SMUD a-Si system performance data from long-fielded systems to that of other third-party research reports and system performance data to provide answers to any lingering questions or remaining misconceptions regarding the performance of a-Si glass laminate thin film PV modules.



SMUD's APS a-Si System, installed 1994



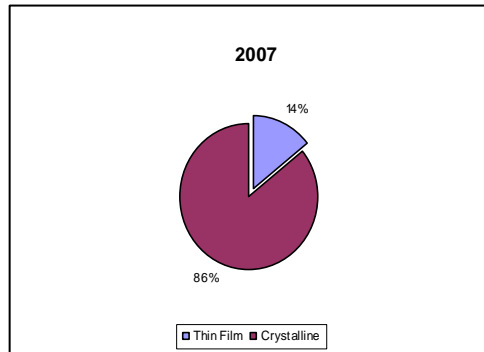
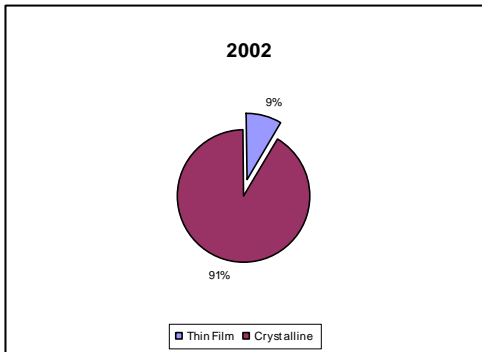
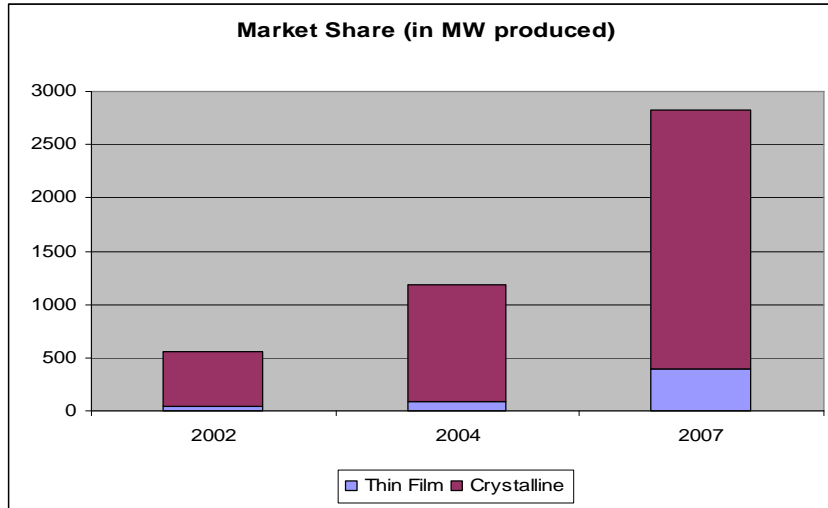
Typical a-Si glass laminate modules

Data collected from SMUD's extensive a-Si field experiences is presented throughout this report alongside third party studies demonstrating that a-Si laminates:

- Exhibit excellent durability once installed with low module cracking, breakage or failure rates.
- Offer excellent long-term stability and performance with a 30+ year useful life.
- Consistently demonstrate annual degradation rates of much less than 1% (typically 0.25% to 0.50% per year).
- Provide long-term stability substantially exceeding the typical 90% 10-year and 80% 20-25 year power warranty (comparable to c-Si and pc-Si modules).
- Offer significantly enhanced summer performance leading to increased kWh production for each kW installed compared to c-Si or pc-Si modules (more kWh/kW).

II.) Thin Film PV Technology

The advantages of thin film PV over the more established crystalline PV technologies have become more pronounced in the industry's recent unprecedented growth period. Typically requiring less than 1% of the semiconductor material consumed in crystalline products, thin films are produced by techniques more amiable to mass production in a manufacturing process that consumes substantially less energy. Lower manufacturing costs (compared to crystalline (c-PV) or polycrystalline (pc-Si) PV products) and therefore lower installation costs have



led to increased market penetration by thin films.

In 2008, thin-film production is expected to exceed 1000 MW. The Prometheus Institute³ expects thin-film production to reach 10 GW in 2012 with some 166 companies producing or gearing up to produce thin-film modules. Of the current thin-film producers, only about 8 currently have 25 MW or more of production capacity with Sharp Solar accounting for 416 MW of the estimated 1,000 MW of a-Si production capacity in 2008. Most thin-film producers focus on a-Si glass laminates because the technology has the “lowest barriers to entry”, glass provides an ideal deposition and encapsulation material, and potential producers are able to purchase turn-key a-Si manufacturing lines from manufacturing systems suppliers such as EPV, Amelio Solar, Applied Materials and Oerlikon. Half of the thin-film production in 2010 is expected to be a-Si.

After SMUD successfully demonstrated large a-Si laminate system deployments from 1994 through 2002 along with performance and cost benefit analyses, large a-Si laminate PV system deployments became more prevalent in the feed-in-tariff PV markets of Europe. Some examples of utility-scale fielded systems in Europe include:

2004	112 kW	Germany	EPV
2005	1.5 MW	Germany	Kaneka
2006	1.7 MW	Germany	Kanek
2007	5.5 MW	Portugal	EPV
2007	2.3 MW	Germany	Kaneka
2005 – 2008	1.8 MW	Germany	Kaneka
2008	2.0 MW	Germany	EPV

Such deployments continue to accelerate. In late 2008 Sharp and Enel SpA (Italy's largest utility) announced a joint venture that will operate as an independent power producer and develop a number of PV systems in Italy with a total capacity of 189 MW by the end of 2012. Part of the deal will involve thin film module manufacturing in Italy. Earlier in 2008 EPV Solar announced a 5 year 250 MW supply agreement for PV power projects in Germany. In the factory deployment sector, Applied Materials announced roughly \$2 Billion of a-Si laminate module factory sales by late 2008. Oerlikon and Amelio Solar have also announced a-Si module production factory sales in Asia, Europe and the Middle East. These announcements coupled with the fact that industry mainstays such as Kaneka and Sharp continue to substantially increase a-Si production capacity points to more growth of a-Si laminate systems, and thus increased need to properly evaluate and predict the long-term performance of those systems.

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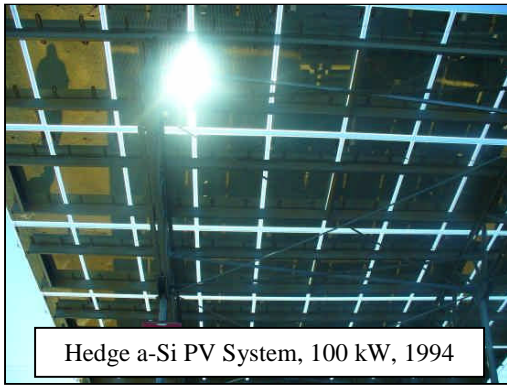
a-Si and other thin film modules will be more economical and efficient with additional research and development. Fundamentally, the prices of the more mature technologies of c-Si and pc-Si are limited by raw material costs, namely high purity silicon, and increased efficiency and decreased prices will happen at a slower rate since these technologies are more mature (40 years old compared to 25) and have already reduced manufacturing costs wherever possible.

III.) The SMUD Program and Thin Film Experience

SMUD, the first utility to commercialize grid-connected PV, has the most extensive field experience with the widest variety of photovoltaic (PV) systems in the world^{4,5}. Since the mid-1980s, SMUD has installed some 14,000 kW of PV in roughly 1,000 systems. By 2002, the utility had installed over half of all the grid-connected PV in the US, setting the stage for the subsequent explosive growth in which the US solar industry gained mainstream attention. From 1994 to 2002, the SMUD Solar Program installed the country's largest concentration of a-Si thin film laminate PV systems, with over 2,000 kW in a-Si systems (system sizes ranging from 2 kW to 700 kW) in a wide variety of applications. Concurrently SMUD installed about 6,000 kW traditional single-crystal silicon (c-SI) and polycrystalline silicon (pc-Si) PV.

The experience gained from this vast array of projects guided the SMUD team of system designers to conclude that the lower price of a-Si modules (while lower in efficiency compared c-Si and pc-Si) often resulted in dramatic turnkey system savings despite increased area-related installation costs. Hence, when area constraints are not a significant factor, a-Si modules provide cost-effective PV solutions in a wide variety of applications. The early cost benefit analysis by SMUD has since been realized by others leading to subsequent increases in a-Si usage for utility

scale project development in Europe and elsewhere.



