ERTHOS

Reducing Degradation Rates with Earth Mount Solar® PV

White Paper

Abstract

Solar module degradation is an important consideration when estimating the future production of a utility-scale photovoltaic (PV) system. Degradation can happen for a variety of reasons and is, at a fundamental level, unavoidable. It is not possible to design a solar installation that does not experience some amount of module degradation, whether as a result of design limitations, environmental impacts, or other factors. It is possible, however, to significantly reduce degradation, thus maximizing your PV system's future power production and protecting the return on your investment.

Earth Mount Solar® PV systems were designed to do precisely this. Because the solar modules in an Earth Mount Solar® PV system are installed directly on the ground, they attenuate several of the causes of module degradation, such as cyclic wind loading, thermal cycling, non-uniform soiling, and potential-induced degradation (PID). This innovation, combined with a higher DC/AC ratio, enables Earth Mount Solar® PV systems to reduce annual effective energy loss by approximately 50% when compared to single-axis tracker (SAT) systems.

Module Degradation

As a module ages, it will be exposed to a variety of factors that negatively impact performance, leading to decreased power output and reduced financial return. These factors are referred to as degradation modes. According to a study published by NREL, the most significant degradation modes for crystalline silicon (c-Si) systems, when accounting for both frequency and severity, are as follows:[1]

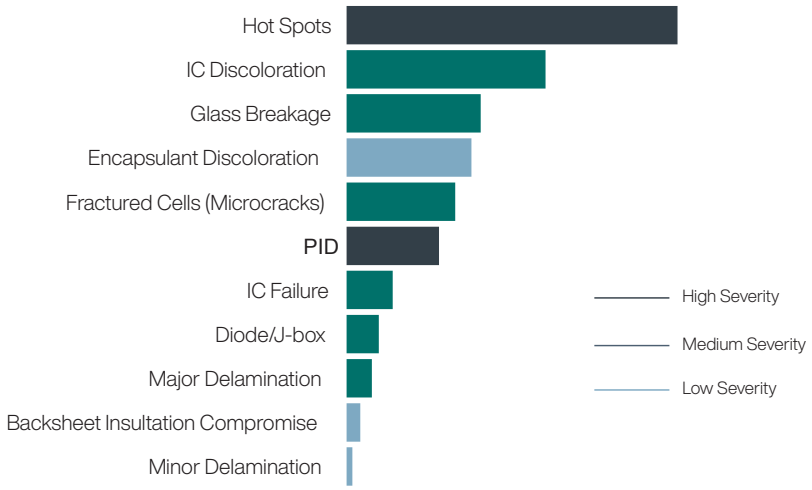

Figure 1 — Most significant degradation modes for c-Si systems, with bar length representing frequency

Understanding how and why modules degrade is vital to minimizing that degradation, maximizing module output, and protecting your long-term investment. In the following pages, we will take a closer look at several of the most significant degradation modes identified in Figure 1 above — hot spots, fractured cells (or microcracks), and potential-induced degradation (PID) — and describe how Earth Mount Solar® PV systems represent a significant advancement in our ability to reduce module degradation.

Cited Reference

1. Photovoltaic Failure and Degradation Modes (Link)

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The Benefits of Earth Mount Solar® PV

Single-axis tracker systems, which are currently the most common system architecture for utility plants, suffer from a range of degradation modes, including most of those in Figure 1 on the previous page. Earth Mount Solar® PV systems, with modules installed directly on the ground, mitigate the frequency and/or severity of three of the most impactful degradation modes — hot spots, fractured cells, and PID — leading to a significant reduction in annual energy loss due to degradation.

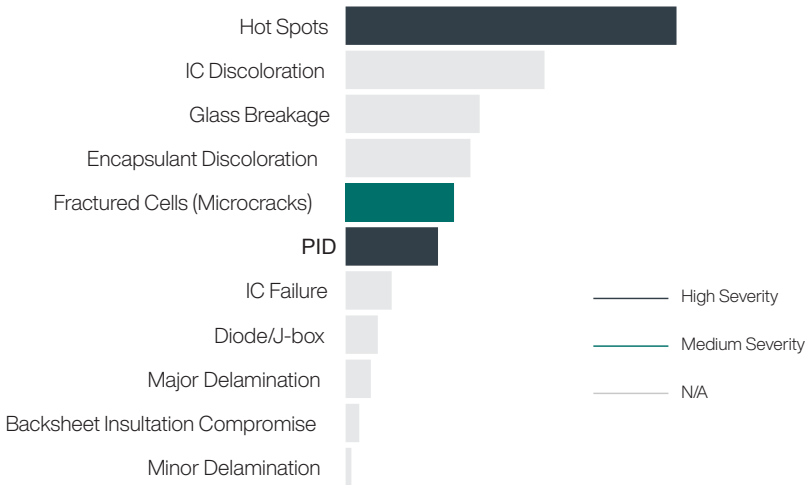

Figure 2 — Highlighted degradation modes

Within each of the three degradation modes highlighted in Figure 2 above, there are specific causes that contribute to the degradation mode in question. Hot spots, for example, are primarily caused by uneven soiling and vegetation, whereas microcracks are most often the result of wind harmonics, anchor points, and thermal cycling, among other reasons.

