SUNPOWER

MORE ENERGY. FOR LIFE.™

SunPower® Module 40-year Useful Life

Executive Summary:

SunPower expects its modules (panels) have a useful life of more than 40 years, defined as 99% of modules producing at least 70% of their power. This is made possible through fundamental design differences which provide robust protection against real-world stresses. These differences are discussed in the context of comparative experimental data. In addition, SunPower's physics-based model, PVLife, provides the expected change in performance over time from major degradation and failure modes. This model matches well with field data. Collectively, these data suggest that a 40 year life is realistic useful life for SunPower modules.

Introduction

Due to the relative immaturity of large scale solar, the market generally assumes that modules have a useful life equal to the warranty period and leave no residual value afterwards. However, in most other industries this is not the case. For instance, consumer electronic products have warranties of one to three years; yet, are used for five to seven years.

SunPower warrants its modules with a linear power warranty, leaving an asset producing at least 87% of warranted power at the end of 25 years[1]. Further, SunPower offers the industry's first combined 25 year product and power warranty. The reason SunPower can confidently offer this high level of guarantee is due to the fundamental design differences of SunPower modules.

Briefly, these design differences include the use of n-type silicon prevents early degradation due to LID. The thickly plated, tin coated copper foundation of the Maxeon® cell is highly resistant against the forces of moisture and oxidation. This metal foundation allows for thinner, more flexible silicon, resulting in a cell which can withstand repeated snow and wind loading and can crack without significant power loss. Electroplating the metal directly onto the cell ensures a strong and uniform bond with low residual stresses. Cells are connected via an interconnect and three solder pads on the edges of each side of a cell, which provide relief for thermal expansion and a redundant electrical connection. Conventional Modules[2] connect the cells through a process intensive ribbon attachment. This difference gives the Maxeon cell extreme robustness against thermal cycling.

Additionally, Maxeon cells have a low breakdown voltage which occurs uniformly across the cell. In a reverse-bias condition (shaded), thermal runaway is mitigated, regardless of whether or not bypass diodes are present. SunPower's X series modules, which make up an increasing portion of the product mix, has even better reverse bias characteristics, resulting in an even more shade tolerant module.

[1] See http://us.sunpowercorp.com/ for current warranty terms.

[2] Definitions used throughout: "Conventional Module" or "Conventional Panel" is a 240W panel, 15% efficient, approximately 1.6 m2, made with Conventional Cells. "Conventional Cells" are silicon cells that have many thin metal lines on the front and 2 or 3 interconnect ribbons soldered along the front and back.

Finally, SunPower modules are highly resistant to potential induced degradation (PID), as shown through independent third party testing.

The purpose of this paper is to define the criteria for a 40 year useful life and to share the experimental and analytical support underlying SunPower's expectation that the panels should have a useful life exceeding 40 years.

"Useful Life" Defined

SunPower defines the end of the useful life of a solar system installation as the time when 1% of the panels have dropped to below 70% power output. Said another way, 99% of modules are producing more than 70% of original rated power. This concept is similar to that used in equipment depreciation, where the useful life is the end of the period during which an asset will be used to generate revenues. There is no standard industry definition for useful life; however, this definition ensures that a site will continue to produce useful energy without incurring significant maintenance or large module current mismatch that will have a serious impact on the output of the solar field. In order to ensure this definition permeates into the product design cycle, SunPower has set this definition in requirements documents for module design and qualification.

Experimental Data

SunPower regularly tests its modules in various stresses meant to accelerate the degradation in the real world as part of its extensive qualification and reliability testing programs [1]. Some summary test results are discussed below.

Heat and Humidity

The certification standard (IEC61215) test for the effects of moisture and humidity effects is the Damp Heat 1000 (DH1000) test, which places the product in an environmental chamber at 85ºC and 85% relative humidity (RH) for 1000 hours. As with other certification requirements, this test is not designed to indicate reliability at 25 years; rather, it is intended to indicate a nominal level of safety in the field. Kempe more recently suggested [2] that 2000-3000 hours may be more appropriate simulating 20 years in a hot and humid climate, such as Miami, Florida or Bangkok, Thailand. Assuming the conservative case that a module is in such a climate, 6000 hours would represent 40 years.

Figure 1 shows data a Fraunhöfer Institute study, performed by TÜV and Fraunhöfer Institute, and published by Köhl [3], for a group of modules from seven unnamed Conventional Module manufacturers with at least 100MW of production per year in 2010. The plot shows performance after increasing hours of exposure to damp heat – well beyond basic industry certifications. While well-built Conventional Modules fare well up to DH2000, shortly thereafter their power output (normalized by initial output) degrades significantly.