Hedge a-Si PV System, 100 kW, 1994

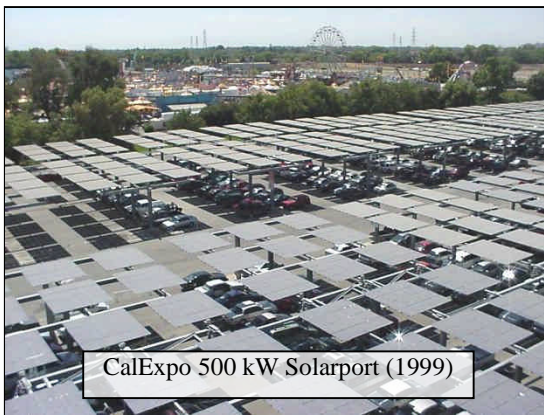
In 1994 SMUD first took the lead with a-Si technology by installing a 100kW system at the SMUD Hedge Substation site with Advanced Photovoltaic Systems (APS) modules. APS was chosen for their lowest bid for a turnkey PV power plant and the system design mirrored a system SMUD had partnered in 2 years earlier at PVUSA in nearby Davis, CA. Space was not a factor due to the availability of utility owned land at the site which also came to host four other “utility scale” power systems..

The primary a-Si module brands deployed by SMUD starting in 1994 were the APS 50, followed by the Solarex/BP Solar MST 43 and the Energy Photovoltaics (“EPV”) 40 modules. The EPV modules were supplied by either EPV’s manufacturing facility

in New Jersey, or by technology EPV partners DunaSolar (Hungary), and TerraSolar USA (now being supplied by Amelio Solar.

The APS, EPV, DunaSolar, and TerraSolar modules belong to a class of a-Si, laminate modules also known as the Kiss a-Si Platform (KaSiP) modules. KaSiP modules are based on the same processing technology and manufacturing equipment and the group also includes more recent suppliers Amelio Solar (USA), Great Tone (China), Solar Thin Films (Hungary), and others. Other large suppliers and installers of a-Si laminate module manufacturing lines include Applied Materials and Oerlikon. Kaneka, Schott, and Sharp, also manufacture increasing quantities of a-Si modules. First Solar, a well-known supplier of CdTe thin-film PV laminate modules, produce modules with a very similar mechanical construction to KaSiP ones.

Table 1, presents a listing of the many SMUD a-Si PV systems installed from 1994 through 2002. These thin film modules were successfully used in various applications including utility power station/substation ground mounted PV systems, SolarPorts, commercial and public building roof top PV systems, residential roof top PV systems, on top of barns, as a bleacher shade structure at a public pool, and for parking lot lighting.



CalExpo 500 kW Solarport (1999)

In 1999, SMUD installed what was for several years, the world’s largest “Solarport” at CalExpo (the site of the CA State Fair) with half of the 500 kW array being KaSiP laminate modules. This was followed in 2001 with 390 kW of KaSiP modules on the horse barns at CalExpo. As a result of the success of the early CalExpo systems with SMUD, the California Construction Authority (CCA), responsible for all construction at State Fair site across the state, chose to install 2727 kW of a-Si laminate PV systems at 11 State Fair sites between 1999 and 2007 plus another 1481 kW of CdTe laminate systems at another 6 sites.

SMUD also gained international recognition for its PV Pioneer Residential Program, which included 85 thin film (a-Si) modules systems totaling 170 kW from 1999-2002. This

unique and ahead of its time program was originally established as a partnership with customers willing to assist in the early adoption of PV technology. SMUD began the program by purchasing, installing, owning, and operating 2 to 4 kW residential rooftop PV systems on the "borrowed" rooftops of SMUD customers. During the period 1992 to 2005, more than 550 PV systems had been installed on the homes of PV Pioneer customers volunteering to lead Sacramento toward the promise of affordable, clean, renewable solar energy by turning their homes into miniature power plants. The program contributed to lowering the cost of PV electricity as SMUD gained valuable experience in pricing strategy, installation, operation, and maintenance of residential PV systems and the PV industry was able to start the serious development of the grid-connected market infrastructure. According, today SMUD customers can

Table 1: Selected a-Si Thin-film PV Systems in the SMUD System

SMUD THIN FILM SYSTEMS 1994-2002			
Project	Module	kW	Year
Hedge PV2	KaSip (APS)	108	1994
CADA	KaSip (APS)	4	1995
WAPA Folsom	KaSip (APS)	2	1995
Effie Yeaw Nature Center	BP MST	7	1998
Roseville Aquatic Center	KaSip	6	1998
Lodi Solarport	KaSip	3	1998
Citrus Heights United Methodist	BP MST	10	1999
Family Bargin Center	BP MST	12	1999
Folsom Water Education Center	BP MST	6	1999
IBEW	BP MST	4	1999
Orangevale Community Center	KaSip	10	1999
Safetyville	KaSip	1	1999
Save Max	BP MST	16	1999
SPCA	BP MST	16	1999
CalExpo Solarport	KaSip	250	1999
Lamn Furniture Solarport	KaSip	30	1999
East End Solarport #1	KaSip	21	1999
Del Paso Church of God	BP MST	20	2000
First Baptist Church, Watt Ave	BP MST	20	2000
New Testament Baptist Church	BP MST	20	2000
East End BIPV Curtainwall	KaSip	8	2000
CalSolar PV Wall	KaSip	8	2000
Cal EPV Roof	KaSip	30	2001
CalExpo Barns	KaSip	390	2001
CSUS Parking Lot	KaSip	6	2001
Rancho Seco PV5	KaSip	700	2002
East End Solarport #2	KaSip	41	2002
4 East End Screen Curtainwalls	KaSip	110	2002
Arden Fair Mall Solarport	KaSip	30	2002
52 Residential PVPII	KaSip	104	as of 6/02
33 Residential PVPII	MST 43	66	as of 6/02
Total		2059	
KasiP: APS, EPV, DunaSolar, TerraSolar			
BP MST: Solarex/ BP Solar MST a-Si laminate modules			
APS are single junction modules. All other a-Si are duel junction			

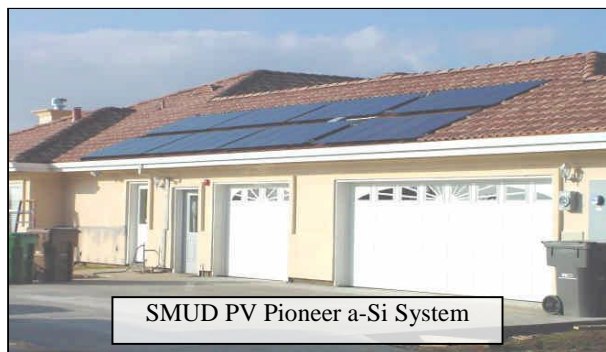
buy their own PV system and use its electricity for themselves through SMUD’s program of rebates under the California Solar Initiative Program.

During the early stages of the SMUD Solar Program (1991 – 2002), SMUD purchased directly the modules, inverters, BOS, and installation services for systems under its PV Program. In evaluating module supply bids, SMUD adjusted the bid price by a factor to account for the area related installation and balance of systems (BOS) costs. SMUD was able to utilized lower efficiency a-Si modules when the price of those modules was lower than the increased area related costs incurred. a-Si modules were installed when the entire price of the turn-key installed system was lower than the entire, turn-key price of higher efficiency PV technologies (i.e. c-Si and pc-Si) systems and the application site was not area constrained.

For rooftop installations with limited area, PV module efficiency can be a major factor in determining the module type. On ground mount systems and rooftops where space is less of a factor, a-Si modules are often ideal depending on cost and the systems size. Large systems installed by SMUD were often installed on SMUD property, over parking lots or on large rooftops with more than sufficient area.

Typically, land area has been less of a consideration factor and ideally PV should be sited on “free land” such as substation or power plant land areas for central station PV in addition to roof tops and parking lot applications.

In terms of current relative efficiencies, an a-Si system requires approximately double the space of typical c-Si or pc-Si to obtain the same nameplate rated power output (kW). This obviously increases the area related portions of the installation cost. Based on SMUD’s extensive field installation experiences, we concluded that the a-Si systems, compared to typical c-Si module



systems, added about \$0.50/W to \$0.80/W in increased area related installation costs for the 5 to 6% efficient a-Si modules that we have typically fielded in simple unistrut roof systems and in non-tracking, ground mounted systems. Therefore, to be cost competitive with c-Si or pc-Si, a-Si module prices must be at least \$0.50/W to \$0.80/W less. The focus of SMUD's evaluation for projects was the fully installed, turn key \$/W price once the basic requirements of reliability and durability were met. Less efficient modules had to be lower enough in price to more than counter the increased area related installation costs incurred.

