PV module characterization

Stefan Krauter & **Paul Grunow**, Photovoltaik Institut Berlin AG, TU-Berlin, Germany

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ABSTRACT

The current industry situation of more competitive business approaches, increased PV project sizes and investments but declining profit margins renders an accurate knowledge of PV performance a vital factor in remaining competitive. Comprehension of expected lifetime and energy yield of PV generators is essential. Therefore, accurate characterization of PV modules is quickly becoming a more and more significant issue. This article gives an overview of the characterization topics of PV modules in terms of safety, failure susceptibility, overall reliability, system performance and energy rating.

Safety

Mechanical safety

While tests for mechanical safety are relatively easy to perform (2,400 Pa for the mechanical load test according to IEC 61215, 61646 and 61730) and should not pose severe problems to the manufacturers, some modules fail these tests, possibly due to enlarging module size without taking into account the mechanical properties (see Figure 1). This issue can be overcome using the following: enhanced mounting clamps with rubber inlays; extra support on the backside; frames with additional cross bars; thicker glass; smaller formats or stiffer back materials.

Electrical safety: isolation

Initial electrical isolation problems are typically due to an insufficient distance of the electrically active areas from the metallic frame, and later throughout the operation phase are due to moisture ingress from the edge.

Electrical isolation is tested using four different methods:

- Application of a high voltage between the terminals and a wrap of conductive foil around the module. The test voltage for the different tests is: for IEC 61215 & 61646 – 1kV plus twice the maximum system voltage for 1 minute; for IEC 61730-2 class A requirements – 2kV plus four times the maximum system voltage; for class B requirements – 1kV plus two times the maximum system voltage. If the measured insulation resistance times the area of the module is less than 40MΩ/m², the module has failed.
- Applying an impulse voltage (MST14 at IEC 61730-2) of up to 8kV at a rise time of 1.2µs and a fall time of 50µs.
- Measurement of the wet leakage current (module drowned) at 500V or the maximum system voltage (10.15 at IEC 61215 & 61646 and MST17 at IEC 61730-2). If the measured insulation resistance times the area of the module is less than 40MΩ/m², the module has failed.
- Using the ground continuity test (MST 13 at IEC 61730-2) for modules with a metal frame or a metallic junction box to demonstrate that there is a conductive path between all exposed conductive surfaces of the module and that they can be adequately grounded in a PV system. The resistance between each conductive component of the module shall be less than 0.1Ω for a current of 2.5 times the maximum over-current protection rating.

Figure 1. Breakage at 2,400 Pa: a-Si 1.4m² module with 2mm x 3mm glass.

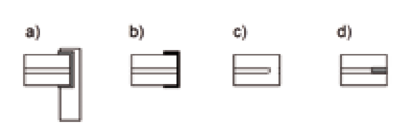

Figure 2. Strategies used to counter moisture ingress: a) wrap sealant in the module frame; b) metal tape around the edges; c) glass bonding; d) in-laminate sealant (showing the cross-section at the edge of a PV module).

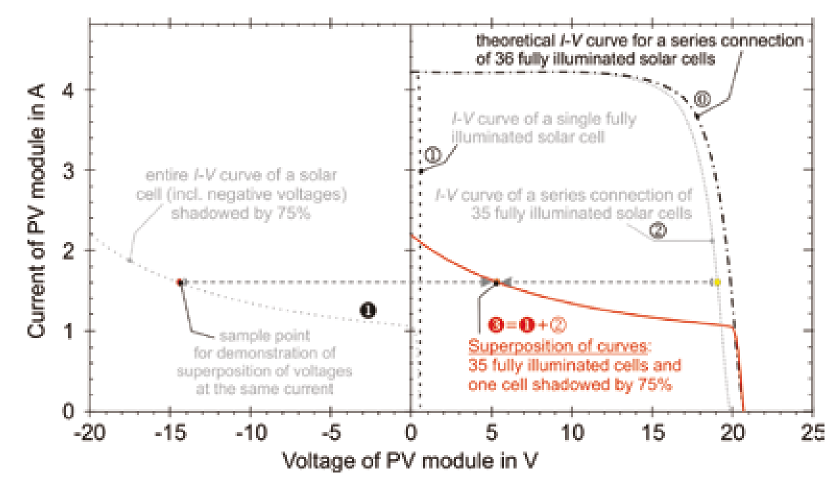

Figure 3. I-V curves showing a fully illuminated module (⓪); an illuminated module with one cell less (②); a shadowed cell (❶); and the resulting I-V curve of a module with one shadowed cell (❸).

