Seventeenth Edition

Photovoltaics International

THE TECHNOLOGY RESOURCE FOR PV PROFESSIONALS

First Solar: greater energy yields in high-temperature conditions

Third Quarter, August 2012

www.pv-tech.org

This paper first appeared in the seventeenth print edition of the *Photovoltaics International* journal, published in August 2012.

Performance characterization and superior energy yield of First Solar PV power plants in high-temperature conditions

N. Strevel, **L. Trippel** & **M. Gloeckler**, First Solar, Perrysburg, Ohio, USA

ABSTRACT

Like all semiconductor photovoltaic devices, cadmium telluride (CdTe) modules have a characteristic response to temperature changes. This paper describes the effects of the temperature coefficient of power, using operational system data to quantify the First Solar CdTe technology energy-yield advantage over typical crystalline silicon technology in high-temperature conditions. This paper also describes the underlying mechanisms of initial stabilization and long-term degradation that influence module efficiency. The processes used to characterize and rate module power output, given these effects, are further discussed. First Solar's significant experience in building and operating power plants in high-temperature conditions, along with associated system performance data and accelerated lab test data, is reviewed to substantiate the warranty considerations and long-term capability of power plants using CdTe PV modules.

Introduction

First Solar has successfully designed, built and operated utility-scale solar power plants in many diverse climates. In high-temperature climates, both initial and long-term module performances are critical to lifetime energy production. The purpose of this paper is to explain the fundamentals of high-temperature operation that influence energy output, module efficiency and module reliability over the power plant's life. First Solar cadmium telluride (CdTe) technology, like all PV modules, has device-specific characteristics which drive observable output changes over time that are taken into account during module rating and future energy predictions.

Instantaneous response – temperature coefficient

First Solar's thin-film CdTe solar modules have a proven high-temperature performance advantage over typical crystalline silicon solar modules. The leading contributor to this performance advantage is the lower temperature coefficient of CdTe semiconductor material, which delivers higher energy yields at elevated temperatures. Module performance has been thoroughly characterized over time to establish power ratings and energy prediction models that are used to set system performance expectations in various climate conditions. PV modules receive their nameplate power rating at standard test conditions (STC) of 1000W/m^2 solar irradiance, AM 1.5 and 25°C module temperature.

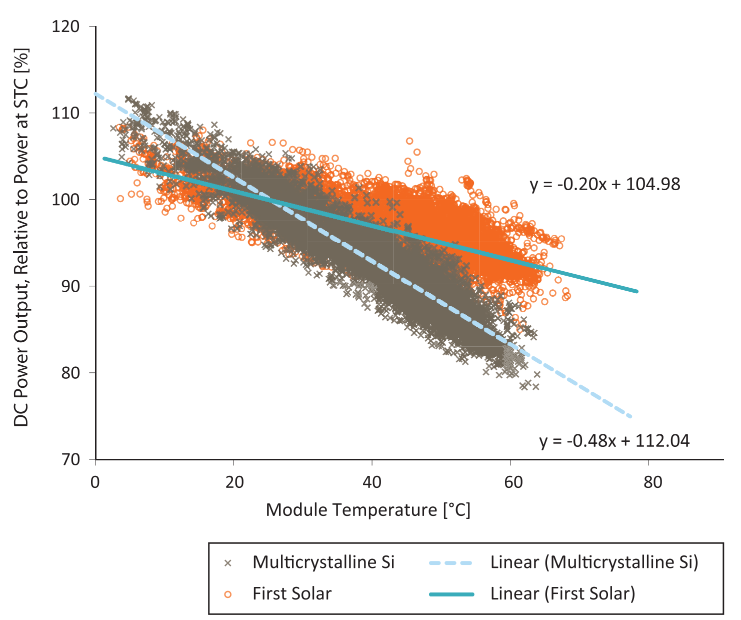

Figure 1. First Solar and multicrystalline DC power output vs. temperature [4].

> "As module temperature rises, all PV semiconductor technologies incur increasing losses in performance."