Numerous SMUD installations demonstrated that in many applications, a-Si modules can be priced low enough compared to c-Si or pc-Si to more than make up for increased installation costs, ultimately providing a better performing and more cost effective system solution. From 1998 to 2002, SMUD purchased a-Si modules of 5 to 6% efficiency at \$1.75 to \$2.50/W and crystalline modules at \$3.25/W (lower than the 2008 prices for PV modules). At the \$2/W price point a-Si modules resulted in a much more cost effective turn-key system, while \$2.50/W for a-Si left the comparison a wash.

IV.) Performance Issues

Generally, the performance of thin film PV modules is one of two key issues of concern voiced in the selection process of PV module technology (the other key issue, durability, is discussed in the following section). The perception of a "stability problem", augmented by early issues of quality control in thin film production, hindered acceptance of a-Si module technology to many in the industry. There are two distinct periods of degrading for a-Si module conversion efficiency: The short term, fairly dramatic efficiency degrading of performance in brand new and unexposed module and then in the longer term gradual degrading of performance. The short-term degradation is irrelevant when modules are properly "nameplate rated" at their "stabilized" or long-term value as is today's standard practice. Of greater importance is the comparison level of long-term performance to that of c-Si and pc-Si products.

In contrast to c-Si or pc-Si modules, a-Si modules are subject to an initial efficiency decline after first light exposure. This process, known as the Stabler-Wronski (SW) effect, is responsible for a decrease of between 18% - 20% (compared to initial output) in performance upon exposure to light. This effect is most pronounced very early on and gradually approaches a "stabilized" value after approximately 3 months or so. In many early, fielded systems, misunderstandings occurred when initial output (pre-stabilized) is represented as or interpreted as a "rated value" of output and performance over time is compared to that initial output value, a mistaken interpretation. The "rated" output value of an a-Si module should always be set at the stabilized value after the SW effect has run its course. The rated DC standard test conditions (STC) value of the module should be equal to the stabilized value after six months of operation in ambient conditions with a daily direct sunlight exposure greater than 500 W/square meter. For any particular module manufacturing process and production operation with good QA/QC procedures in place, the amount of degradation from initial conditions to stabilized condition can be accurately determined from initial flash tests for standard production runs. While uncommon in 2002, it is now the industry standard for the module nameplate rating to be the stabilized value. Sufficient QA/QC procedures must be put in place so that the actual stabilized output value equals or exceeds the rated (nameplate) value.

Extensive early field experience at SMUD^{1,2} confirmed that after 3 months, a-Si modules perform very close to the stabilized (rated) value. After 6 months the modules operate at the stabilized value. Differences thereafter are attributed to either the long-term degradation of the module performance (less than 0.5% per year, typically about 0.25% per year) or to the seasonal reannealing process that results in the sinusoidal season-to-season fluctuation of module performance for a-Si modules. This seasonal variation (shown in the 2001 EPV 1,400 day test curves in Figure 1 below) can easily be 5 to 10% and tends to swamp out the ability to see the much smaller longer-term effects. The EPV 40 is a typical dual-junction, a-Si, glass on glass module with a 40 watt STC rating. Fig. 1⁶ depicts 4 randomly selected EPV 40 modules with over 1,000 days of exposure tested at the Arizona State University PV Test Laboratory (ASU-PTL). While the initial Pmax is in the 47 to 49 watt range, the range of "stabilized" Pmax is 36.5 to 41 watts for the "40-watt" rated modules. Note that each module shows a seasonal variation of 3 to 4 watts and that the start dates for the modules do not coincide. At the time these modules were supplied (circa 1997), a +/- 10% on nameplate rating to actual, stabilized Pmax was common throughout the module industry (for all module types not just thin film) and was more often than not at the lower end of that range. Today, with improved QA/QC,

module ratings are far more reflective of actual module performance.

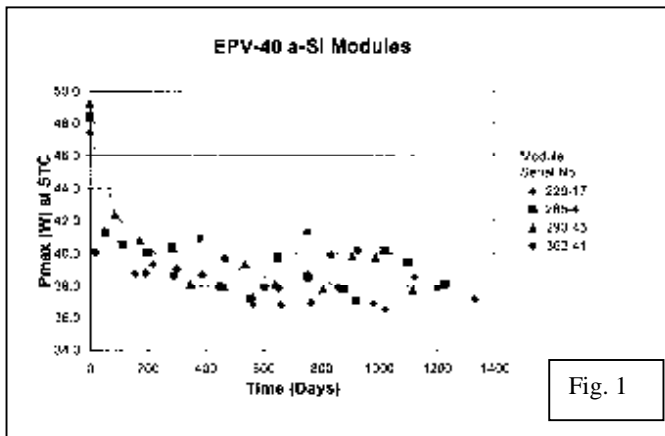


Fig. 1

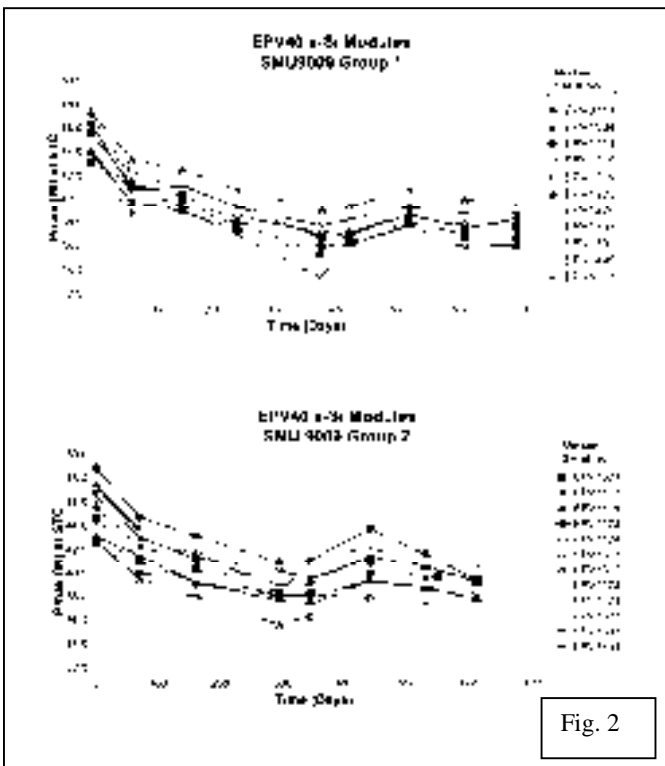


Fig. 2

Figure 2⁶ depicts a larger sample of EPV 40 modules with 600 to 700 days of exposure. The start dates in Figure 2 do coincide and more clearly show the seasonal variation. Again, with modules of about the same vintage, the modules exhibited stabilized Pmax values of 36 to 41 W for the 40-watt rated modules. When accounting for seasonal variation, the average summer Pmax for the modules ranged from 38 to 41 W, the average winter Pmax for the modules ranged from 36 to 40 W, with an annual average Pmax of approximately 38 to 39 W representing about 2.5% to 5% lower stabilized peak power from the rated value. The data suggests that the proper rated value for these modules would have been a bit less than the 40 W rated value. From experience with longer cumulative exposure times at SMUD, it is expected that this peak power value will hold fairly constant for several decades with well less than 1% per year average degradation superimposed on those values (on the order of about 0.5% to 0.25%), well within the typical 20-year/80% power warranties. Again, this is about the same as with other module technologies.

The long-term peak power degradation is typically composed of three factors which can be clearly seen on the following idealized curve in Fig. 3¹ (after Delahoy⁷):

1.) The first is the degradation to the “stabilized” value (curve A). Seen in the first few months and known as the Staebler-Wronski effect, most of the decline takes place in the first few weeks and asymptotically approaches a “stabilized” Pmax value ideally equal to or greater than the module rated Pmax (nameplate) value. In this case, the 40 W rated module has an initial Pmax of 47.7 W stabilizing in the first few months to the rated value of 40 W.

2.) Then a seasonal variation of some 5% to 10% is seen with the Pmax cycling around the stabilized Pmax value (sine curve C).

10% is seen with the Pmax cycling around the stabilized Pmax value (sine curve C).

3.) Superimposed upon this seasonal cycle is a gradual long-term degradation, typically of some 0.25% to 0.5% for the Note that modules have the same starting date for day 0

This combination of three degradation mechanisms was identified by the author when at the University of Arizona Solar and Energy Research Facility⁸ in the mid-1980s has since been confirmed frequently by others.