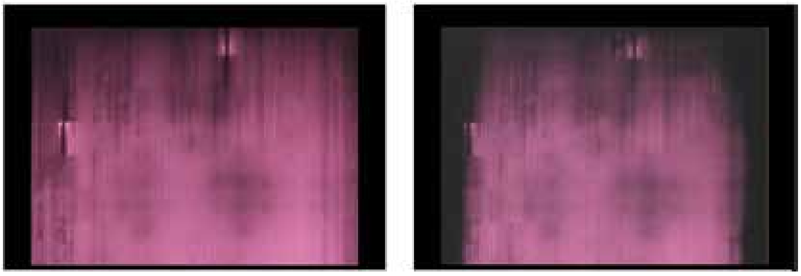

Figure 4. EL photography applied to a-Si modules, showing initial state (left) and after 1000h of damp-heat treatment (right – considerable reduction of photovoltaic active areas due to TCO corrosion (see TCO corrosion section overleaf).

To simulate several years of use, a damp heat test (1000 hours at +85°C and 85% of relative humidity), a thermal cycling test (200 times between -40°C and +85°C) and a humidity freeze test (10 fast drops from 85°C to -40°C at 85% humidity) are applied, at which point the isolation test and the wet leakage current test are repeated.

While PVB is more susceptible to moisture ingress than EVA, EVA is more commonly used.

However, PVB would tend to provide a better fit to the building code requirements.

Several different strategies are used to inhibit the moisture ingress (see Figure 2), including: wrap sealant in the module frame; metal tape around the edge; glass bonding, and in-laminate sealant.

While glass bonding offers the most secure sealant for moisture, it is quite costly. Manufacturers are currently researching using 'breathable' membranes in the sealant in different configurations.

Reliability

Hot-spot susceptibility

While the photovoltaic conversion process itself is very reliable, the interconnection of the cells in series may cause problems. As with all series connections, the element with the lowest current defines the total current. The current of a single cell may be reduced by local shadowing (due, for example, to dirt on the surface of the module), which therefore limits the total current and power output, as shown in Figure 3. If the string is large enough, the (reverse) voltage at the shadowed cell can surpass the negative breakthrough voltage and could lead to a local power dissipation that could even destroy parts of the cell ('hot spot').

The hot spot problem can be avoided by reduced voltage or a reduced cell area (limitation of current) or via appropriate bypass diodes or cells with a low reverse breakthrough voltage (which are – interestingly – usually 'bad' (low efficiency) cells).

Failure susceptibility

Electroluminescence

Failure diagnostics are essential to finding out issues of failure susceptibility. Electroluminescence (EL) is a suitable process for checking that the entire module area is incorporated in the photovoltaic energy conversion process. Electroluminescence is the use of a solar cell in a reverse manner to how it was intended to be used: instead of converting irradiance into electricity, electricity (supplied via the cell's electrical contacts) is converted into radiation in the near infra-red and is emitted via the cell's surface. The intensity of the radiation emission is an indicator for the local efficiency and quality of the photovoltaic conversion process. An extensive description of the EL tool can be found in the authors' contribution to the first edition of *Photovoltaics International*, entitled: 'Wafer, Cell and Module Quality Requirements', on page 59.

Failures in the lamination process

Failures in the lamination process can be caused by various factors:

- Old and oxidized EVA
- Insufficient glass-washing
- Wrong temperature
- Insufficient duration and pressure of the lamination process
- Lack of curing of EVA due to shortened process.