SunPower performed testing in the same standard DH conditions (note SunPower's Reliability lab is certified by UL to carry out its own testing to UL standards). The black line shows that SunPower's current generation of modules degrade less than 3% after DH7500. SunPower's linear degradation indicates that the stress causes a slow and steady wear-out, as opposed to abrupt catastrophic failure.

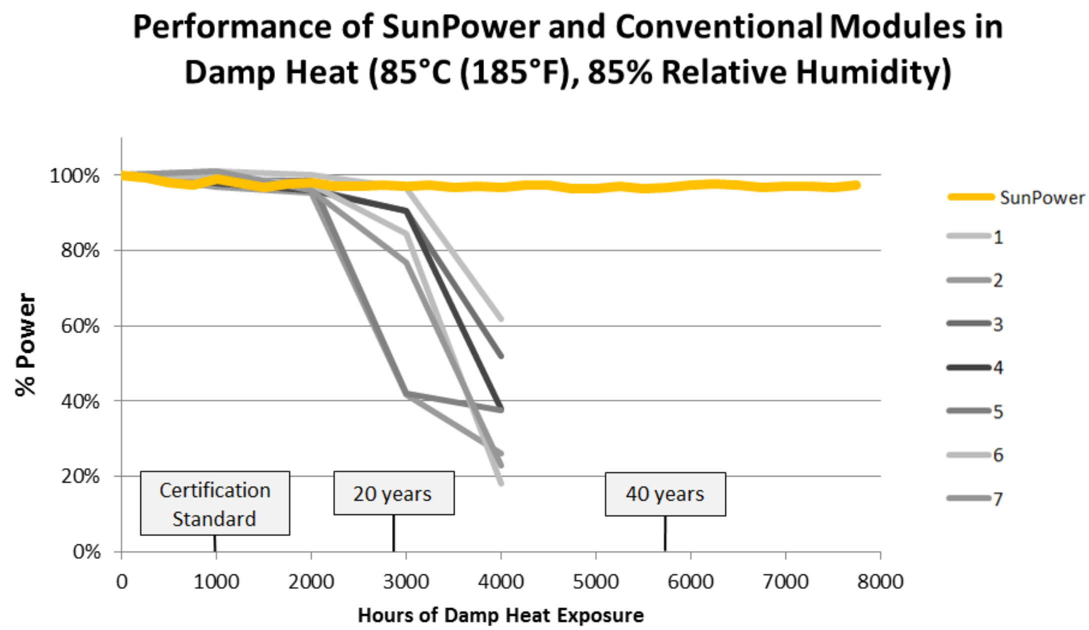


Figure 1: Damp heat testing of seven Conventional and SunPower modules. The Conventional Modules in Köhl's study show a sharp power drop starting after 2000 hours, while SunPower modules remain relatively unaffected beyond 7000 hours. Equivalent years in a hot and humid environment (e.g. Bangkok) [2] are shown on bottom axis. Sensitivity analysis gives ±30% on 20 year equivalent time.

The difference in performance under damp-heat stress is due to the design differences of the cells. Conventional Cells have thin metal lines on the sunny side to conduct current through the module, and those lines are susceptible to corrosion due to their necessarily small size (so as not to block the incoming photons), and their composition (silver paste). SunPower has no metal on the front of the cell, and the entire back of the cell is covered with a tin-plated copper foundation. The tin-plated copper is very resistant to corrosion, and the volume of metal is so large that even substantial corrosion stress causes very little change in the resistance of the circuit, providing high robustness against the effects of moisture.

Temperature Cycling

The industry-standard certification test for reliability against moisture and humidity effects is thermal cycling for 200 cycles (TC200), which places the product in an environmental chamber which swings from -40ºC to 85ºC 200 times. There is no consensus on the acceleration factor of this test due to the dependency on environmental factors, so it is difficult to relate number of cycles to years in the field.

SunPower conducted a comparison using internal test data and data from Köhl's publication [3] (Figure 2). The results for the Conventional Module manufacturers vary substantially. While some manufacturers perform well for the period of testing; only degrading a few percent even at TC800, one product is down 10% by TC400, and down >25% by TC500; two other products are down 8%-9% by TC800. Note that all of these products pass the standard IEC certification standard of TC200. In contrast, SunPower's modules well in the test, exhibiting only 2% degradation at TC2000, ten times the duration of the IEC certification standard.