Since the long-term degradation factor is considerably less than the cyclic seasonal variation, its value is can be easily masked. Early studies suggested that the long-term degradation of c-Si or pc-Si and a-Si were fairly comparable, quoting a long-term annual degradation value of 1 to 2%. This value is difficult to determine because it

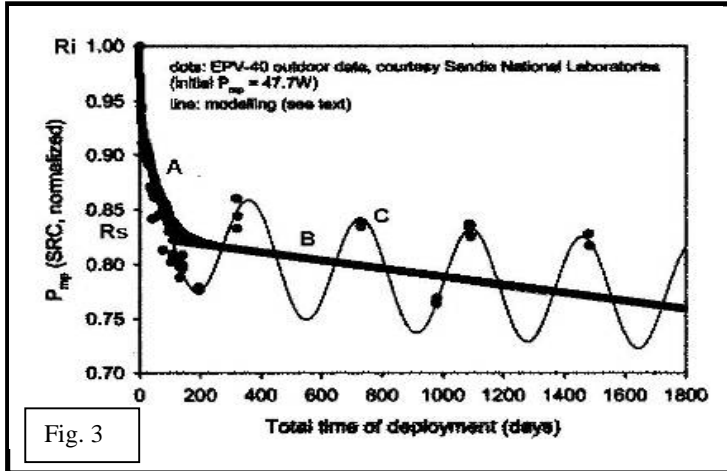


Fig. 3

is often swamped out by the pronounced seasonal effects and other effects and differs radically with some materials used in the manufacture of modules, such as early forms of EVA. Collected data by SMUD suggested much lower degradation values for modules in climates like Sacramento of 0.25 to 0.50% per year. This range of 0.25 to 0.5% has since been confirmed by a number of other studies. Some studies reporting higher values need to be questioned as depending on the season in which measurements are made the seasonal effect is sometimes mistaken for a value for determining the long-term degradation of the module.

Researchers at EPV⁹ pointed out that the actual long term degradation curve appears to be an asymptotic curve rather than the straight line curve assumed in the author's original 2002 report. When plotted on a log scale (figure 4⁹) the curve would then become a straight

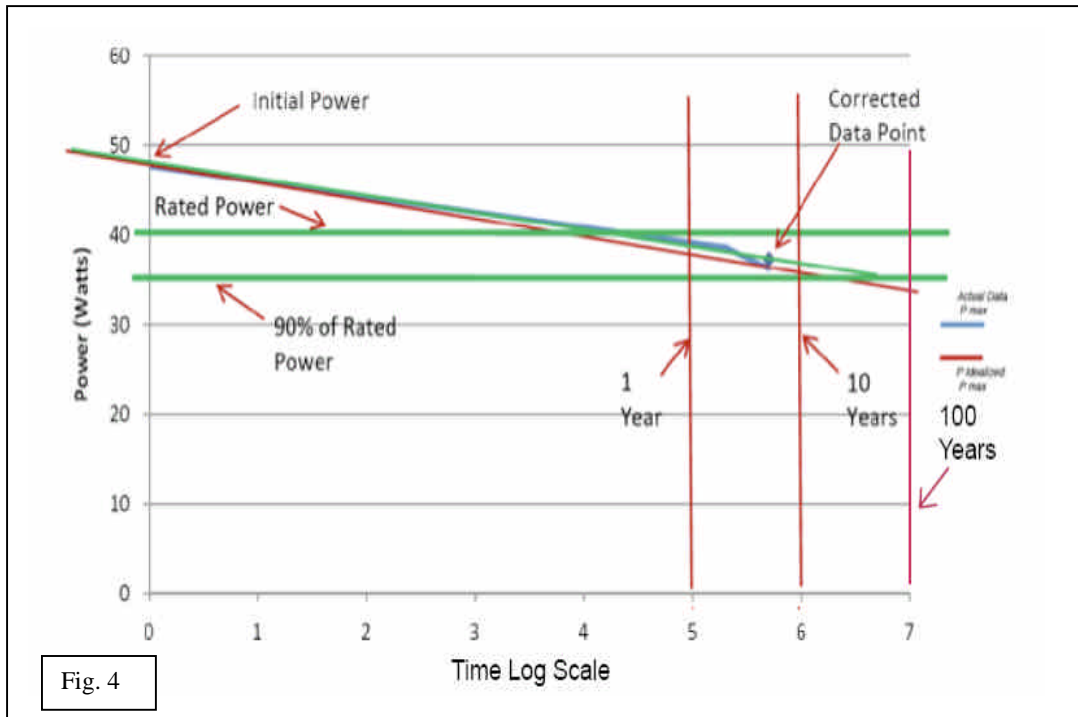


Fig. 4

line. Original data from the 2002 Osborn paper¹, when re-plotted, show less than 10% degradation after 10 years reaching the 10% degradation after approximately 20+ years. This is a less than 0.50% per year average degradation and well within the 90% 10 year, 80% 20 or 25 year module power warranties that are typical. In performance analyses of multi-year c-Si, CdTe, and a-Si PV systems, researchers at the NREL SERF test facility, found similar long term degradation rates for c-Si, a-Si, and CdTe modules¹⁰. In fact, the a-Si system on site showed the lowest rate of long-term degradation.

As previously noted, early SMUD installations accounted for the Staebler-Wronski effect in the initial "system" design, the pricing of module purchases, and for determining module payment. Therefore system cost to the end user was calculated with the "stabilized rated value" after several months of outdoor exposure.

The issue of the seasonal effect on a “stabilized value” had not been resolved prior to putting the SMUD module purchase contracts in place and SMUD ended up - by default- using the more liberal upper part of the seasonal effect range. Today a-Si modules from major suppliers have module nameplate ratings very close to stabilized values and these nameplate ratings can easily be estimated within a couple of percent from the initial performance flash test. From 1994 to 2001 modules were guaranteed to be within +/- 10% of the rated value and, typically, modules – whether crystalline or thin-film -- would fall closer to the -10% side of the range. Today, modules typically test out at or slightly higher than the rated value.

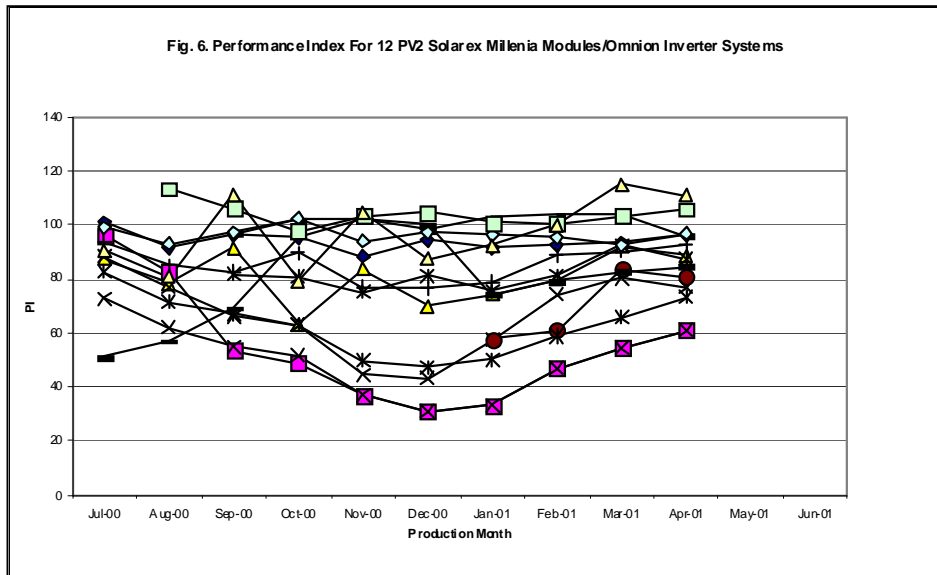
Recent a-Si module performance studies conducted by third party laboratories on modules exposed to several years of field exposure are useful in determining how actual field data compares to module rated values, predicted performance of these modules, and the expected long-term performance. In 2007 the Photovoltaic Test Laboratory at

40 W a-Si Laminate Module S/N	Years in field	ASU- PTL at STC (W)
402-39	3	41.5
299-7	3	43.5
285-7	3	41.8
400-32	3	43.1
304-24	3.4	43.3
330-19	3.4	42.8
297-22	3.4	42.1
328-28	3.4	41.9
302-30	3.4	41.7
402-8	3.4	41.4
402-29	3.4	43.5
402-37	3.4	40.8

Figure: 5 STC Power Ratings of Field Exposed a-Si (EPV) Modules

Arizona State University (ASU-PTL) conducted module rating tests on 14 EPV 40 watt laminate modules (Fig. 5)¹¹ removed from the field after 3 to 4 years of exposure. All the modules tested above the 40 watt nameplate rating with an average of 42.2 watts.