As module temperature rises, all PV semiconductor technologies incur increasing losses in performance, primarily due to the drop in open-circuit voltage of the PV cell. The temperature coefficient expresses the rate of change of power output as a function of module operating temperature. Crystalline silicon solar modules typically have a temperature coefficient of –0.45 to –0.5% per degree Celsius [1,2]. First Solar's CdTe PV modules have a temperature coefficient of –0.25% per degree Celsius, resulting in about half the incremental power loss compared to conventional solar modules [3]. Fig. 1 shows the DC power of two PV systems consisting of CdTe and multicrystalline silicon (mc-Si) modules. As module temperatures rise above 25°C, CdTe solar modules experience an increasing performance advantage.

In a typical region of high solar irradiance, module temperatures in peak operating conditions often reach 65°C (40°C above STC) or higher. At 65°C, the power output of conventional solar modules is reduced by up to 20%, while the power output of First Solar modules is reduced by approximately 10%. For example, on a day with an ambient temperature of 37°C and a module temperature of 65°C, a 50 megawatt peak (MWp) multicrystalline silicon solar system will produce approximately 40 megawatts (MW) at 1000W/m^2 irradiance, while an equivalent First Solar power plant will produce approximately 45MW, resulting in 10% more power output. As this effect continues over time for a typical hot-climate power plant, the result is an increase in annual energy output of 5–9% for the same nameplate-rated plant. Consistent with this performance range, a comparison performed by a major system integrator concluded that, in southern Italy, CdTe modules outperformed mc-Si in annual specific yield by 5.7% [5]. Energy prediction simulations performed using industry-standard tools such as PV SYST further illustrate the behaviour.

"The majority of solar energy production occurs when module cell temperature is greater than ambient temperature."

The majority of solar energy production occurs when module cell temperature is greater than ambient temperature. Fig. 2 shows the annual distribution of ambient temperature and of the temperature measured on the back surface of a solar module for an operational First Solar power plant in the US desert Southwest. The figure shows the frequency distribution of module temperature over a full year period. Note that the distribution of ambient temperature ranges from 0 to 45°C, and is centred on approximately 25°C, while the distribution of back-surface temperature ranges from 0 to 70°C, and is centred on approximately 40°C. The back-surface temperature is a good approximation of the actual cell temperature, and studies have shown that cells typically run 3°C warmer than back-surface temperatures for glass–glass laminate construction [6].

The majority of solar energy production occurs when the module operating temperature is much greater than 25°C. Fig. 3 overlays the distribution of energy production at high (≥ 25°C) and low (<25°C) temperatures for the same operational PV plant described in Fig. 2. The availability of irradiance represented by the energy production in Fig. 3 indicates that the relevant energy-weighted average temperature is approximately 45°C.

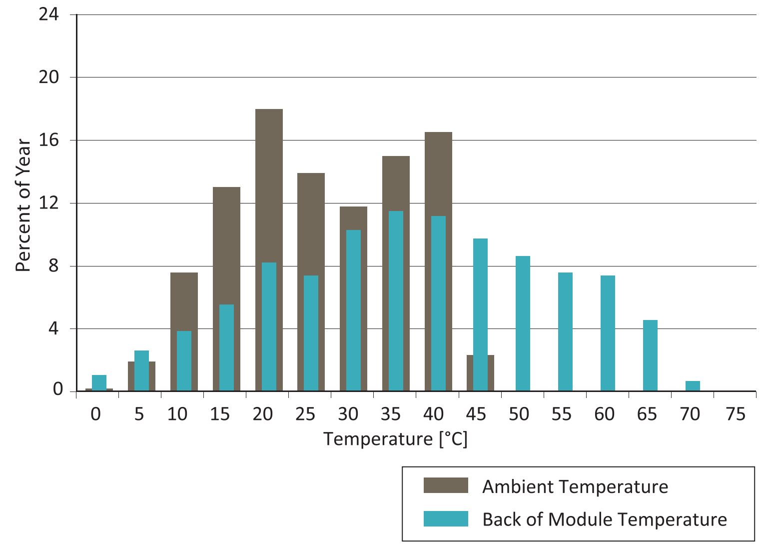

Figure 2. Distribution of ambient and back-surface temperatures, measured in a First Solar constructed US desert Southwest array.