Compared to standard SAT installations, Earth Mount Solar® PV systems are more effective at mitigating the causes for each of these three degradation modes, as shown in Figure 3 on the next page. Additional detail on each cause and mode, and the Earth Mount Solar® PV system's solution for each of them, is provided beginning on page 6.

Degradation Modes	Cause(s)	Comparison of Earth Mount Solar over SAT system	Benefit of Earth Mount Solar® PV
Hot Spots	Uneven Soiling	Beneficial	Automated nightly robotic cleaning of entire array prevents hot spots due to soiling.
	Vegetation	Beneficial	Vegetation growth is greatly reduced because of the tight configuration of the modules and the application of geoenzymes and pre-emergents to the soil.
Fractured Cells (Microcracks)	Wind Harmonics	Beneficial	No module instability even in extreme wind speeds up to 194 MPH.[2] Front-side-only wind loading prevents significant harmonics.
	Limited Anchor Points	Beneficial	Evenly distributed support of the frame, rather than at four distinct anchor points as is common in SAT systems, eliminates localized stresses.
	Thermal Cycling	Beneficial	Reduced wind exposure and greater heat exchange with adjacent earth result in more stable/uniform operating temperatures.
	Hail	Variable	Hail, typically accompanied by wind, falls at an angle creating a lower impact force that is non-perpendicular to modules mounted flat on the ground. Earth Mount Solar modules do not rely on hail stow strategies, which depend on timely hail alert systems, human interaction, and predicting wind direction (which can change).
	Maintenance Activity	Neutral	Maintenance activity loads (nightly robotic cleaning and rare manual service) induce loads that are below module manufacturer warranty limits.
PID	Soiling	Beneficial	Nightly robotic cleaning mitigates PID due to soiling.
	Microcracks	Beneficial	Reduction in cyclic wind loading, anchor point stresses, and thermal cycling results in reduced PID due to microcracks.
	Temperature	Neutral	PID tends to increase with module temperature, but PID recovery also tends to increase with module temperature. These effects largely cancel each other out.
Combined Effects	Multiple	Beneficial	Degradation modes are often interconnected, with reductions in one mode often leading to reductions in another.

Figure 3 — Highlighted degradation modes and Earth Mount Solar® PV benefits

Hot Spots

Module hot spots often occur when some portion of a cell is shaded, causing it to go into reverse bias and dissipate (in the form of heat) some of the power generated from the other cells. The hot spot itself results in a loss of performance, but more seriously it can lead to significant degradation and even catastrophic failure. The two most common sources of localized shading are uneven soiling (such as bird droppings, leaves, or soil accumulation) and vegetation growth.

Most utility sites are unmanned, receiving several visits per year, while those that are manned are generally so large that localized shading can go unnoticed for long periods of time. Small, localized shading events are generally impossible to detect remotely through inverter-level performance data, but it is precisely these events that usually lead to hot spots, since larger shading situations would tend to activate module diodes or result in less power to be dissipated over more cells.

To combat the formation of hot spots, the Earth Mount Solar® PV system incorporates nightly robotic cleaning, an automated process that virtually eliminates localized soiling. Vegetation growth is also greatly reduced beneath Earth Mount Solar® PV systems, due in large part to the tight configuration of the modules, which allows minimal light to pass through, and the application of geoenzymatic soil stabilizers that are commonly used under roads and foundations. In locations where some vegetation does occur, the automated robotic system will be used to control it daily.

Fractured Cells (Microcracks)

Cell fractures, more commonly referred to as microcracks, restrict the flow of current through cells, reducing power and potentially leading to hotspots. They can form and propagate from mechanical or thermal stresses encountered throughout the lifecycle of a module, from transportation and installation through operation and maintenance. In recent years, most new SAT PV plants have utilized modules with glass/glass rather than glass/backsheet construction. Glass/glass construction allows for bifacial energy capture and keeps cells in a more neutral plane, thereby alleviating mechanical stress and reducing microcrack propagation.[3, 4]