a-Si systems installed by the early SMUD PV Pioneer Program demonstrated quality system performance on a consistent basis. An analysis of the operational data for 36 residential a-Si module PV Pioneer II systems that had been fielded for at least 18 months (as of mid 2001)- with a minimum 12 months of monthly production data beyond the initial 6 months- an average capacity factor of 18% was determined, somewhat higher than the design capacity factor and comparable to capacity factors of similar crystalline systems. In a separate study, 12 more

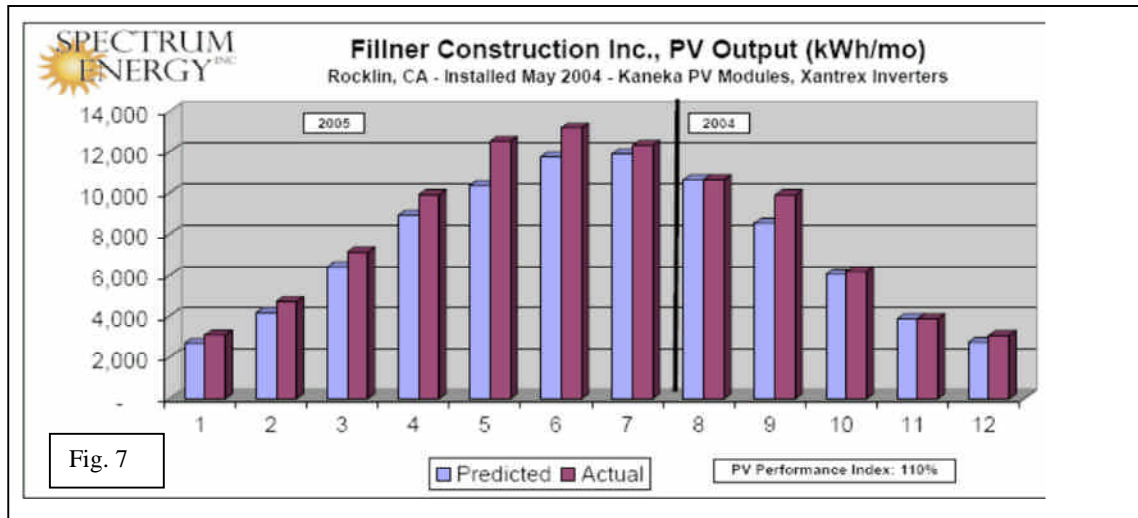


a-Si residential PVPII systems (Figure 6) were analyzed for their Performance Index (ratio of actual performance to expected performance of PI). These systems (Solarex Millennia a-Si Modules and Omnion inverters) demonstrated excellent PIs with a high average PI of 104%, a low average PI of 55% and an overall average PI of 80%. It is noteworthy that service inspections of the lower performing systems determined the causes to be inverter, wiring

and shade related, not module malfunctions. The PIs for a-Si systems were very similar to those of c-Si or pc-Si systems installed by SMUD during the same period.

Commercial size a-Si laminate PV systems also demonstrate excellent field performance. In 2004 Spectrum Energy installed a 58 kW system with Kaneka a-Si modules near Sacramento, California (Fig 7). The system recorded a performance index of 110% for the period of August 2004 through July 2005 (period starting almost 4 months after commissioning and 5 months after initial module exposure).

For a-Si systems, inverters must be selected according to the expectation that newly installed modules have a higher



output that stabilized ones. Nevertheless SMUD's experiences led to the conclusion that over-sizing the inverter to account for this difference (and thus incur additional costs) is unnecessary. Most of the initial degradation is early, short term and predictable. The module itself is not producing peak output during most of the year or most of the day for that matter. When short term module production does exceed inverter DC input limits, most inverters simply cut off at the limit thus losing some of the excess energy produced.

V.) Durability Issues

Today PV modules are expected to operate in harsh outdoor environments with minimal maintenance environments for up to 30 years. Fortunately, most major brands of modern PV modules (thin film or crystalline) are up to task. In terms of reliability and durability, data from SMUD installations demonstrate that a-Si modules perform well. The SMUD experience shows that fielded a-Si unframed, glass laminate modules demonstrates reliability and durability directly comparable to that of c-Si and pc-Si modules with one major exception: when unframed, glass laminate modules have been mishandled during the installation process durability can be compromised.

The primary area for concern in module QA/QC in the SMUD experience was the prevention of "edge chips" that provide a crack propagation point. It is vital that unframed laminate edges be finished properly in the factory to reduce the size and number of any small edge chips. For example, EPV 40 watt panels utilize untempered glass and require round-sanded edges to minimize edge chip occurrence. Afterwards modules must be handled with reasonable care to prevent new edge damage. The main defect leading to glass-on-glass a-Si laminate module failure in the field is edge chips propagating into glass cracks that may become continuously larger, often appearing months after installation and resulting in an expensive replacement "call-back."

Care must be taken to handle the panels properly to avoid impact and stress related cracks when unframed glass-on-glass laminates are handled, transported, and installed. These cracks, which may appear weeks or months after installation, are usually due to edge chips or small edge cracks that propagate as a result of thermal or structural stress. At SMUD, the cracks were often traced to mishandling in uncrating: setting a module on its corner or knocking an edge accidentally while taking the modules out of the box for example. The over-stressing of the

module during installation from excessive torque on the mounting bolts, the lack of stress relief washers (rubber or nylon washers on mounting bolts), or unaligned mounting rails may also result in significant bending and therefore be detrimental. Once the issue was isolated, SMUD found that modest training for handlers and installers quickly reduced an initial failure/rejection rate of nearly 15% to a small fraction of 1%, a failure rate directly comparable to that seen by SMUD with c-Si and pc-Si modules.

Essential training points for all handlers and installers working with unframed glass laminates include:

- Never rest the module on the edge of a surface (such as the edge of the shipping box) when handling the modules,
- NEVER rest the module on its corner,
- Take care not to bump or knock module edges,
- Be sure that modules are shipped in containers designed to protect the modules in shipment and to facilitate the easy removal of modules in a way that does not require handlers to shift hand positions when lifting the modules out (this will avoid the temptation to rest a module on the edge of the container).

The majority of a-Si modules fielded by SMUD were unframed laminates, shipped without the frames that theoretically provide a module damage-protection in poor handling. In general we observed that frames are valuable until the PV system installation is complete; afterward the value is negligible and actually enhances soiling. Thus, as long as proper care and training is provided in the transport, handling, and installation steps, frames turned out to be an additional cost that was not necessary. An exception to this would be framing systems that also provide simplified, lower cost installation on selected roof-types. Obviously, the benefit of the frame in lowering onsite installation costs should be greater than the cost of the frame for a worthwhile trade-off. The Solarex/BP Millennia Module Integra Frame for use on composition shingle roofs was an example of such a trade off. The Integra frame also acted as the wiring chase.

Another issue that was of concern was module edge sealing of the glass laminates. SMUD encountered minimal problems with edge sealing even though this had been an issue with earlier thin film modules. One exception was a module batch produced by a factory undergoing the distraction of change of management and sale, leading to an unfortunate QA/QC lapse. We did observe various minor “worms” and other blemishes that developed with age but we found no performance decrease related to these visible “defects.” While minor worming and other blemishes may not be a problem, excessive worming, often a clear sign of poor QA/QC, may lead to delamination or other processes that result in moisture intrusion into the silicon film layers and therefore premature module failure. Delaminations observed in some pre-2002 modules were traced to poorly applied transparent oxide coatings (TOC)

on the glass as provided by the glass suppliers to the panel manufacturers, a problem that was corrected.

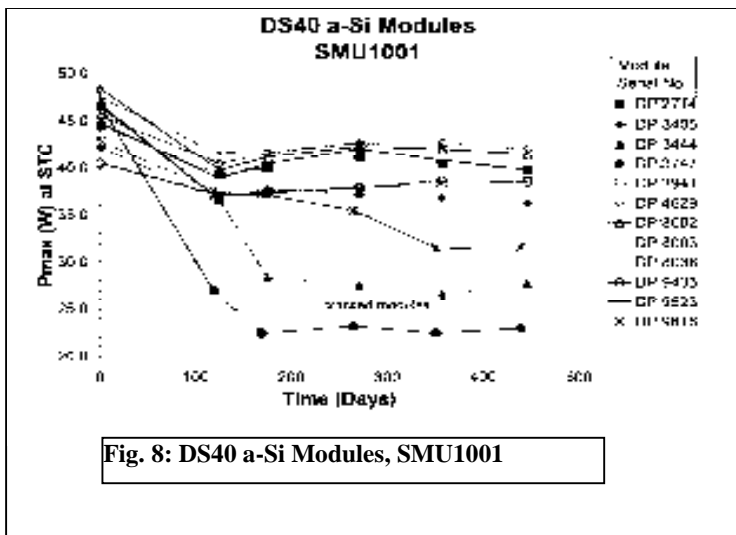


Fig. 8: DS40 a-Si Modules, SMU1001

Nevertheless, unframed glass laminates are more durable and reliable than even experienced installers would expect. In 2001 SMUD shipped 12 DunaSolar (EPV 40 type) modules, modules rejected by SMUD subcontractors (following factory training on what to reject and what to accept) due to edge defects and other rejection criteria, to the ASU-PTL (see Fig. 8⁶). Impressively, all 12 performed well in the initial test quarter with Pmax values ranging from 41 to 48 watts for 40 watt rated modules. In the second testing quarter two modules cracked and failed and one more module developed a crack later and failed in the third quarter round.