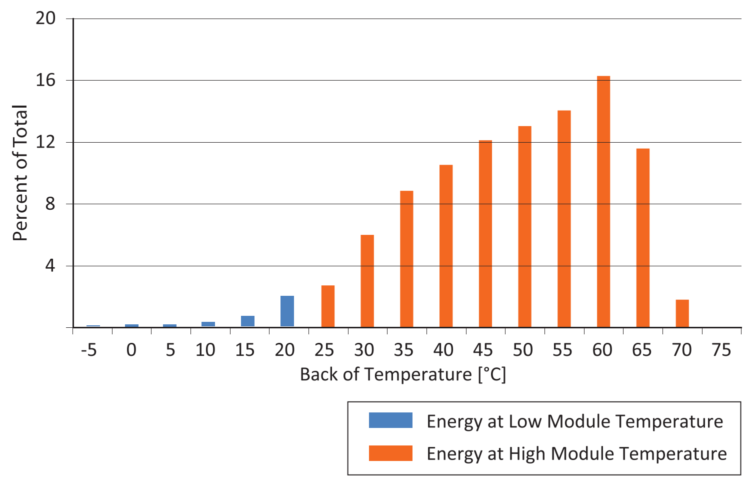

Figure 3. Distribution of power production vs. back-surface module temperatures [7].

"Solar power plants in high-temperature climates spend the majority of their operational lives above 25°C, where CdTe modules have a proven performance advantage over crystalline silicon solar modules."

For this operational First Solar power plant in the US desert Southwest, 94% of total energy was produced when the panels were operating at module temperatures of 25°C or higher. It is concluded that solar power plants in high-temperature climates spend the majority of their operational lives above 25°C, where CdTe modules have a proven performance advantage over crystalline silicon solar modules, producing more kilowatt hours of energy per installed kilowatt of capacity. The fundamental advantage of the low temperature coefficient of thin-film CdTe modules in high-temperature climates results in more energy output and therefore higher financial returns for system owners.

Short-term response – initial stabilization

Most PV technologies exhibit some form of non-linear initial efficiency loss, for several reasons. P-type monocrystalline silicon may experience light-induced degradation

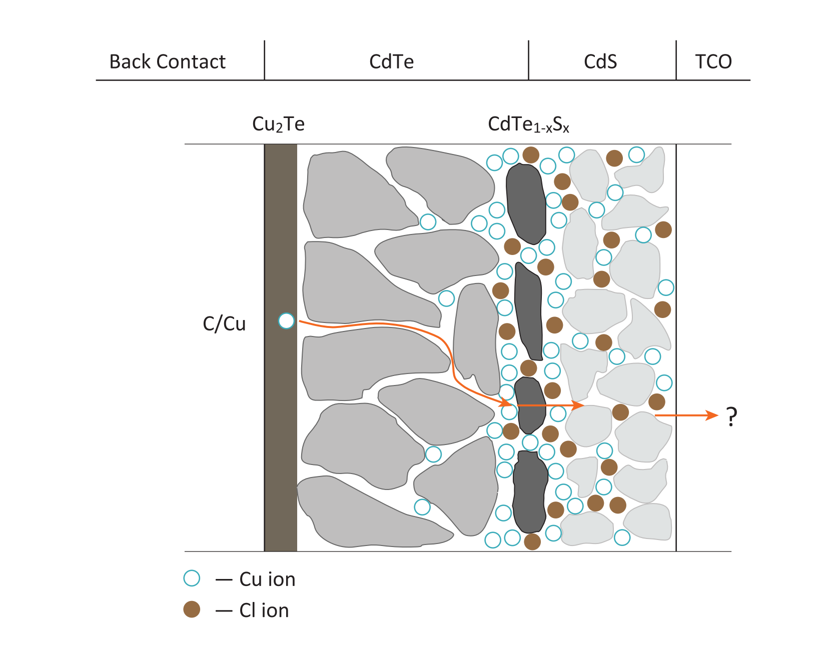

Figure 4. Copper migration through a CdTe device model (after Cahen et al. [10]).