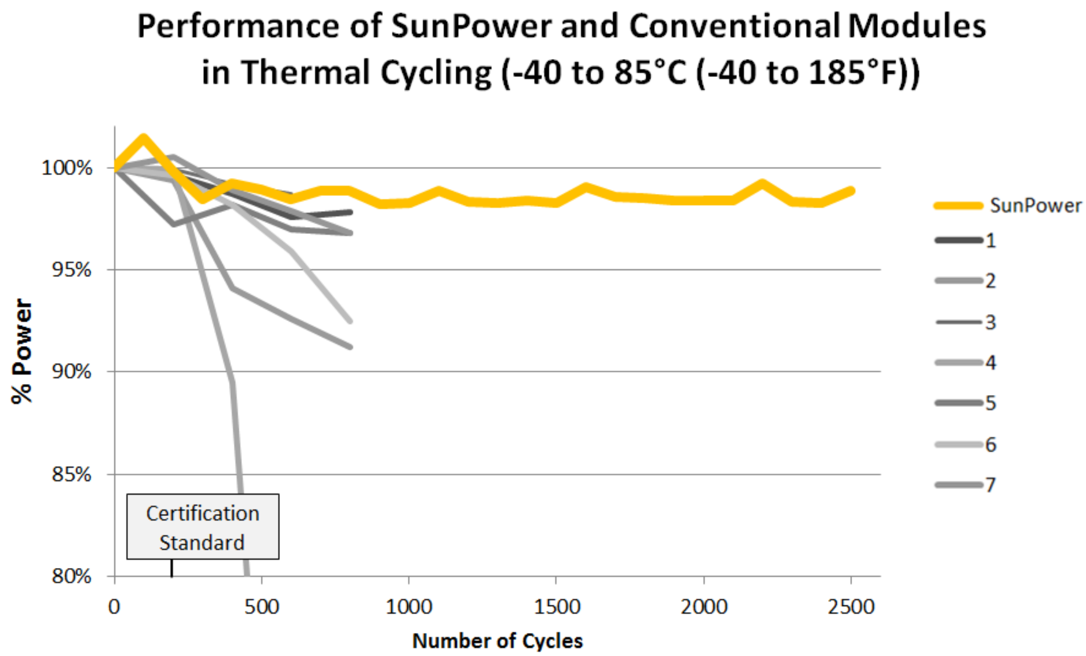


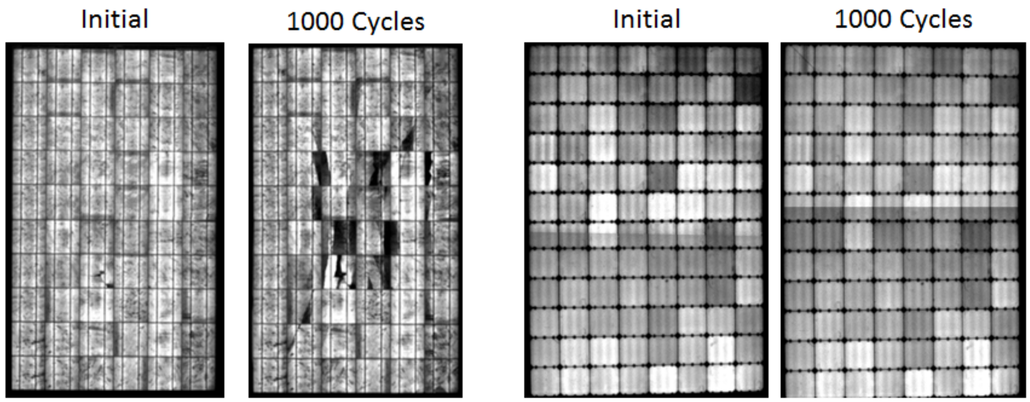
Figure 2: Thermal cycle testing of seven Conventional and SunPower Modules. The Conventional Modules in Köhl's study start to degrade steadily after 200 cycles, while SunPower remains practically unaffected at 2500 cycles.

The primary reason that SunPower cells are more robust has to do with cell interconnection. The cell interconnect on a Conventional Cell is performed by soldering two or three metal ribbons at multiple points across the entire cell. Due to the difference in the amount of thermal expansion between the ribbon and the cell, stress can build up on the solder joints, which can act as initiation points for cracks and power loss [4]. Further, a difficult to perform strain-relief bend should be applied between cells to extend the lifetime [5]. In contrast, SunPower cells are connected with a strain-relieved copper bar and six solder pads per cell. Solder joints are small, so the mismatch from thermal expansion results in less stress in the joint. Further, multiple solder joints provide redundancy in case a single joint fails.

Dynamic Loading

SunPower's design qualification includes a dynamic load test (DLT), where a force of 2400Pa is repeatedly applied to the front and back of the module, deflecting it back and forth cyclically. This is equivalent to 50 lb/ft^2 (244 kg/m^2) load or a sustained wind speed of 90mph (145kph) – equivalent to a category one hurricane. This test is designed to ensure that a product can withstand a lifetime of shipping, installation, and environmental stresses.