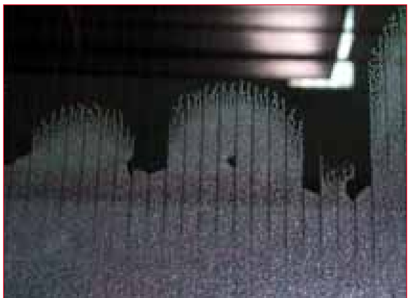

Figure 5. TCO corrosion: commercial a-Si module after 1000h of IEC damp heat treatment (85°C at 85% RH) at a voltage of -1,000V against ground at PI Berlin. >20% of the area becomes corroded and inactive.

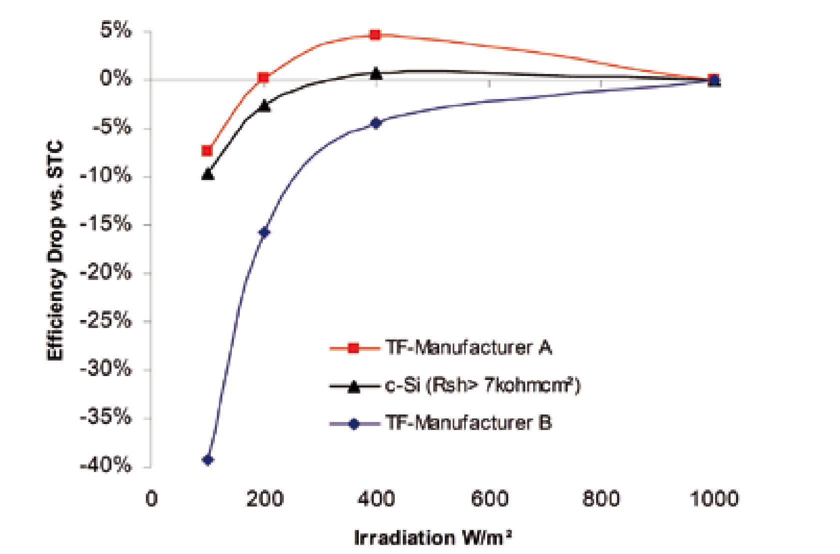

Figure 6. Change in power output as a function irradiance level for PV modules based on crystalline and thin-film technologies.

These failures can be detected by a gel content test of the cured EVA or by a backsheet peel-off test (forcing the peel off the backsheet from the module).

System compatibility and system performance

TCO corrosion

Some technologies that use a transparent conductive oxide (TCO) for the front contacts frequently experience problems if a high negative voltage is applied to the TCO (see Figure 5).

The effect can be explained by the sodium ions' electrochemical corrosion with water at the TCO/glass interface, causing de-lamination of the TCO.

Major drivers of this process are:

- Negative cell polarity vs. ground
- Moisture ingression
- High operation temperature
- Na (sodium) content in glass.

Therefore, module manufacturers tend to recommend inverters that allow for a positive voltage of the module against ground.

Energy rating

An electrical energy rating can be carried out from knowledge based on experience of long-term-outdoor tests or simulation – or a combination of both – to achieve validation.

Energy rating based on laboratory measurements

Parameters that influence the energy yield have to be measured in detail as input data for energy yield simulations and comparison of technologies, including efficiency at different irradiance levels (weak light performance), temperature coefficients, spectral efficiency and optical parameters (performance at flat incidence angles, refractive indices).

Energy rating via simulation

The correct simulation of direct and diffuse irradiance via their spectral-spatial appearance allows for an accurate representation of the module reaching irradiance. After passing the different layers of the encapsulation and being reflected according to the Fresnel laws - considering actual incidence angles and refractive indices, this irradiance forms the cell-reaching spectrum. The photoelectric conversion efficiency depends on