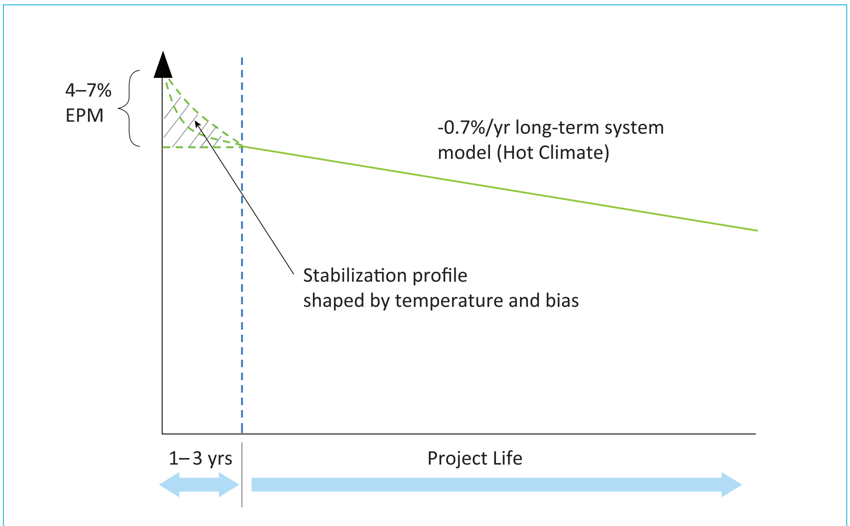

Figure 5. First Solar CdTe PV system degradation profile.

of approximately 2.5 to 3.5%, which varies as a function of the oxygen content of the wafers [8]. This is clearly reflected in tier 1 crystalline silicon manufacturers' warranties that discount module power output by 3% in year one [9]. Thin-film CdTe modules exhibit a similar phenomenon, but as a result of a different fundamental mechanism. The CdTe semiconductor device stabilizes because of the grain boundary diffusion of copper (Cu) from the back contact [10]. Although some details of the mechanisms remain elusive owing to the nanoscopic nature of the changes, it is generally accepted that Cu diffuses from a Cu-rich back-contact area through the CdTe absorber along grain boundaries and can accumulate at the CdTe/cadmium sulphide (CdS) interface. This is graphically depicted in Fig. 4, reproduced from Cahen et al. [10]. First Solar has optimized its product through the reduction and tighter control of the Cu introduced into the device and by reducing the sensitivity of the CdTe/CdS interface to the presence of Cu.

The process of diffusion can be accelerated in the laboratory by performing accelerated life tests under increased temperature and cell bias. At elevated temperatures it is observed that the longer the device is operated above its maximum power point voltage, the greater the efficiency loss will be. The mechanism can be explained by the built-in electric field of the solar cell opposing the thermal diffusion of ionic Cu, the applied bias effectively reducing the electric field strength, and, hence, enabling accelerated diffusion to the heterojunction [11]. A similar increase in efficiency loss because of an increased cell bias has been observed in accelerated life tests. When installed modules experience prolonged open-circuit conditions, cell bias is increased compared to the typical levels experienced when operating in normal, maximum power point conditions. This behaviour drives First Solar's recommendations that module open-circuit exposure time be minimized.

The magnitude of this initial efficiency loss is approximately 4–7% within the first one to three years, depending on climate and system interconnection factors, as shown in Fig. 5. High-temperature climates tend to accelerate this initial stabilization, while moderate climates tend to prolong this behaviour, so that it becomes difficult to distinguish from long-term device degradation.