Cited References

3. Solar Panel Design Factors to Reduce the Impact of Cracked Cells and the Tendency for Crack Propogation (Link)

4. Cracking Down on PV Module Design: Results from Independent Testing (Link)

Figure 4 — Vegetation growth in a fixed-tilt system

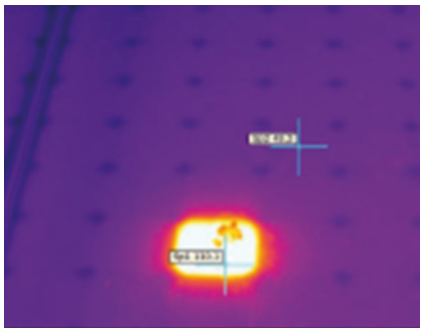

Figure 5 — Infrared thermographic image of a module hot spot

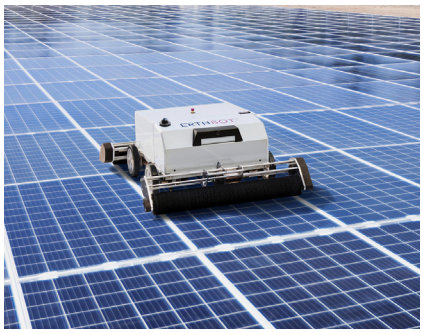

Figure 6 — The automated cleaning robot eliminates localized soiling and helps control vegetation growth

Earth Mount Solar® PV systems also use glass/glass modules and so also receive these mechanical benefits. While the more neutral plane achieved by glass/glass modules does not make them completely immune to mechanical degradation, Earth Mount Solar® PV systems have additional features, described below, that further reduce microcracks and their associated degradation effects.

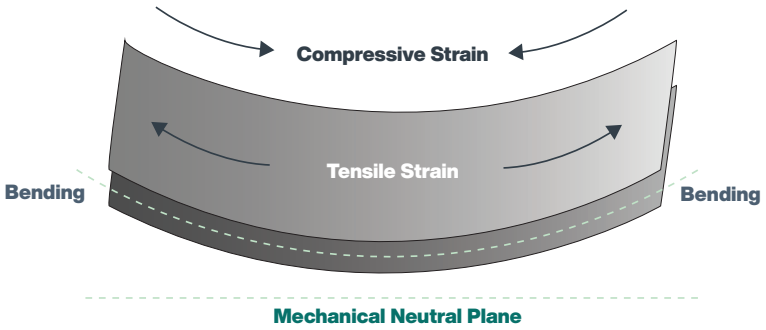

Figure 7 — Glass/glass modules alleviate mechanical stress and reduce microcrack propagation

Wind Harmonics

Modules mounted on trackers experience a variety of responses to wind loadings depending on the windspeed and direction, rigidity of the mounting structure, and module tilt. These static and dynamic loads will lead to cell damage over time. In a white paper titled “Designing for the Wind,” the authors provide several experimental and computer-modeled videos that demonstrate the dynamic instabilities experienced by tracker-mounted modules under various wind conditions. They note that dynamic wind loads during instability can exceed five times that of static wind loads and module instability can occur at windspeeds as low as 55 miles per hour on low-angled, tracker-mounted modules. For this reason, it is recommended that tracker-mounted modules are stowed at higher tilt angles during wind events, as opposed to being stowed flat — because even though higher-angled stowing results in higher static wind loads, it also increases the system’s stability overall, including during high wind gusts.[5]

Yet, high-angle stowing comes with its own problems. If power to the system is interrupted, for example, then the system will be unable to go to a safe stow position during a high-wind event, leaving it vulnerable to damage. To avoid this scenario, many tracker-mounted plants utilize uninterrupted

Cited Reference

5. Designing for the Wind Using Dynamic Wind Analysis and Protective Stow Strategies to Lower Solar Tracker Lifetime Costs (Link)

power sources, but these add cost and complexity to the system.

The Earth Mount Solar® PV system, on the other hand, is at ground level, which provides several benefits. Not only are wind speeds much lower at ground level (approaching zero) than they are several meters above the ground, but the modules themselves are more stable — and thus capable of withstanding higher wind speeds — since they are installed directly on the earth. Whereas SAT systems are typically designed to withstand wind speeds up to 120 miles per hour, the Earth Mount Solar PV system can withstand speeds exceeding 194 miles per hour.[2] This is because any wind that does encounter the system flows only on the top surface, eliminating cyclic vortex shedding.