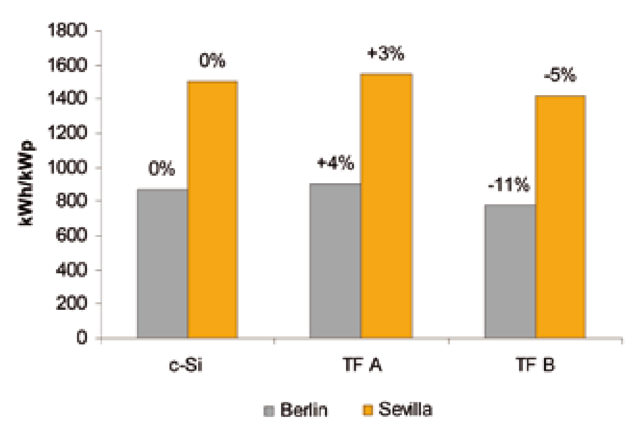

Figure 7. Effect on energy yield of the weak light performance differences as shown in Figure 6 (c-Si and two thin-film modules (TF A, TF B)) for different locations of installation.

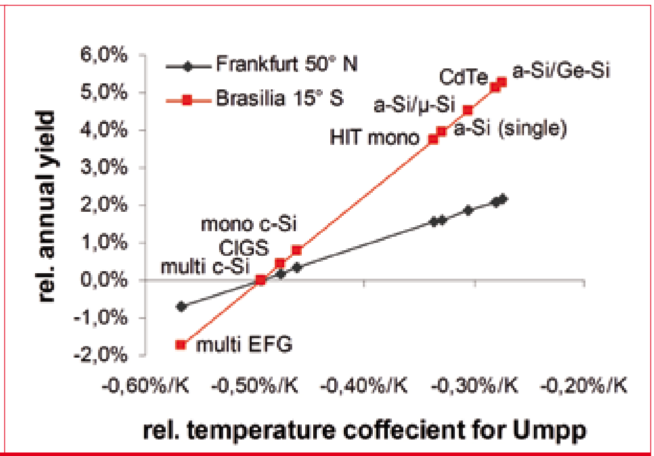

Figure 8. Relative change in energy yield (related to multi-crystalline silicon) of different technologies (along with their inherent temperature coefficients) for two different locations.

matching of the cell-reaching spectrum with the cell's spectral response and the actual operating cell temperature (which is derived from a balance of energy flow of absorbed irradiance, electricity generation and heat dissipation). The procedure for energy yield simulation is shown in Figure 10, with the results depicted in the graphs of Figures 7, 8 and 9.

A further analysis of the different parameters (e.g., performance vs. module inclination angle) can be carried out (see Figure 11). An interesting effect is that the inclination angle of the module does not influence the irradiance on the plane of the module, but has a significant effect on the convective heat transfer of the module. For horizontal mounting (module elevation angle: 0°), the convection capability and convective heat transfer at the module are reduced, thus causing high operating cell temperatures and a considerable dip in conversion efficiency around noon. This dip is drastically reduced for more inclined modules, allowing an effective flow of air and convection along the module.

The minima of conversion efficiencies 20 minutes after sunrise at 6 a.m. and 20 minutes before sunset at 6 p.m. can be explained by the extremely flat angle of incidence of the direct irradiance during those times of the day. From these examples, it is clear that the quality of yield prediction depends rather on the comprehension of the entire optical-thermal-electrical composition of the installed PV panel than on the knowledge of an isolated PV module.

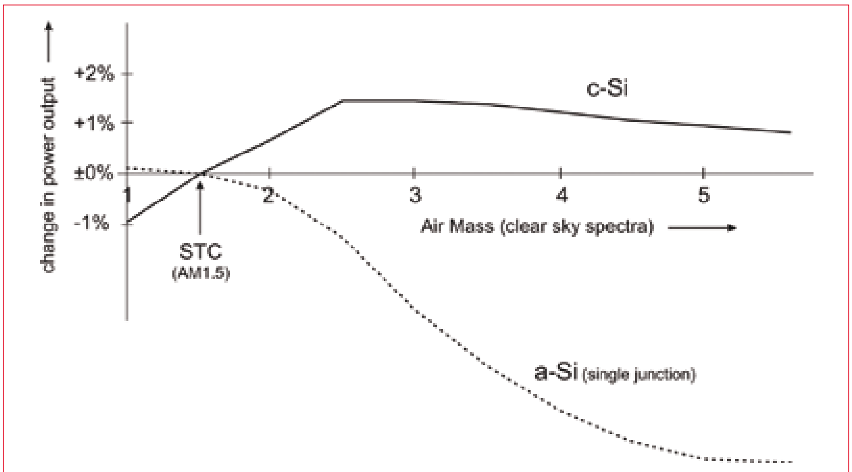

Figure 9. Change in power output as a function of the spectrum (AM) for PV modules based on crystalline and amorphous silicon.