To compensate for this initial efficiency loss, First Solar reduces the end-of-line measured module power to a lower nameplate power, which represents expected field-stabilized module power. To accomplish this, First Solar utilizes a proprietary module-rating process that applies an engineered performance margin (EPM). The EPM takes into account the expected initial stabilization derived from many megawatts of multi-year field exposure in hot climates. The EPM is applied at the end of the manufacturing line, after the simulator flash test and before module labelling.

"To compensate for this initial efficiency loss, First Solar reduces the end-of-line measured module power to a lower nameplate power, which represents expected field-stabilized module power."

On the basis of accelerated reliability and performance test data, combined with an historical evaluation of actual field performance, First Solar's energy prediction recommendation is to use nameplate module rating for the first year of energy prediction and to apply long-term degradation rates starting in the second year of operation. While the energy production in year one for a well-constructed system is likely to exceed nameplate-based energy prediction (because of the EPM), First Solar recommends maintaining nameplate-based energy prediction for a project's energy and financial pro forma in year one.

Long-term response – degradation

Starting in the second year of operation and for each year thereafter, First Solar recommends modelling system degradation rates of –0.5%/year in temperate climates and –0.7%/year in high-temperature climates. First Solar has thoroughly studied the two primary drivers of long-term module degradation – device stability and package integrity. The combined evaluation of these two primary long-term behaviours is used to establish long-term modelled degradation rates.

> "The copper diffusion mechanism, which drives the initial stabilization of the module, is also the primary contributor to the long-term degradation behaviour of the module."

The copper diffusion mechanism, which drives the initial stabilization of the module, is also the primary contributor to the long-term degradation behaviour of the module. On the basis of accelerated long-term light soaking and field data, it is observed that the rate of copper diffusion slows significantly as the device stabilizes in the first one to three years, and continues to drive a small sub-linear degradation of module efficiency year over year thereafter. The linear assumption is conservative, considering the underlying diffusion mechanisms, but in agreement with available field and accelerated life testing data.

A National Renewable Energy Laboratories (NREL) study captured in Fig. 6 provides some indication of observed degradation rates in multiple PV technologies' long-term operation. It also clearly shows that most technologies have demonstrated improvements in long-term observed degradation rates when comparing older vintage products built prior to the year 2000 ('Pre') with newer products built after the year 2000 ('Post'). Observed degradation rates for thin-film CdTe technology product built after 2000 are distinctly better than other thin-film technologies, and comparable to traditional crystalline silicon technologies.

> "After almost two decades of monitoring, NREL confirms the excellent reliability of First Solar's module technology, with no module failures in system operation."

The long-term performance of First Solar thin-film CdTe modules can be more specifically observed by examining the 17-year study performed by NREL, which reports a long-term degradation-rate linear fit of –0.53%/year (Fig. 7), based on the performance of a system in Golden, Colorado, USA [13]. After almost two decades of monitoring, NREL confirms the excellent reliability of First Solar's module technology, with no module failures in system operation.

First Solar has one of the largest monitored PV solar installation databases in the world, with more than 270MW (AC) worldwide and expanding to well over 1GW (AC) in the next few years. Fig. 8 shows the performance data extracted from these systems for a variety of sites ranging from a few kW to tens of MW.

The predicted energy ratio (PER) is the lifetime ratio of actual energy produced to the energy predicted. The PER substantiates First Solar's field performance record and validates First Solar's accuracy in predicting field performance. Degradation guidance of –0.5%/year in temperate climates and –0.7%/year in high-temperature climates is modelled

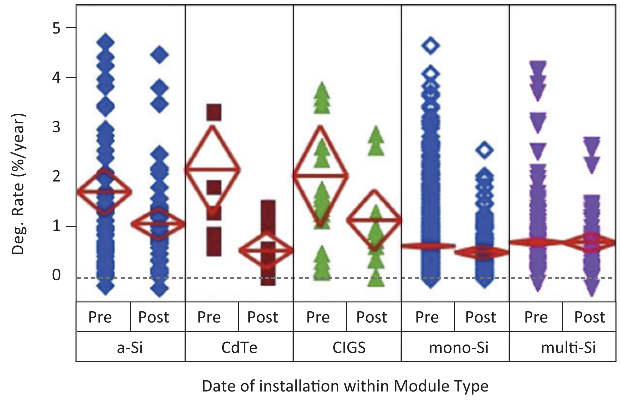

Figure 6. NREL study of degradation rates of various PV technologies [12].