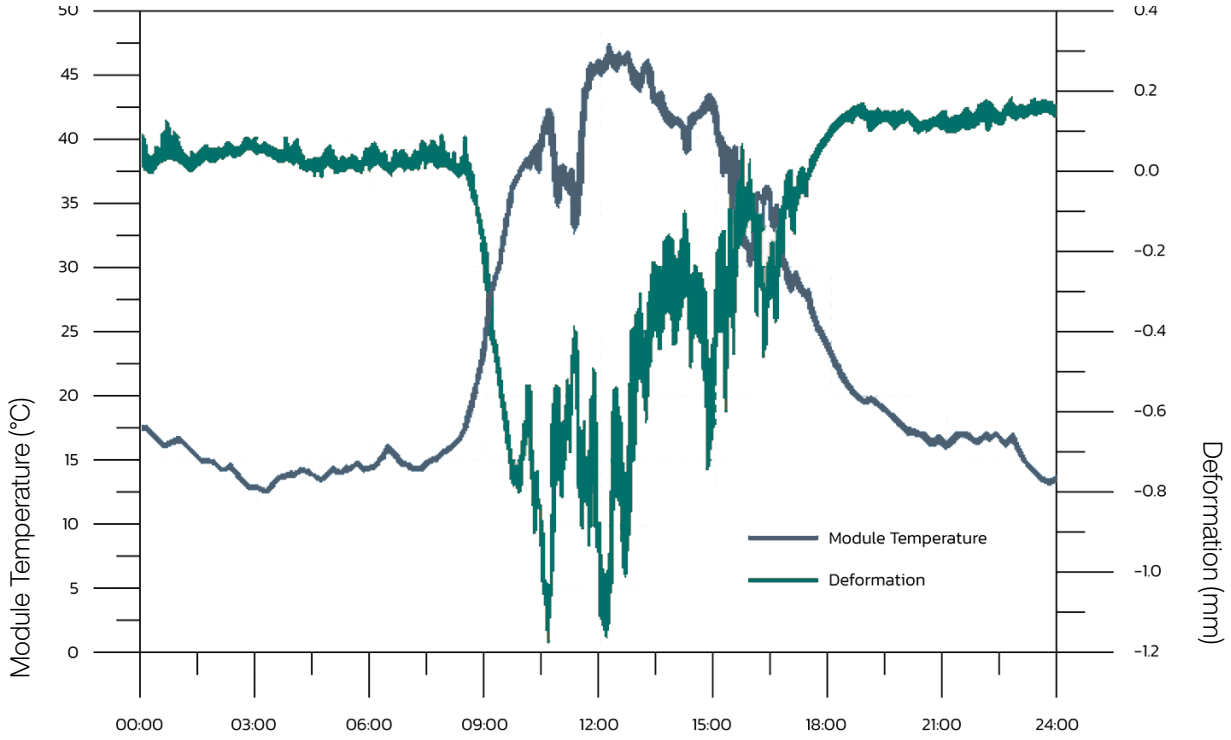

Figure 8 — Daily Bending Cycles in an SAT system over the course of a day

Compared to SAT systems, which experience numerous bending cycles over the course of a normal day as shown in Figure 8[6] above, Earth Mount Solar® PV systems experience significantly lower wind loads and harmonics, more stable module temperatures, and less degradation. As an added benefit, Earth Mount Solar® PV systems do not sacrifice efficiency during high-wind events since they do not need to change their stow position to a safer (but less optimal) angle.

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2. Erthos Aeroelastic Study (Performed by CPP Wind Engineering Consultants)

6. Categorization of Weathering Stresses for Photovoltaic Modules (Link)

Limited Anchor Points

As noted previously, the industry has been moving away from glass/backsheet modules to ones with more mechanically robust and symmetrical glass/glass construction, which have demonstrated "extremely low degradation rates," even in challenging environments. While glass/glass modules are now the widely accepted industry standard, they are still susceptible to the bending forces that concentrate at module anchor points. Tracker systems commonly support their glass/glass modules with four anchor points near the edges, but this is not enough to deconcentrate the bending forces caused by wind loads. The result is greater localized stress at each anchor point, which contributes to degradation over time.[3]

The Earth Mount Solar® PV system achieves the benefits of glass/glass construction while overcoming the challenge associated with anchor points. With a frame that is supported continuously at all points, Earth Mount Solar® PV modules are not subject to these bending forces, and thus not to the degradation they introduce.

Thermal Cycling

All modules will be exposed to temperature variation throughout a day due to factors such as shading, passing clouds, or varying wind loads. This results in thermal expansion and contraction of the module, which in turn introduces mechanical stresses and can lead to microcracking. To visualize this phenomenon, refer to Figure 8 on the previous page, which shows wind- and temperature-induced module deformation on a rack-mounted module over the course of a single day.[6]

The relationship between wind, module temperature, and deformation is clear. Because Earth Mount Solar® PV systems are installed directly on the ground, they experience less degradation due to thermal cycling than any tracker system on the market. This is true for two reasons: there is less wind-induced temperature variation at ground level, since wind exposure is minimal; and the ground has high thermal capacitance, which helps stabilize module temperature.

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3. Solar Panel Design Factors to Reduce the Impact of Cracked Cells and the Tendency for Crack Propagation (Link)

6. Categorization of Weathering Stresses for Photovoltaic Modules (Link)

Hail

In recent mechanical stress sequences (MSS) conducted by PVEL, glass/glass modules showed "no cracking post-MSS."[7] Earth Mount Solar® PV systems exclusively use glass/glass modules, giving them very high tolerance to hail, regardless of module orientation. In hail-prone locations, the modules used in Earth Mount Solar® PV systems can be specified with thicker glass or different chemistries to increase hail resistance, whereas with tracker plants the added weight increases structural steel requirements, making that path uneconomical.