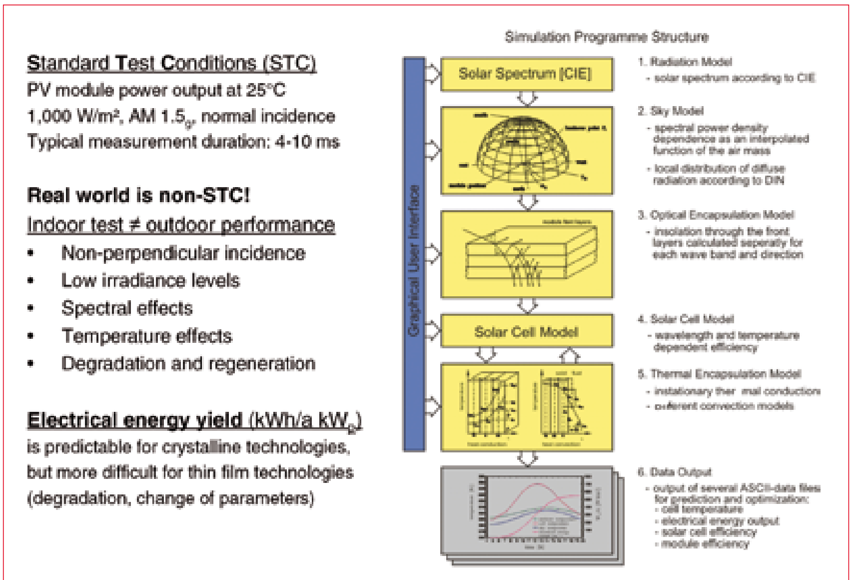

Figure 10. Structure of simulation process - yield becomes more important than power output at STC.

Energy rating using outdoor data

Collection and study of outdoor, real-world data is the most accurate, but also the most time-consuming method of collecting data on energy yield.

Degradation

While the power output of crystalline technologies showed only a little degradation, a-Si modules degrade considerably. To accelerate the process of degradation, so-called 'light soaking' at high irradiance levels (600 (800) – 1,000W/m²) and at constant temperatures (50°C ± 10°C) is applied according to IEC 61646. Current-induced light soaking was tested in order to facilitate light soaking: for a-Si, degradation was similar, but current-induced light soaking did not reach the degradation level achieved via light soaking (6% difference, see Figure 13).

A PV module based on a combination of amorphous and microcrystalline silicon has shown almost no degradation at all

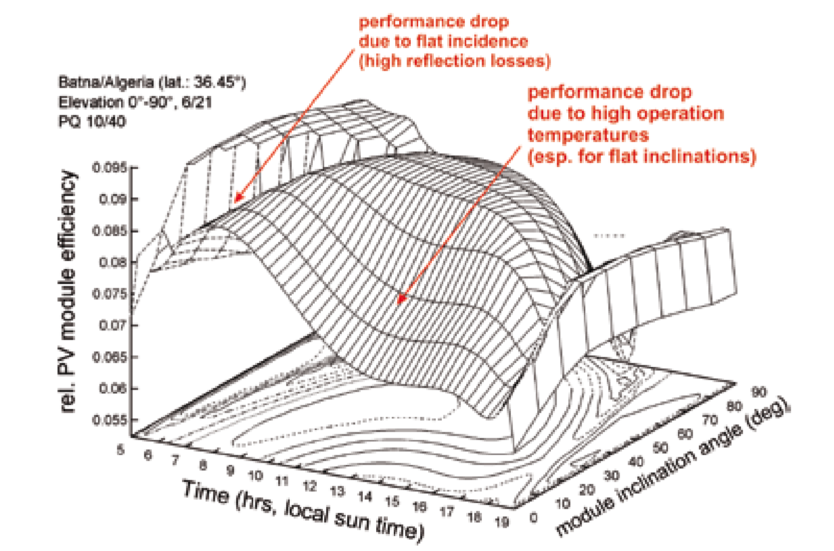

Figure 11. Results of simulation of a PV module. Image shows course of PV conversion efficiency during a day as a function of inclination angle of the module.