9 of the 12 modules recorded durability with Pmax values of 36 to 42 watts for the 40 watt rated modules (all above 90% of rated value) after 450 days, with 8 of 9 at 96% or better of rated value.

The a-Si laminate PV systems installed by SMUD between 1994 and 2002 have an impressively low rate of cracking and module breakage, demonstrating that unframed glass laminate thin film modules are durable and perform well upon installation. These systems had a program of routine service and inspections from 2002 through 2008. Out of 20,275 such modules installed only 68 (0.34%) were reported as cracked during and subsequently serviced by SMUD technicians. This breakage or “failure” rate for a-Si is less than for some SMUD c-Si and pc-Si module systems installed during the same period.

Reported Occurrences of Cracked a-Si laminate modules at SMUD						
As reported by SMUD lead PV tech 9/08			Post installation module cracking from 2002 to 2008			
	Year Installed	kW	# Mods	# cracked, modules	% modules cracked	Notes
APS Hedge Array	1994	100	2500	12	0.48%	
CalExpo Solarport	1999	250	6250	24	0.38%	note 1
East End Garage	666/667	61	1525	0	0.00%	none reported
East end BIPV	2002	110	2750	0	0.00%	none reported
CalEPA roof	2001	30	750	0	0.00%	none reported
Arden Fair Solarport	2002	30	750	2	0.27%	
Residential PVP1	1998-2001	170	4250	30	0.71%	4 or 5 cracked modules/yr
Limn Furniture	1999	60	1500	0	0.00%	none reported
		811	20275	68	0.34%	Ave. over last 6 yrs of inspections

SMUD PV Techs report higher percentages of cracked/broken modules for the Solarex MSX64 polyxtal modules, Solec 60W xtal modules, Atlantis Sunslate xtal modules, and KSI KC120 Xtal modules.

Note 1: Does not include a batch of about 120 modules with a manufacturing defect that failed at the solder joint at the 90 deg bend in the collector wire strip.

In 2002 Spectrum Energy installed at a Sacramento area turkey farm the earliest independent, commercial installation utilizing First Solar modules, the CdTe thin film, glass-on-glass technology. While a higher efficiency thin-film, the First Solar’s CdTe modules are mechanically almost identical to KaSip modules such as EPV. After six years in the field the 52 kW system (1440 modules) recorded a breakage rate virtually equal to that of SMUDs a-Si laminates installed from 1994 to 2002: 0.35% or 5 modules. In this particular system the appearance of the damage on two of the cracked modules, adjacent to each other, suggested physical impact, and only those two modules recorded a performance decrease, while the small edge cracks on the others did not adversely affect performance in the short term. A “jumping goat” is the suspect causing the “physical impact” on the two failed modules.



“Goat damaged” First Solar laminate

It has been demonstrated that when manufacturing QA/QC procedures are followed a-Si module reliability is high regardless of the module manufacturer or type. On the other hand significant problems clearly crop up when QA/QC slips at the manufacturing, packaging or shipping stages. In SMUD’s experience with several different suppliers and different module factories, there were periods when each major a-Si module supplier slacked on QA/QC procedures to the point of allowing production runs with a higher percentage of under spec (less efficient) modules which resulted in increased the area related installed costs for SMUD. For example we noted an approximately 8¢ to 13¢/W increased installation cost when the average efficiency slipped from 5.5% to 4.5% (a decrease of 18%) from one a-Si supplier. This meant that

a 2kW residential was about \$266 more expensive to install. Once proper QA/QC procedures were re-established at each of these manufacturing facilities, the subsequent shipments showed expected efficiencies and performance.

VI. Collected Third Party a-Si Data

Since the release of the original 2002 report various 3rd party studies have positively reinforced the high performance and durability expectations of a-Si. The results, which either rely on system performance data (albeit with a smaller volume of systems samples compared to SMUD) or laboratory control tests, underscore SMUDs conclusions not only for performance and durability of the modules but also for the dependence on each thin film manufacturers commitment to QA/QC and quality production.

In *Performance of Amorphous Silicon Double Junction Photovoltaic Systems in Different Climatic Zones*¹² by Gottschalg, et al in 2002, dual junction a-Si systems already operating for several years in a wide variety of climate zones, including Brazil, China, Spain, Switzerland, and the UK were evaluated. The report found initial degradation to be about 20%, typically stabilizing to a value corresponding to the system design value. The report concluded that for well designed and properly installed systems once “stabilized”, “amorphous silicon systems operating in different climatic conditions can exhibit very high performance ratios” of 86% to nearly 100% (where the performance ratio is the ratio of the actual energy output to the expected, rated performance). Furthermore, Gottschalg confirms that “all systems exhibit a relatively stable operation after the initial degradation.”¹

After four years of continuous operation in Brazil, Ruther et al¹³, also in 2002, noted a high performance ratio of 83% AC and 91% DC, the difference indicating inverter problems. Ruther also observed a-Si to be particularly well suited to warmer climates compared to crystalline modules due to the smaller temperature coefficient of a-Si compared to c-Si and pc-Si in addition to noticeable increases of thermal annealing caused by higher operating temperatures thus reducing the degree of initial degradation. Ruther noted:

New generation multi-junction a-Si thin-film photovoltaic systems have now been in operation at various international sites for a number of years. After a bad start in the 80's, with first generation single-junction a-Si installations -whose output performance degraded badly over time- the industry evolved with better materials and device design to circumvent the Staebler-Wronski effect. Most of the recent reports depict a-Si PV systems operating well and at stabilized output levels after an initial light-induced degradation, with performance ratios comparable with those of traditional crystalline silicon (c-Si). Some a-Si PV manufacturers offer warranties on stabilized output performance of up to 20 years [now often 25 years], demonstrating the confidence in a technology that should experience an increase in market share in the near future, especially in warm climates where it reaches its best performance.

In a fascinating performance comparison of different module brands, another 2002 study, *Product Quality in the Kenyan SHS Market*¹⁴, Duke et al examine solar home systems in Kenya's climate. In general, a-Si modules had stabilized output values below the rated nameplate value of the modules. Significantly, the researchers in Kenya concluded that even modules from well known manufacturers demonstrated a stabilized performance of only 90% of the rated value. For comparison, Duke also notes that:

well-made a-Si modules appear to exhibit modest long-term degradation roughly comparable to that of crystalline modules” and that “average performance levels for crystalline modules are also often just above the warranty level, which is typically about 90% of rated power.

These findings are similar to SMUDs for different module technologies in that they underscore the necessity at that time for manufacturers to improve their accuracy of rating modules in QA/QC. Such data also reinforced SMUD's choice to both purchase modules on a “per stabilized watt basis” and conduct independent testing.

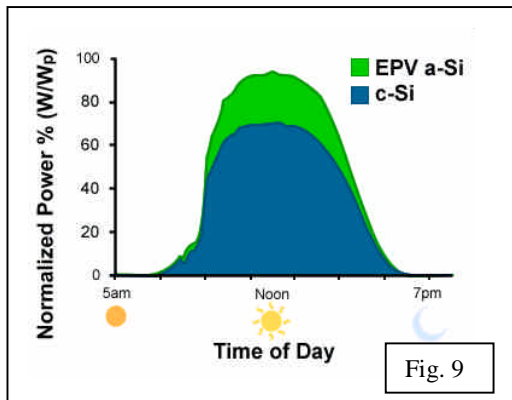
Duke did attribute the difficulties in predicting the performance of a-Si to complex degradation mechanisms, but felt that these matters were understood well enough to permit careful and high-quality manufacturers to determine proper and accurate (to a couple of percent) stabilized rating for modules.