A side-by-side comparison of a Conventional Module and a SunPower module in this dynamic load test is shown in Figure 3. After 1000 cycles, the standard efficiency module shows several broken cells in the center, and a power loss of nearly 4%. The shunt resistance, an indication of module integrity, has dropped 25%. The SunPower module, on the other hand, shows no broken cells and no measurable power loss; the shunt resistance appears to have risen slightly but this is within the tolerance of flash testing accuracy.



	Initial	500	1000
Power (W)	233.2	232.2	224.2
% change	0%	0%	-4%
Rsh (ohm)	2116	1695	1587
% change	0%	-20%	-25%

	Initial	500	1000
Power (W)	319.1	318.8	319.2
% change	0%	0%	0%
Rsh (ohm)	7441	7412	7484
% change	0%	0%	1%

Figure 3: Electroluminescent images flash test data after 1000 cycles of dynamic loading to 2400Pa (equivalent to 130mph (209kph) wind), conducted at SunPower. The Conventional Module (left) suffered from power loss while the SunPower module (right) was not significantly affected.

Reverse Bias and Bypass Diodes

When cells are put into reverse bias, instead of converting photons to electricity, they convert electricity to heat. This happens any time the current generated by the rest of the cells in the string of modules exceeds the current that a cell can support. Common causes of reverse bias are shading from leaves, chimneys, or the buildup of soiling along the bottom of a module.

If too much heat is dissipated from a reverse bias cell, particularly if that heat is concentrated to a small defect region on the solar cell, the heating can cause failure of the other components within the module, such as the backsheet, glass, or encapsulant. Conventional Modules rely on bypass diodes to deactivate the portion(s) of the module where one or more cells are shaded, typically resulting in a 33% power drop. While this has a negative effect on energy output, it mitigates the heating issue. One tradeoff of this design is that the reliability of the module is tied to the bypass diode.

Diode life depends on several factors such as diode quality, junction box handling, and module installation; but, all diodes will eventually fail with use. This is because an activated diode runs at an elevated temperature, reducing the remaining life of the diode [6], [7]. Depending on how a diode fails, it can permanently remove a substring from the module or allow a shaded cell to run unmitigated in reverse bias, leading to module failure.

SunPower's cells run in reverse bias at much lower temperatures, so bypass diodes are not required to ensure long term reliability (Table 1). However, when enough cells are in reverse bias, the cumulative power loss from the shaded cells can exceed the power produced from the cells in forward bias, so SunPower includes diode protection to enhance energy yield.

Table 1: Illustrative comparison of estimated cell power dissipation with one cell in reverse bias

	SunPower X21	SunPower E20	Conventional Module
Module Power	345	327	240
Number of cells	96	96	60
I_{mp} (STC, amps)	6.02	5.98	8.14
V_{mp} (STC, volts)	57.3	54.7	29.5
V_{Rb} (reverse bias, volts)	2.5	5.5	17[1]
Heat (W)[2]	**15**	**33**	**138**
% Module power remaining:			
with diode	**96%**	**90%**	**67%[3]**
without diode	**96%**	**90%**	**42%**

[1] V_{RB} value from literature [8].
[2] $Power_{Rb} = V_{Rb} \times I_{mp}$, all of this power is dissipated as heat.
[3] % Power = Dissipated Watts / Module Power. Assumes diode shorts 1/3 of the Conventional Module when present. If diode does not activate, assumes power dissipates as heat. Estimate for comparison purposes only.

The average power dissipation indicates the impact on module power, but it does not indicate the lifetime challenge when a cell is in reverse bias. For a SunPower cell, the heat dissipation is uniform over the surface area of the cell and the temperature rise is moderate. This is because the cell architecture places a heavily doped positive region immediately adjacent to a heavily doped negative region evenly across the back of the cell, resulting in a lower voltage potential for a cell in reverse bias.

The design of the Conventional Cell places a heavily doped region at the top and bottom, with a lightly doped region in between. When the cell is forced into reverse-bias, the current finds the weakest point in the cell to get from the positive side to the negative side – often at a small region along the edge of the cell – creating a focused hotspot. For example, using the values in Table 1, and assuming a hotspot region of 9 cm^2, the Conventional Module has a heat flux of more than 15 W/cm^2. Higher heat flux causes results in higher temperatures, as shown in a recent study, where a Conventional Cell in reverse bias ran more than 70℃ (159℉) hotter than an equivalently shaded Maxeon cell, causing irreversible damage to the Conventional Module.

Summary of experimental data

SunPower modules show significantly less degradation than Conventional Modules in the industry standard reliability stresses meant to simulate hot and humid environments and constant thermal cycling. Testing for the dynamic loading affects from shipping, installation, and field exposure also show less degradation. Finally, SunPower modules do not require a diode for safe operation in shaded conditions, removing the potential for a single point of failure.