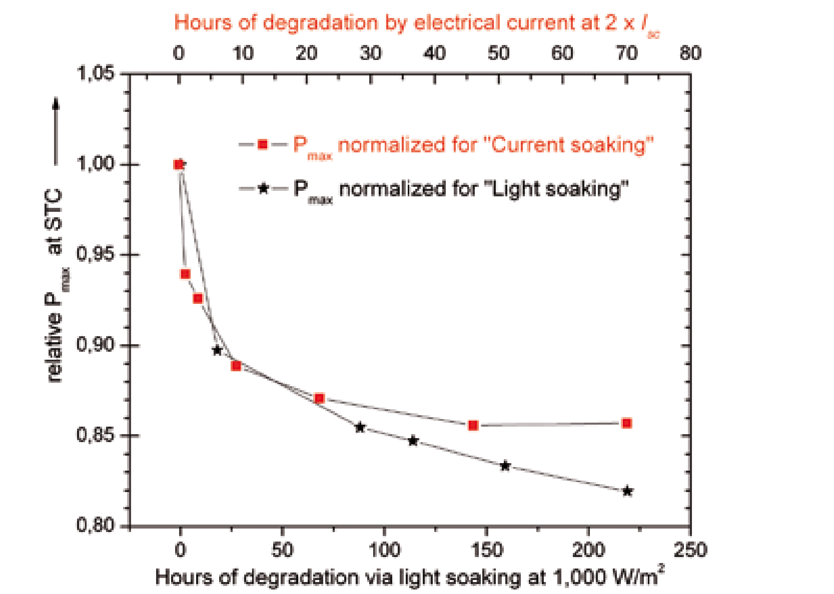

Figure 12. Comparison of degradation of an a-Si PV module via light soaking and via current (twice I_{SC}).

by current soaking, while conventional light soaking has shown a similar level of degradation on an a-Si module.

Conclusion and outlook

The experience of PI shows that energy rating is most critical for thin-film technologies, while

- Degradation is still the most important factor on energy yields for a-Si and µ-Si/a-Si
- TCO corrosion mostly solved by in-laminate sealing or injected frames and adequate inverter technology
- Degradation and spectral effects in silicon thin-film modules require new modeling in future simulation
- The tandem-junction structure of µ-Si/a-Si is complicating energy yield prediction due to the interdependence of degradation and spectral effects.

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PV Modules

About the Authors

Prof. Stefan Krauter received his Ph.D. in electrical engineering from the University of Technology Berlin (TUB) in 1993. In 1996 he co-founded Solon, and 10 years later – after a visiting professorship at UFRJ and UECE in Brazil – he co-founded the Photovoltaic Institute Berlin, for which organisation he acts as a senior consultant and sits on the board of directors. He is a professor for PV Energy Systems at TUB and at the Biberach University for Applied Sciences (HBC).

Dr. Paul Grunow received his Ph.D. in physics in 1993 from the Hahn Meitner Institute (HMI) and Free University Berlin (FUB) and carried out his post-doc studies on thin-film solar cells at the Federal University of Rio de Janeiro in Brazil (UFRJ-COPPE). He cofounded Solon AG in 1996 and, together with Reiner Lemoine, founded Q-Cells AG in 1998. In 2006 he co-founded the Photovoltaic Institute Berlin where he sits on the board of directors and acts as a senior consultant. He also is a lecturer at the University of Applied Sciences for Technology and Economics Berlin (HTW).

Enquiries

Photovoltaik Institut Berlin AG
c/o TU-Berlin, Einsteinufer 25-CO
D-10587 Berlin
Germany
Tel: +49 30 314 25977
Fax: +49 30 314 26617
Emails: krauter@pi-berlin.com
grunow@pi-berlin.com