Another consideration is that hail is typically accompanied by wind, meaning that "hail can fall at an angle or even nearly sideways," according to the NOAA.[8] While Earth Mount Solar® PV systems are installed flat on the ground, tracker systems endure wind events by stowing at non-zero angles facing into or away from the wind. Hail falling at an angle may be more likely to directly impact a tilted SAT module than it would a flat, ground-mounted module in an Earth Mount Solar® PV array. SAT system stow modes also rely on coordination between severe weather alert services, anemometers to collect wind speed and direction, software and mechanical systems to move trackers to a stow position in a timely manner, and human intervention to determine when and in which direction to stow, all of which present possible points of failure. Furthermore, tracker warranties may not cover damage resulting from a hail storm if the manufacturer's proprietary software was not used and detailed procedures were not properly followed.

Maintenance Activity

Because Earth Mount Solar® PV systems are installed on the ground and consist of fewer materials and no moving parts, the activities required to maintain them are simple, with negligible impact to long-term degradation. The primary form of maintenance is automated nightly cleaning, which is carried out by a robot designed specifically to interface with the Earth Mount Solar® PV system without exceeding the system's 5.4 kPa module static load limit. The load of the robot is distributed almost entirely to the module frames rather than the glass module; and the frames, as mentioned earlier, are supported uniformly rather than at four anchor points, meaning the weight of the robot is not localized like it is in load-testing scenarios.

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7. From Random to Repeatable: Inside the Hail Stress Sequence for PVEL's PV Module Product Qualification Program (Link)

8. Hail Basics, NOAA National Severe Storms Laboratory (Link)

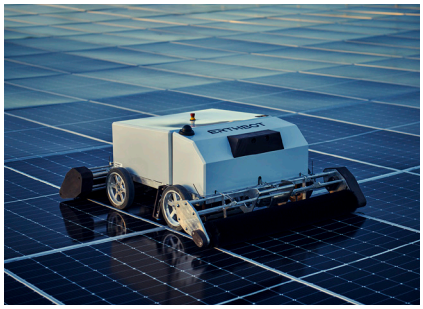

Figure 9 — The automated robot cleans the modules daily without exceeding the system's load limit

The second form of maintenance, which happens only very rarely, involves walking on the modules. All service personnel carrying out this form of maintenance are required to utilize special pads that, like the robot, have been designed to stay below the system's 5.4 kPa module static load limit. Also like the robot, most of this load will be distributed to the uniformly anchored frame rather than to the module itself, resulting in minimal loading on the glass. Again, service of this nature will be extremely rare. When compared to SAT systems, the Earth Mount Solar® PV system has fewer materials, no moving parts, is easier to access, and requires less human maintenance.

Potential-induced Degradation (PID)

In utility PV systems, modules are connected in strings. The voltage within a string generally goes up to 1000V or 1500V, whereas the module frames are grounded for safety reasons. The voltage potential between the cells and frame causes leakage currents to flow from one to the other depending on their location along the string, resulting in PID. Figure 10 below, taken from a review of the available literature, illustrates the many different paths by which this current can flow. The greater the voltage difference between a cell and the frame, and the lower the electrical resistance between the two, the greater the leakage current along that path.[9]

PID is a complicated subject, and while much is known there is still much that remains unknown. Rates of PID can differ

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9. Potential-induced Degradation in Photovoltaic Modules: a Critical Review (Link)