Analytical Data

In addition to reliability testing, SunPower engages in fundamental research, supported by both accelerated testing and field data. Years of research on all key degradation modes are integrated into a cell-by-cell, hour-by-hour performance model called PVLife which has been validated and published in scientific conference proceedings [9], [10], [11], [12] .

PVLife primarily models the physics of each failure mode – it is not a statistical or "reliability block-diagram" model. Instead, the intent is to solve for a specific system/array's degradation rate, given the module used, its electrical and physical configuration, its mounting, and the weather and irradiance expected. PVLife solves the coupled electro-thermal equations that predict module performance for a given set of weather conditions in order to obtain cell temperature and electrical parameters; at each hour of the day for every day of the system's life. It computes the incident spectrum, electrical operating point, and temperature of each individual cell. PVLife uses this electrical and thermal solution as input to physical models for the key degradation and failure modes and computes incremental degradation and chance for failure during each time-step in the simulation. Also, different modes are coupled via the electro-thermal solver.

In order to determine the effects of different degradation modes, SunPower invested in years of fundamental research. Through experimentation and corroboration with field data, the underlying physics of failure for each mode were identified and quantified.

The degradation modes modeled for SunPower modules are:

- Cell damage induced by ultraviolet (UV) radiation
- Photo-thermal encapsulant browning
- Polarization
- High-voltage degradation
- Soiling
- Other effects

An example of a PVLife analysis for a SunPower module installed on a T0/Oasis tracker in a harsh desert location indicates less than 10% power degradation at fifty years (black line, Figure 4). The lower 90% confidence level, reflecting model uncertainties, shows less than 20% power degradation.

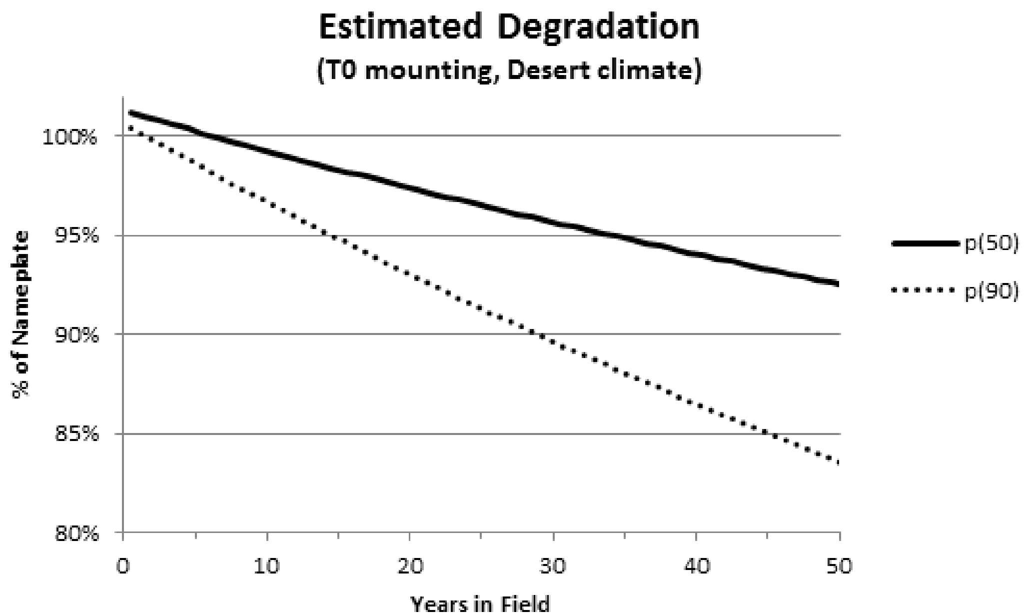


Figure 4: PVLife output for the current generation of Maxeon cells (solid line) in a utility installation and a desert climate. Lower 90% confidence level (dashed line) reflects the combined uncertainties from degradation modes. Module starting point is offset to match mean module power distribution above nameplate rating.

Failure Modes

Unlike degradation modes, failure modes do not cause appreciable degradation in performance until catastrophic failure. Two key failure modes govern the life of SunPower modules:

- Backsheet cracking due to relative humidity and hydrolysis
- Solder-joint failure due to temperature cycling

Backsheet Failure

PVLife conservatively defines the onset of an abrupt reduction of strength, as documented by McMahon [13], to a 100% chance of failure. McMahon showed that, as polymer chains break down due to humidity and heat, the entire polymer network slowly weakens to a critical point at which the tensile strength starts to decrease at an accelerated rate. This is conservative because at the critical point, the backsheet material still maintains at least 60-65% of its initial strength. Based on these criteria, the analysis indicates that SunPower backsheet materials are robust against this failure mode for well over 70 years (Figure 5) even in harsh desert climates.