In *Stabilization and Performance Characteristics of Commercial Amorphous-Silicon PV Modules*¹⁵, David King and researchers at the Sandia National Laboratories tested multiple modules from four different manufacturers over several years of continuous outdoor exposure in New Mexico. Modules included EPV and BP a-Si modules widely installed by SMUD's solar programs. King concludes:

Fortunately, many of the characteristics observed were common to all the modules evaluated. If "stabilized" is defined as the power level achieved after about 1-yr exposure and midway between seasonal oscillations, the following general observations can be made:

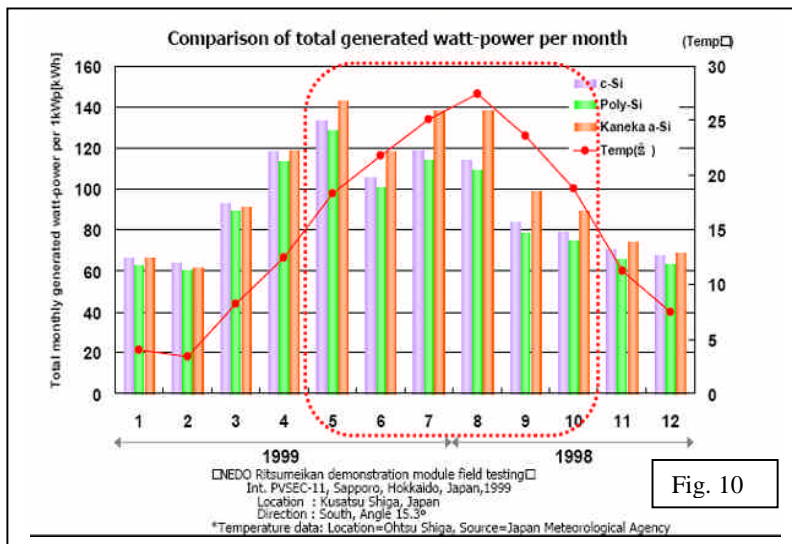
1. *Previously unexposed a-Si modules showed an initial rapid degradation in power over the first 6 months,*
2. *The majority of the modules tested reached a "stabilized" power level about 20% below the initial (1st day) power after about 1 year,*
3. *Modules initially exposed at different times of year stabilized at the same level,*
4. *The effect of seasonal oscillation (thermal annealing) was clearly evident in all modules tested accounting for about $\pm 4\%$ variation from the "stabilized" level,*
5. *Module operating temperatures $>40^\circ\text{C}$ was needed before the thermal annealing process occurred,*

King also noted that, due to the combination of seasonal thermal annealing and seasonal solar spectrum distribution influences, a-Si module efficiency is "about 13% higher in the summer than winter, consistent with field experience for a-Si systems". c-Si and pc-Si systems exhibit the opposite behavior with significantly degraded performance under high summer temperatures. This is a significant advantage to a-Si modules in areas with summer utility peak loads.



This advantage to a-Si modules in areas with summer utility peak loads has also been noted by numerous other researchers and tests, including the Florida Solar Energy Center (FSEC) which highlighted the superior relative performance of a-Si modules under high summer temperatures¹⁶. EPV modules demonstrated a striking higher wattage produced compared to its STC rated wattage (W/Wp) when juxtaposed to that of c-Si modules. In essence the FSEC results point to more kWh

production per installed kW and a clear higher power production for the same nameplate sized PV system when compared to c-Si systems.

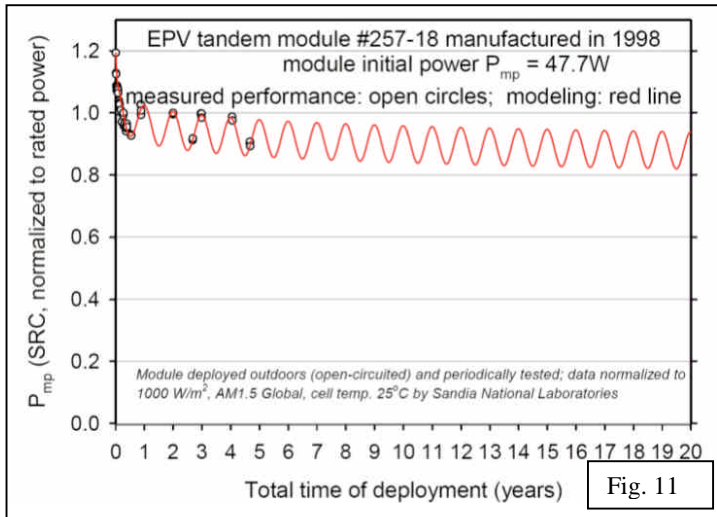


These conclusions complement a Japanese study on Kanaka a-Si modules¹⁷ (figure 10) also verified considerably increased annual and summer relative performance (kWh produced to kW rated) for a-Si compared to both c-Si (9% greater) and pc-Si (14% greater). For the critical summer months of peak loads and higher rates, the difference is more pronounced with a-Si producing 15% more kWh than the c-Si for the same kW installed, and 20% more than the pc-Si module.

a-Si modules also produces power at significantly lower light levels than c-Si or pc-Si. However, this

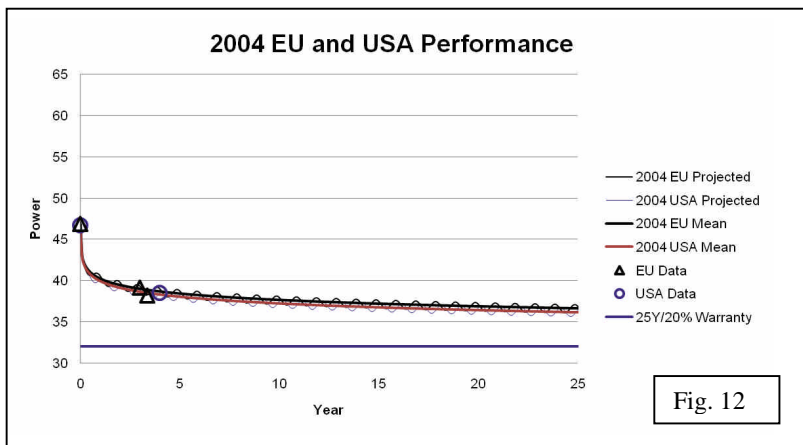
effect is minimal in normally sunny climates such as Sacramento and further limited by the inverter set points, which have very sharp drop offs in efficiencies at a DC load at about 5 to 10% of rated power. Although an a-Si array may generate DC power at low light levels, the amount of AC generated will be well below this cut off. From SMUD's perspective low light level operation was low on the list of benefits and considerations with respect to the overall system performance in sunny Sacramento. In cloudier climates these considerations and benefits could carry more significance.

Sandia National Laboratory (SNL) conducted routine performance tests on an outdoor deployed EPV 40 watt a-Si laminate module for 5 years. The test depicts very good long term stability once the stabilized level is reached (after first 3 or 4 months of exposure). The performance results¹⁸ (fig. 11) superimposed on the 20 year predicted



performance curve illustrate excellent agreement and the predicted curve shows an average performance of roughly 90% of the stabilized rated, name plate performance of the module after 20 years.

EPV 40 watt modules were also tested over a 5 year period in Mannheim, Germany and Sacramento, California¹¹. (fig. 12) The bottom line of figure 12 indicates the performance at the 25 year warranty level of 20% reduction from the rated, nameplate module power. The projected performance, based on the actual data curves show better than 90% of nameplate performance after 25 years, compared to the standard warranty of 80% after 20 to 25 years.



In the often cited overview, *Technology and Market Challenges to Mainstream Thin-film Photovoltaic Modules and Applications*¹⁹, Rajeewa Arya (currently at Moses Baer PV) reconfirms the functionality of a-Si in outdoor testing and applications also highlights the importance of encapsulation:

The outdoor reliability of modules is largely a function of the efficacy of the encapsulation and the packaging system in keeping moisture out of the active solar cells. Moisture ingress, contact

reliability under thermal cycling and humidity-freeze cycling are the main modes of failure. Many organizations have developed packaging schemes that pass the testing requirements for 20 year outdoor applications.

Figure 13 (below, left) shows the outdoor reliability of a 40 watt a-Si laminate module produced by EPV and studied at Sandia Laboratories¹⁸ and again the results shows very good long term stability once the stabilized level is reached (after first 3 or 4 months of exposure).

The Florida Solar Energy Center also monitored EPV modules in conducting outdoor exposure and monitoring tests of an a-Si laminate PV system for a 2 year period following stabilization. The results²⁰ by Dhere and FSEC researcher in 2007 in Fig. 14 (below, right) showed no degradation in the a-Si system performance over the 2 year period.