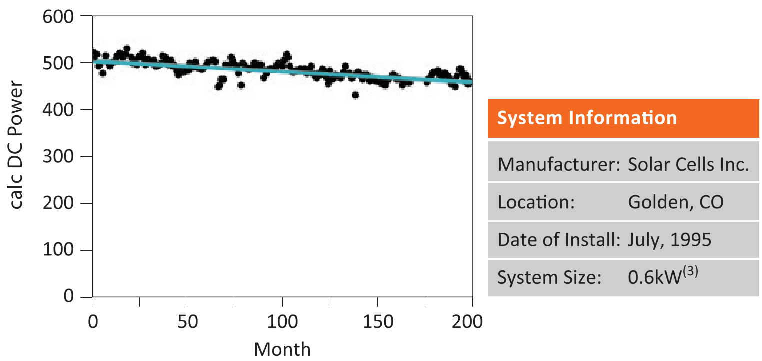

Figure 7. NREL January 2012 study of a First Solar system installed in 1995.

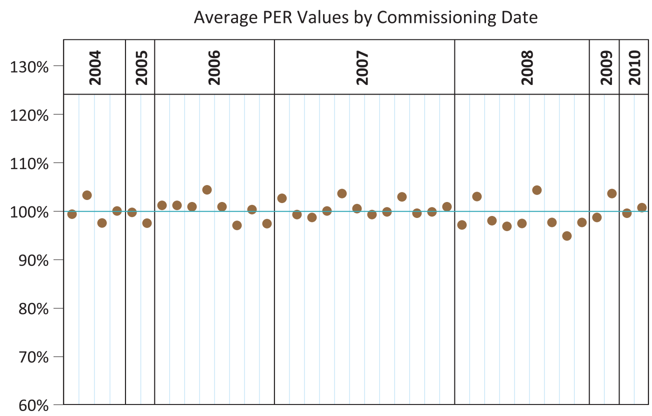

Figure 8. Predicted energy ratio for 270MW of installed systems using First Solar modules: >270MW monitored installations base, including >130MW of hot-climate deployments.

Power Generation

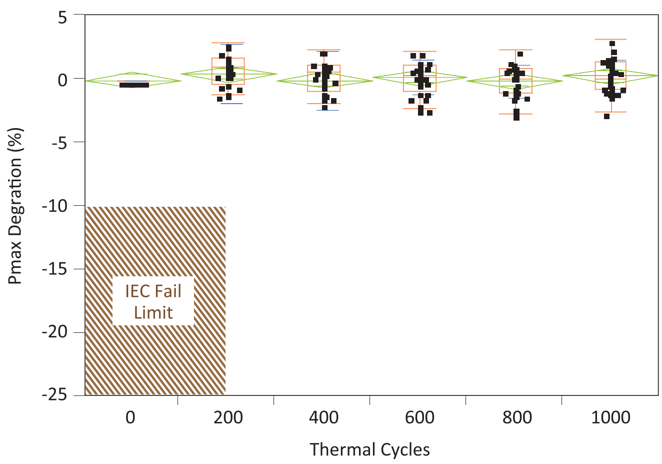

Figure 9. TC1000 testing results for First Solar modules (5X IEC TC200).

into predictions. As shown in Fig. 8, actual performance is close to 100% of the P50 prediction energy [14,15]. This indicates system performance consistent with First Solar's degradation model and supports the conclusion that First Solar can accurately predict system performance for power plants using its thin-film CdTe modules.