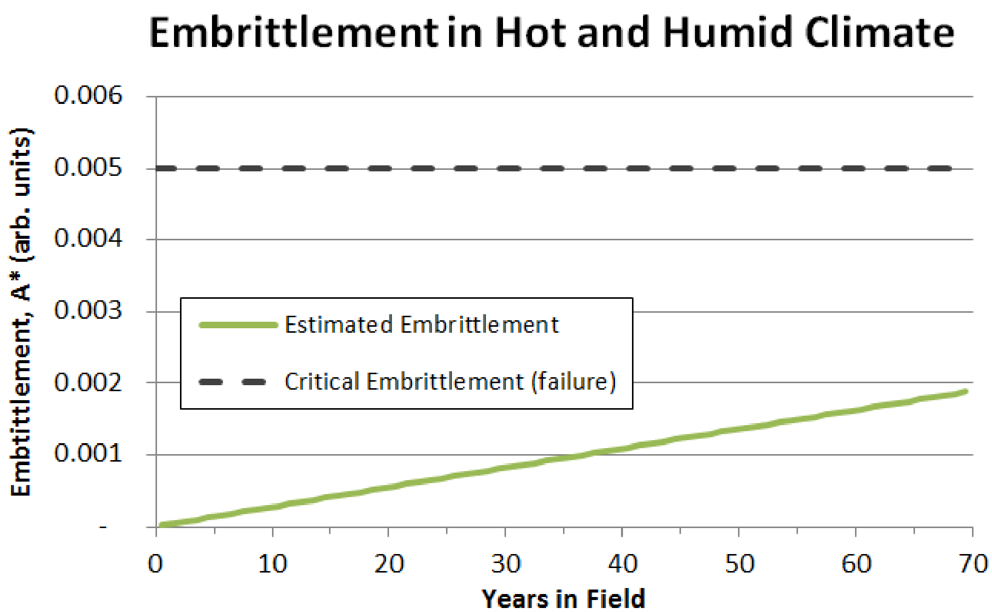


Figure 5: Backsheet degradation, based on experimental data fit to McMahon's model, suggests sufficient backsheet strength for more than 40 years

Solder Joint Failure

SunPower conducted thermal cycling experiments with different temperature profiles. Using the failure time in these accelerated tests and an acceleration factor calculator, the lifetime distribution of solder joints in any given environment can be determined. Solder joint failure is expected to be the dominant end of life failure mode for SunPower modules.

SunPower cells have three solder connections on each side of a cell. In the event that one solder joint fails, the power can travel through the other two, resulting in redundant cell interconnection.

Failure for a module is considered to occur when the probability of all three solder joints on one side of a cell breaking is above 1%. Because current cannot pass through the substring, running instead through the bypass diode, the module power will fall below the 70% criteria.

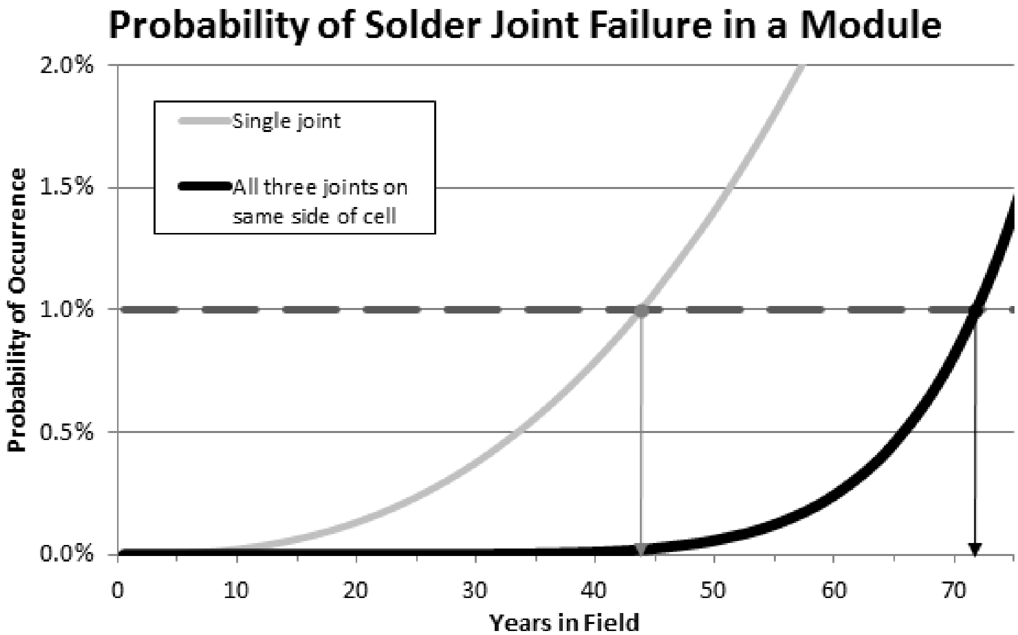


Figure 6: results of solder joint sub-model show that the probability of module failure exceeds the 1% threshold after 70 years. Module failure is defined as all three joints on one side of a side of a cell within a module failing.