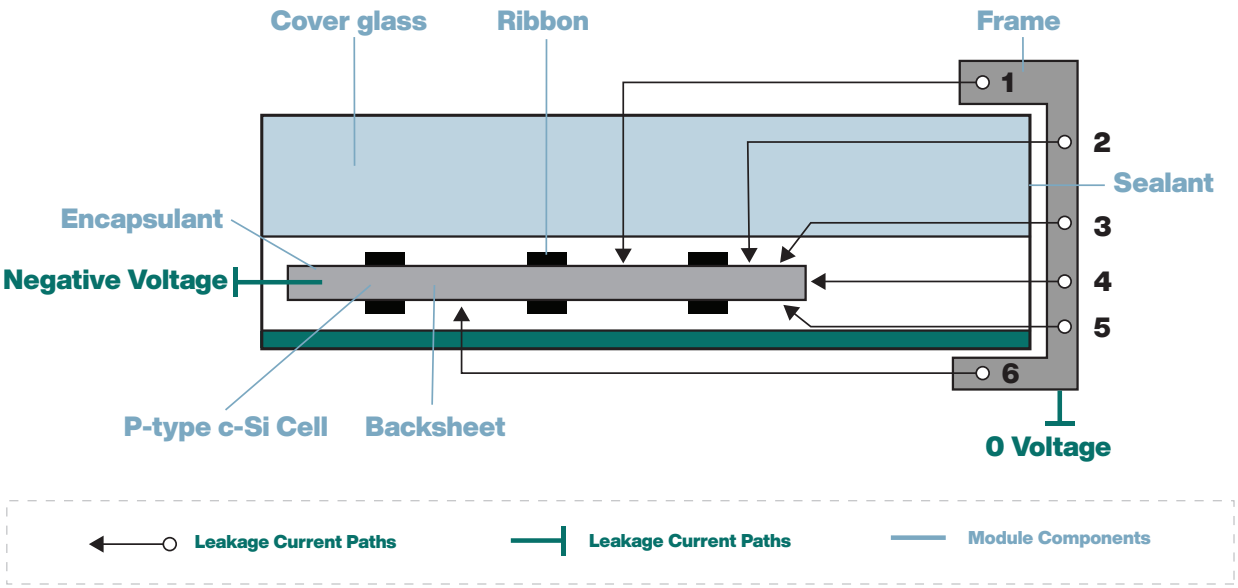

Figure 10 — Leakage current flow

from system to system depending on cell technology, module construction, the coatings used, a range of environmental factors, and how the system itself is configured. This is why the Earth Mount Solar® PV system experiences less PID than SAT systems, even though it uses the same modules and string voltages — because it outperforms SAT systems in such areas as soiling, temperature stability, and microcracking.

Soiling

Soiling on the module surface has been found to decrease leakage resistance along path 1 in Figure 10 on the previous page. The corresponding increase in leakage current depends on soil type and humidity, and can result in two to 10 times the amount of leakage current.[10] The Earth Mount Solar® PV system's nightly robotic cleaning process virtually eliminates soil buildup, therefore eliminating this PID mechanism.

Temperature

While PID is known to increase with module temperature, PID recovery also increases with temperature. Because Earth Mount Solar® PV systems are installed directly on the ground, air does not move freely beneath and around the Earth Mount Solar® PV modules. This is a benefit that enables the system to withstand 194-mph winds with no visible movement, but it also slightly raises module temperatures. However, the ground also acts as a heat sink on the underside of the modules, thus lowering module temperatures. These combined effects bring small, offsetting increases in both PID and PID recovery.

Microcracks

Microcracks do not just affect output directly; they also increase PID, with larger microcracks leading to greater PID. This is demonstrated in Figure 11 on the next page, in which the lettered curves A-E show progressively greater PID as microcrack length increases. As explained previously, the Earth Mount Solar® PV system will experience less microcracking and therefore less microcracking-related PID.[11]