The reliability of module construction, which protects the active semiconductor device, is critical to maintaining reliable long-term product performance. First Solar conducts a variety of test sequences to ensure the longevity of the module material, encapsulation and connections. These tests consist of standardized certification protocols, extended versions of certification-based protocols, and proprietary accelerated life and stress tests. For example, one particularly applicable test for high-temperature climate performance is module thermal cycling (TC). This test cyclically exposes modules in a controlled environmental chamber to extreme temperatures from –40°C to +85°C. The intention is to stress connections in the module and compatibility of different materials' thermal expansion properties to ensure that the module maintains its power output and package integrity. The standard IEC-defined protocol for this test is 200 cycles (TC200) [16], and First Solar maintains successful IEC 61646 certification for the standard test protocol. To provide additional confidence in long-term reliability performance, First Solar modules are further evaluated in several tests which significantly extend these standard IEC protocols. As an example, a random population of 28 modules undergoes TC1000 testing consisting of five times more temperature cycles than the standard test protocol. Fig. 9 demonstrates that First Solar power output and electrical integrity remain effectively unchanged.

"First Solar modules are further evaluated in several tests which significantly extend these standard IEC protocols."

Independent third parties, including NREL, have observed and validated First Solar's long-term performance. Reputable global independent engineering firms have validated First Solar's energy prediction model, and long-term performance and gigawatts of projects using First Solar technology have been successfully financed.

Warranty accruals in high-temperature conditions

High-temperature conditions directly affect warranty failures of PV modules and balance-of-system components. Elevated temperatures accelerate physical processes, resulting in increased stress on conductors, connectors and other electrical equipment. Heat also has a negative impact on stress corrosion cracking in glass [17], polymer creep [18] and impurity diffusion processes [19]. This is the case for all PV technologies.

As previously discussed, high-temperature conditions also influence the initial stabilization and degradation behaviour of First Solar CdTe modules. The EPM is applied to First Solar modules to account for this temperature-driven behaviour and provide appropriate rating with regard to First Solar performance modelling and warranty constructs. In consideration of all these factors, First Solar's comprehensive reliability and performance testing, combined with actual field performance in high-temperature conditions, predicts that warranty failure rates in high-temperature climates should be slightly higher than in temperate climates. In anticipation of increasing sales in high-temperature locations, First Solar proactively increased its warranty reserve by one percentage point to ensure sufficient reserves to cover slightly higher expected failure rates. As other PV companies gain experience in designing, building and operating utility-scale solar power plants in high-temperature climates, it is likely that higher warranty reserves in these conditions will become more common.

Conclusions

First Solar has characterized module performance in hot climates and has addressed many of the challenges related to deploying PV solar power plants in high-temperature conditions:

- Solar modules deployed in high-temperature climates operate most of the time at module temperatures above 25°C, where the better temperature coefficient of CdTe relative to crystalline silicon results in higher energy yield.
- First Solar accounts for initial stabilization in its module efficiency by applying an engineered performance margin in the nameplate module power rating so that it represents expected field-stabilized efficiency.
- First Solar's energy prediction recommendation is to use nameplate module rating for the first year of energy prediction and to apply long-term degradation rates starting in the second year of operation. First Solar's long-term degradation modelling recommendation is –0.5%/year for moderate climates and –0.7%/year for hot climates.
- Long-term degradation is substantiated by an understanding of physical mechanisms and is reinforced by a combination of third-party evaluation, field data comparisons to predictions, and accelerated lab testing.
- The detailed performance characteristics of First Solar's PV modules – including temperature coefficient, initial stabilization, EPM and long-term degradation – are critical inputs to an accurate energy prediction model for power plants in high-temperature conditions.
- First Solar has significant experience in building and operating solar plants in high-temperature conditions and proactively increased its warranty reserve to compensate for slightly increased expected warranty failure rates in high-temperature conditions.