PVLife Validation

SunPower has deployed over 3GW of modules globally and manages two fleets of Conventional Modules from acquisitions, 240MW from twenty manufacturers and 500MW from a high quality European manufacturer.

Recently, SunPower conducted a system level degradation study of 445 utility systems within the SunPower operating fleet [14]. The study included 266 systems (86MW) using SunPower modules as old as 5.5 years, and 179 systems (42MW) using non-SunPower modules as old as 11.5 years. Data spanning back to the site commissioning date were used to determine fleet-wide degradation rates, representing 3.2 million module-years of monitored data. Black and Veatch, an independent engineering firm, audited the methods and results for the SunPower fleet [15].

The annual system power degradation rate (AC side of the inverter) for SunPower systems using the previous generation of modules, was -0.32±0.05% (95% confidence) per year, and for non-SunPower Conventional Module systems was -1.25±0.05% (95% confidence) per year, and in both cases was shown to be constant with time.

SunPower is currently collecting field data on its current generation of modules in order to conduct a similar analysis; however, these modules have not been fielded in significant quantities for enough time.

PVLife estimates for the previous generation SunPower module compare well with laboratory accelerated testing data as well as field data obtained from various SunPower product monitoring efforts. These results serve to validate the electro-thermal model, degradation sub-models, and increase the understanding of the coupled effects of degradation.

The analyzed field data of the previous generation of SunPower modules compares very well with the PVLife simulations (Figure 7).

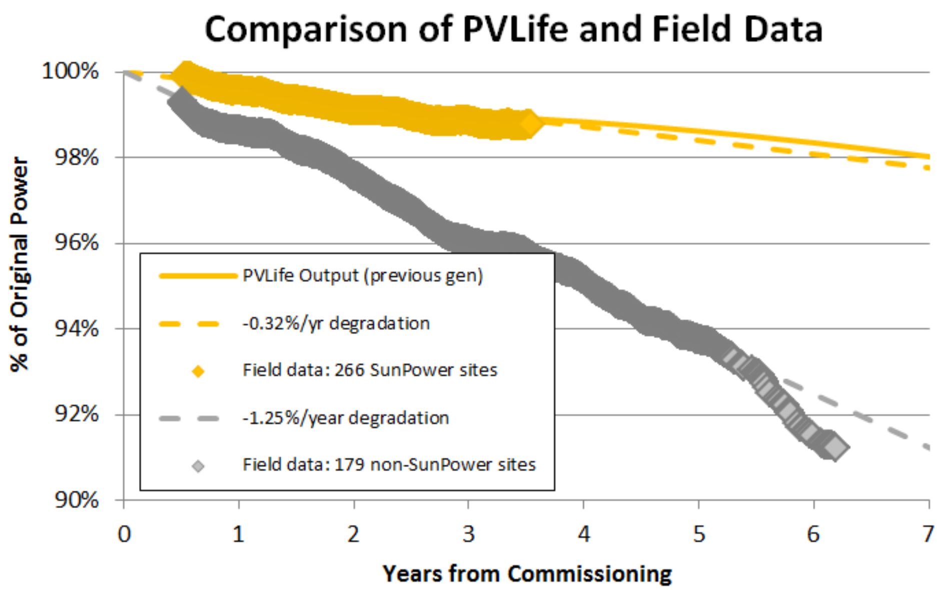


Figure 7: Comparison of PVLife and analyzed field data from the previous generation of SunPower modules (yellow). PVLife compares well with field data. For reference, the degradation of Conventional Modules is included (grey).

Summary of Analytic Data

The physical model of degradation and catastrophic failure, which is backed up by field data and stress tests, suggests that SunPower modules should have a total degradation well under 30% over 40 years due to the primary degradation modes. Further, catastrophic module failure from backsheet delamination or solder joint failure should be well below 1% even after 40 years. SunPower continues to actively pursue design changes to reduce the impact of degradation and failure modes to further extend module lifetime.

Conclusion

SunPower has invested heavily in module design, qualification, and analysis to design panels with an expected useful life exceeding 40 years. SunPower defines the end of the useful life of a solar system installation as the time when 1% of the panels have dropped to below 70% power output. Experimental data which emulate stresses seen in the real world show that SunPower modules are robust against a variety of stresses. Further, PVLife, a model which simulates hour-by-hour degradation in a particular climate and is based on years of fundamental research, was used to estimate degradation and failure rate for SunPower modules. PVLife has been validated through various comparisons against measured field data. These data suggest that it is reasonable to expect SunPower modules to have a useful life exceeding 40 years.