Cited Reference

10. Effects of PV Module Soiling on Glass Surface Resistance and Potential-induced Degradation (Link)

11. The Effect of Microcrack Length in Silicon Cells on the Potential-induced Degradation Behavior (Link)

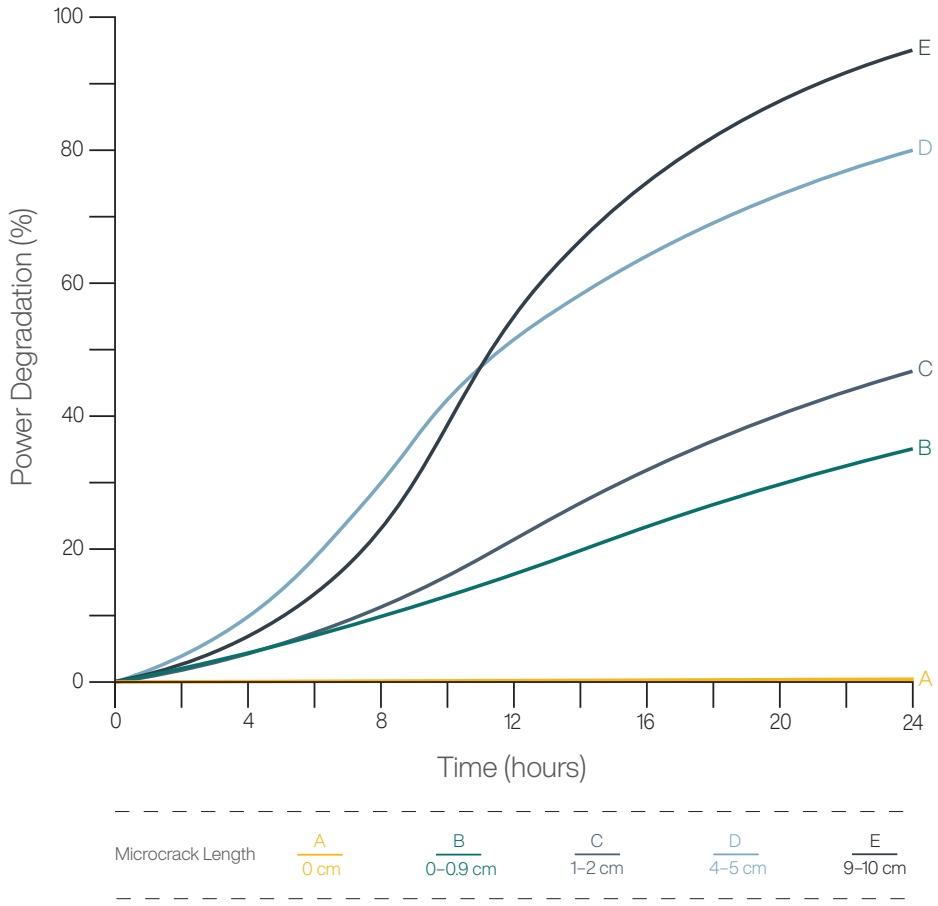

Figure 11 — Microcrack length and PID

Combined Effects

Many of the degradation modes identified above are interrelated, so by improving one of them, others are also improved. For example, the Earth Mount Solar® PV system reduces microcracks caused by wind harmonics, anchor point stresses, and temperature fluctuations, which in turn reduces hot spots. By addressing the primary causes for microcracking — and thereby reducing the formation of hot spots — the Earth Mount Solar® PV system dramatically reduces degradation over time.

There is also the matter of mismatch loss and its effect on overall system degradation. When a system's I-V characteristics differ from module to module, all modules/strings are forced to operate at common, non-optimal current/voltages, leading to power loss due to mismatch. As modules degrade unevenly over time, their I-V characteristics diverge even more, increasing this loss further. Because Earth Mount Solar® PV systems reduce both the prevalence and severity of multiple degradation modes, they also achieve reduced mismatch loss and thus reduced system degradation overall. All factors considered, the Earth Mount Solar® PV system is expected to achieve annual degradation rates approximately 0.2% lower than a comparable SAT system.

Higher DC/AC Ratio

As a module degrades, it produces less power. However, once an array has hit its inverter clipping limit, this degradation will have no effect on output. A system with a high DC/AC ratio will spend more time at the clipping limit than a comparable system with a lower DC/ AC limit, and will therefore experience less annual energy loss due to degradation. As time goes by and the modules degrade, the effective DC/AC ratio will decrease, and the realized loss due to degradation will increase and approach the actual total degradation loss.

Earth Mount Solar® PV systems are designed with a DC/AC ratio of 1.7 — rather than the 1.2-1.4 ratio typically seen in SAT systems — and will have 25-30% less energy loss due to degradation assuming the same nominal degradation rate of 0.7%. However, Earth Mount Solar® PV systems can be expected to achieve nominal degradation rates around 0.5% annually, delivering total degradation losses approximately 50% lower than those achieved by comparable SAT systems.

To illustrate this effect, refer to Figure 12 on the next page, which charts the daily power output for a system with a DC/AC ratio of 1.7 normalized to an AC benchmark of 100. Three example days are shown: one with clear skies, one that was partially cloudy, and one that was cloudy all day. The four colored lines represent the system's power output on each example day in years 1, 10, 20, and 30. The DC power that would be produced if there were no inverter clipping limit is shown on the top plot, while the AC (or clipped) power is shown in the bottom plot.

In the clear day sample, although there is a 5% difference in energy between years 10 and 20 on the DC curve, there is very little difference in energy between these two lines on the AC curve. On less clear days, where more time is spent below the clipping limit, the energy loss due to degradation increased.

A system with a lower DC/AC ratio spends more time below the clipping limit and therefore experiences higher energy loss due to degradation. In Figure 13 on the next page, we can see the relative effective degradation for two systems, one with a DC/AC ratio of 1.7 and one with a ratio of 1.3. In year 30, looking at the clear day sample, the system has an effective degradation of about 2.5% and 4% for the 1.7 and 1.3 DC/AC systems, respectively, rather than the actual degradation of 15% (0.5% per year times 30 years). Looking at the cloudy day data, the 1.3 DC/ AC system experiences all the actual degradation since the system is below the clipping limit for the entire day.