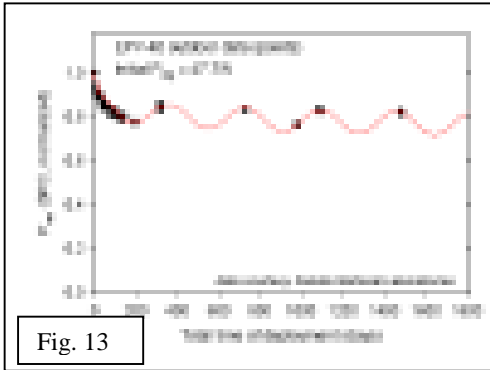


Fig. 13

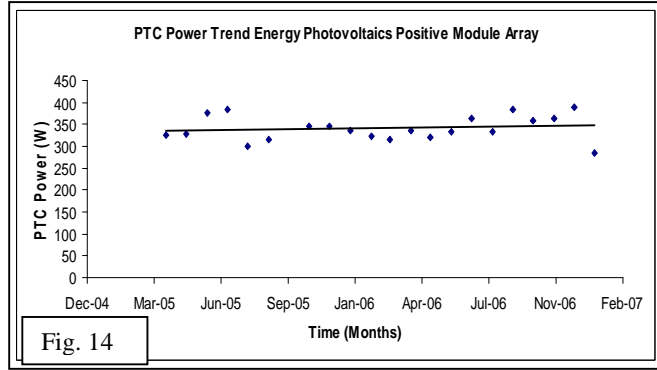


Fig. 14

The Japan Quality Assurance Organization (JQA), under subcontract to Japan's New Energy and Industrial Development Organization (NEDO), conducted accelerated testing of Kaneka a-Si laminate modules to evaluate reliability and performance over a 30 year period following full stabilization. JQA conducted an accelerated life test on the module including variations of solar radiation and temperature to simulate 30 years of exposure including seasonal variations. The study¹⁷ concluded that the modules will produce 90% of the nameplate rated capacity after 30 years, or an average annual degradation of about 0.33%. The general shape of the degradation curve matches with the asymptotic curve model of long-term degradation of a-Si module

performance.

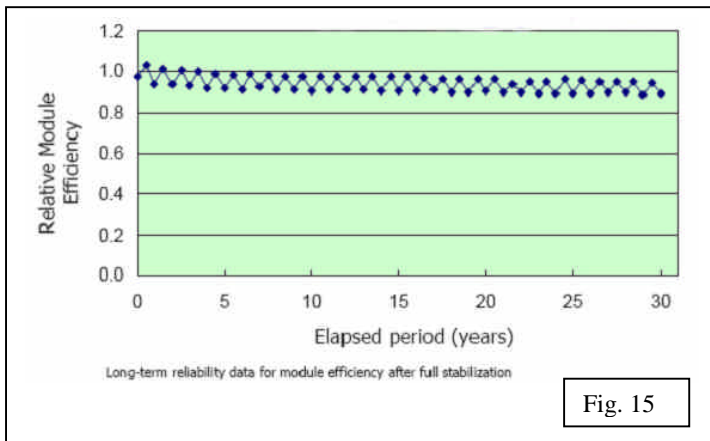


Fig. 15

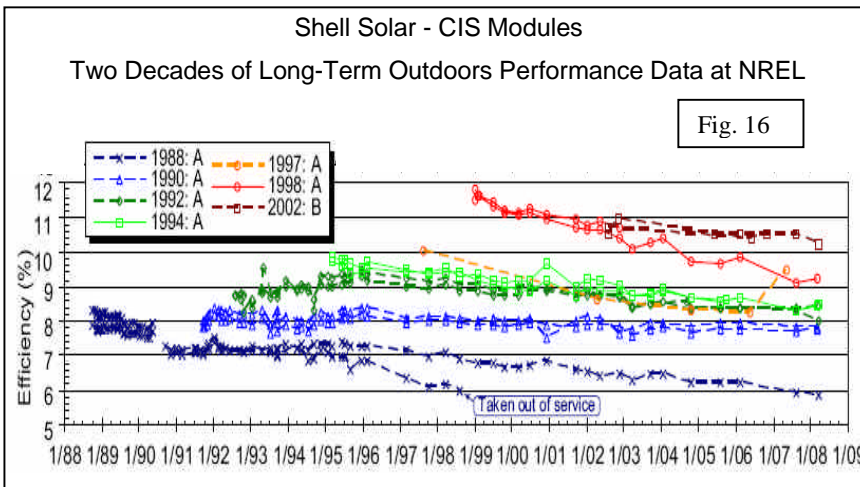


Fig. 16

Twenty years of outdoor exposure testing has been accumulated by NREL researchers on CIGS glass on glass laminates²¹. The modules, mechanically similar to standard a-Si glass laminates show excellent stability with most of the modules showing very little performance degradation.

Based on a number of accelerated lifetime tests, outdoor exposure tests, and field experience reports,

researchers at NREL researchers in the United States concluded¹⁸ a-Si as the most dependable thin-film module to last for more than 20 years. Moreover, the same NREL review determined CIGS and CdTe to be more moisture sensitive than a-Si, often require better module encapsulation schemes than a-Si. When proper encapsulation methods are employed, these modules also show long useful life and stability. According to NREL, "Glass-to-glass (foil) laminates [are] most suited for large field installations" being the most reliable and cost-effective

encapsulation method and that the “stability of thin-film modules is acceptable ($\leq 1\%$ per year power loss) if the right manufacturing processes are used for manufacturing”.

V. Conclusions

Based on the extensive experience over a lengthy period of time in the SMUD Solar Program -- having installed over 2,000 kW of amorphous silicon, thin film (a-Si) laminate PV systems from 1994 to 2002 in systems ranging from 2 kW to 700 kW -- and on other reported experience worldwide, it is clear that thin film PV laminates, such as a-Si glass on glass laminates, demonstrate excellent performance, reliability, stability, and durability in the field and thus offer substantial potential advantages over the better-established crystalline PV materials. While lower in efficiency compared to the more traditional single-crystal silicon (c-Si) and polycrystalline silicon (pc-Si) PV modules, the significantly lower price of a-Si can often result in dramatic turnkey system savings despite increased area-related installation costs.

SMUD's field experience over the past 14 years, confirmed and extended by field experience and by independent, third party module testing worldwide over the past 6 years, clearly show that when good QA/QC procedures are followed in the manufacture and shipment of the modules and proper handling and installation techniques are followed, thin film glass laminate modules perform very well and are directly comparable to c-Si or pc-Si modules.

- a-Si laminates show excellent long-term stability and performance.
 - 30+ year useful life
 - Annual degradation rates well under 1%, typically 0.25 to 0.50% per year
 - Stability exceeding the typical 90% 10 year and 80% 20-25 year power warranties
 - At least comparable to c-Si and pc-Si modules
- Exhibit excellent durability once installed with module cracking/breakage/failure rates comparable to framed c-Si and pc-Si modules.
- a-Si offers significantly enhanced summer performance leading to significantly increased kWh production for each kW installed compared to c-Si or pc-Si modules (more kWh/kW).
- Provide long-term stability substantially exceeding the typical 90% 10-year and 80% 20-25 year power warranty (comparable to c-Si and pc-Si modules).

When special care and training is taken, unframed glass-glass laminate thin film modules can be fielded very successfully. Other differences in module reliability compared to c-Si and pc-Si were due to the specific QA/QC procedures undertaken for a particular production run of modules rather than the module material. Where good manufacturing QA/QC procedures are followed, a-Si module reliability can be very high, regardless of the module manufacturer or type. Where QA/QC slips, SMUD demonstrated a significant increase in module related problems. The success in application of a-Si modules is very dependent on the quality of the manufacturer's QA/QC efforts and their commitment to quality production.

Because of the SMUD extensive field experience, long term module field testing at NREL and SNL, accelerated aging tests done by various suppliers, and analysis of the failure modes of a-Si module systems by SMUD engineers and others, we fully expect well made a-Si modules to continue to reliably produce power well in excess of the 25 year, 80% power warranty periods. We treat them as a 30+-year useful life expectancy. Experience at SMUD to date tends to confirm this assumption. With this base of demonstrated experience, a-Si laminate PV systems continue to offer a very viable option for a wide range of PV system applications.

V. Acknowledgements

I would like to acknowledge the assistance by a number of groups who provided support, material, and information that made this report possible. These organizations include: Applied Materials, EPV, Amelio Solar, NREL, SNL, ASU-PTL, and SMUD. I would also like to thank Dave Collier, Walker Wright, and Cathy Boone for their help in analysis and editing.

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