Bibliography

[1] D. Degraaff, S. Caldwell, R. Lacerda, G. Buena, A. Terao, and D. Rose, “Qualification, Manufacturing, and Reliability Testing Methodologies for Deploying High-Reliability Solar Modules,” in *European Photovoltaic Solar Energy Conference and Exhibition, 25th*, 2010.

[2] M. Kempe, J. Wohlgemuth, D. Miller, M. Reese, and A. Dameron, “Modeling the Ranges of Stresses for Different Climates / Applications,” in *International PV Module QA Forum*, 2011.

[3] M. Köhl, K. Weiss, M. Heck, and D. Philipp, “PV reliability : Results of a German four-year joint project Part I : accelerated ageing tests and modelling of degradation,” in *European Photovoltaic Solar Energy Conference and Exhibition, 24th*, 2009.

[4] J. Wendt, M. Träger, M. Mette, A. Pfennig, and B. Jaeckel, “The Link Between Mechanical Stress Induced By Soldering And Micro Damages In Silicon Solar Cells,” in *European Photovoltaic Solar Energy Conference and Exhibition, 24th*, 2009, pp. 3420–3423.

[5] N. Bosco, “Modeling Metal Fatigue As a Key Step in PV Module Life Time Prediction outline • Modeling metal fatigue,” in *PV Module Reliability Workshop*, 2012.

[6] E. Maset, E. Sanchis-kilders, J. B. Ejea, A. Ferreres, J. Jordán, V. Esteve, P. Brosselard, X. Jordà, M. Vellvehi, and P. Godignon, “Accelerated Life Test for SiC Schottky Blocking Diodes in High-Temperature Environment,” *IEEE Transactions on Device and Materials Reliability*, vol. 9, no. 4, pp. 557–562, 2009.

[7] S. Somisetty, P. Ersland, X. Yang, and J. Barrett, “Reliability investigation and characterization of failure modes in Schottky diodes,” *Microelectronics Reliability*, vol. 46, no. 8, pp. 1254–1260, Aug. 2006.

[8] K. Bothe, K. Ramspeck, D. Hinken, C. Schinke, J. Schmidt, S. Herlufsen, R. Brendel, J. Bauer, J.-M. Wagner, N. Zakharov, and O. Breitenstein, “Luminescence emission from forward- and reverse-biased multicrystalline silicon solar cells,” *Journal of Applied Physics*, vol. 106, no. 10, p. 104510, 2009.

[9] M. Mikofski, M. Anderson, S. Caldwell, D. Degraaff, E. Hasselbrink, D. Kavulak, R. Lacerda, D. Okawa, Y. Shen, A. Tedjasaputra, A. Terao, and Z. Xie, “A Dynamic Cell-by-Cell PV System Model to Predict Lifetime Performance and Reliability,” in *European Photovoltaic Solar Energy Conference and Exhibition, 26th*, 2011.

[10] M. A. Mikofski, D. F. J. Kavulak, D. Okawa, Y. Shen, A. Terao, M. Anderson, S. Caldwell, D. Kim, N. Boitnott, J. Castro, L. Ann, L. Smith, R. Lacerda, D. Benjamin, and E. Hasselbrink, "PVLife : An Integrated Model for Predicting PV Performance Degradation over 25 + Years," in *IEEE Photovoltaic Specialists Conference, 38th*, 2012, no. 3, pp. 1744–1749.

[11] E. Hasselbrink, M. Anderson, Z. Defreitas, M. Mikofski, Y.-C. Shen, S. Caldwell, A. Terao, D. Kavulak, Z. Campeau, and D. DeGraaff, "Validation of the PVLife Model Against 3 Million Module-Years of Live Site Data," in *IEEE Photovoltaic Specialists Conference, 39th*, 2013.

[12] E. F. C. Hasselbrink, D. Ph, C. Mark, D. F. J. Kavulak, D. Okawa, Y. Shen, A. Terao, M. Anderson, W. Caldwell, D. Kim, N. Boitnott, L. Ann, L. Smith, and R. Lacerda, "Module Lifetime Prediction through Integrated Modeling of Known Failure Modes," in *PV Module Reliability Workshop*, 2012, pp. 1–18.

[13] W. McMahon, H. A. Birdsall, G. R. Johnson, and C. T. Camilli, "Degradation Studies of Polyethylene Terephthalate," *Journal of Chemical Engineering Data*, vol. 4, pp. 57–79, 1959.

[14] M. Anderson and Z. Defreitas, "A SunPower Fleet-Wide System Degradation Study using Year-over-Year Performance Index Analysis," 2012.

[15] R. Romero, "Review of SunPower Fleet-Wide System Degradation Study using Year-over-Year Performance Index Analysis."