References

[1] Yingli Solar 2011, YGE 285 Series Datasheet, 1.
[2] Solar World 2010, Sunmodule SW 130/140 poly R6A Datasheet, 2.
[3] First Solar 2012, First Solar FS Series 3 Datasheet, 2.
[4] First Solar Competitive Array 2006–2007, Perrysburg, Ohio, USA.
[5] Collins, F. 2010, "Field performance of thin-film", *PHOTON 2nd Thin-Film Conf.*
[6] King, D.L., Boyson, W.E. & Kratochvil, J.A. 2004, "Photovoltaic array performance model", Sandia National Laboratories, Albuquerque, New Mexico.
[7] First Solar US Desert Southwest Array Data.
[8] Munoz, M.A., Chenlo, F. & Alonso-Garcia, M.C. 2010, "Influence of initial power stabilization over crystalline-Si photovoltaic modules maximum power", *Progr. Photovolt.: Res. Appl.*
[9] Trina Solar 2011 (July), Trina Solar Limited Warranty, 2.
[10] Cahen, D., Hodes, G. & Gartsman, K. 2000 (August). "Overcoming degradation mechanisms in CdTe solar cells", Second Annual Report (prepared under Subcontract No. AAK-8-17619-15), Weizmann Institute of Science, Rehovol, Israel.
[11] Corwine, C.R. et al. 2004, "Copper inclusion and migration from the back contact in CdTe solar cells", Department of Physics, Colorado State University, USA [available online at www.physics.colostate.edu/groups/photovoltaic/PDFs/CuMigrAsPub.pdf].
[12] Jordan, D.C. & Kurtz, S.R. 2011 (August), "Photovoltaic degradation rates – An analytical review", National Renewable Energy Laboratory (NREL).
[13] NREL & SCI (Solar Cells Inc.) 2012 (April), "NREL module performance report", First Solar Application Note PD-5-615.
[14] First Solar. "Series 3 recommended parametric descriptions for PVSYST", First Solar Application Note PD-5-301-03 MS.
[15] First Solar. "System parameter specs for PVSYST simulations", First Solar Application Note PD-5-301-SS.
[16] IEC 61646 (May 2008), "Thin-film terrestrial photovoltaic (PV) modules – Design qualification and type approval", International Electrotechnical Commission, Edn 2.
[17] Wiederhorn, S.M. & Bolz, L.H. 1970, "Stress corrosion and static fatigue of glass", Institute for Materials Research, National Bureau of Standards, Washington, DC.
[18] Miller, D.C. et al. 2010, "Creep in photovoltaic modules: Examining the stability of polymeric materials and components", National Renewable Energy Laboratory (NREL).
[19] Baetzner, D.L. et al. 2003, "Study of spatially resolved impurity diffusion in CdTe solar cells using voltage dependent quantum efficiency", Thin Film Physics Group, Zurich.

About the Authors

Nicholas Strevel is a technical sales engineer at First Solar, specializing in PV module technology and performance. He has worked in the thin-film PV technology field for six years, in module manufacturing, application engineering and business development. Nicholas has a BSME in mechanical engineering from Michigan State University, and also studied at the Rheinisch-Westfälische Technische Hochschule Aachen.

Lou Trippel is module product line director at First Solar, where he leads module product management and technical sales and is responsible for First Solar's PV module product life cycle management program. He has a bachelor's degree in electrical engineering from the University of Dayton and a master's degree in technology management from Stevens Institute of Technology. Having previously held several positions on First Solar's product management and technical sales teams, Lou has over a decade of experience in new product development and product management.

Markus Gloeckler is vice president of advanced research at First Solar. He received a Ph.D. in solid-state physics from Colorado State University and a bachelor's degree from the University of Applied Sciences Regensburg, Germany. Markus collaborated at Colorado State with several members of the US thin-film partnership program and the National Renewable Energy Laboratory. Since joining First Solar, he has had responsibilities in the areas of product characterization, modelling, efficiency improvement and the physics of reliability.

Enquiries

First Solar
Tel: 1-877-850-FSLR (3757)
Email: info@firstsolar.com

Experience You Can Trust, Reliability You Can Count On

First Solar is the premier provider of utility-grade PV power solutions, offering expertise and innovation across the entire solar value chain.

Learn more at firstsolar.com.

First Solar®