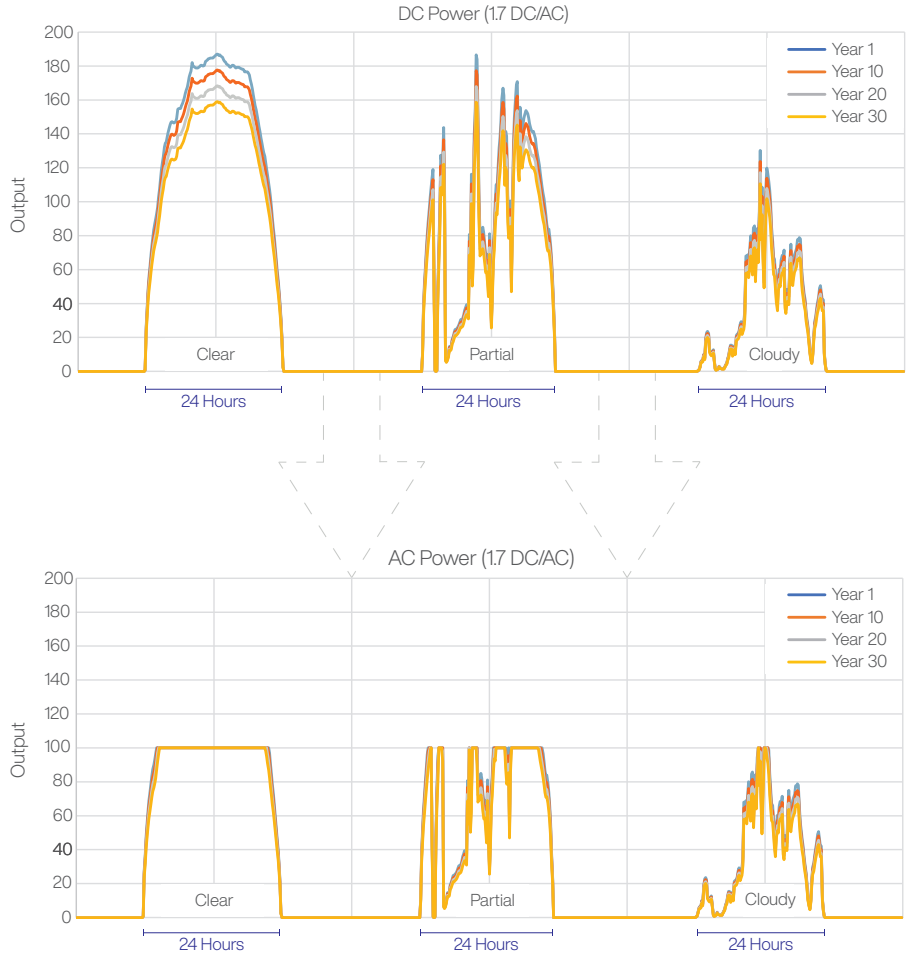

Figure 12 — Daily power output and the inverter clipping limit

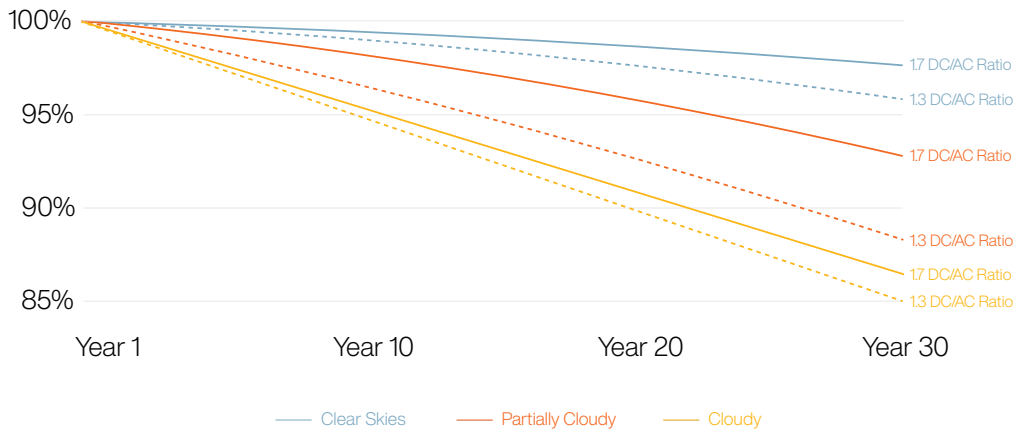

Figure 13 — Degradation attentuation due to clipping limit

Figures 12 and 13 on the previous page were created to illustrate the salient concepts and make them easier to understand. For a more realistic estimate, PVSyst was used to simulate the degradation rates of an Earth Mount Solar® PV system as well as those of a SAT system. The performance of each system was simulated using identical inputs wherever possible (e.g., weather data, module type, inverter type), but with system-specific settings (such as temperature coefficients) when appropriate. The model's assumed number of strings per inverter was also different for the Earth Mount Solar® PV and SAT systems, to accurately reflect their respective 1.7 and 1.3 DC/AC ratios.

The resulting degradation rates and energy losses over time for each system are shown in Figures 14 and 15 below. Assuming a 0.7% annual degradation rate, the Earth Mount Solar® PV system delivers an effective degradation rate that is 25-30% lower than the SAT system. However, as explained earlier, the base degradation rate for an Earth Mount Solar® PV system is expected to be approximately 0.2% lower than an SAT system. Taking this into account and assuming a nominal degradation of 0.5% per year for the Earth Mount Solar system — compared to 0.7% for an SAT system — we can see that the rate of degradation experienced by an Earth Mount Solar® PV system will be approximately 50% lower than the rate experienced by a comparable SAT system.

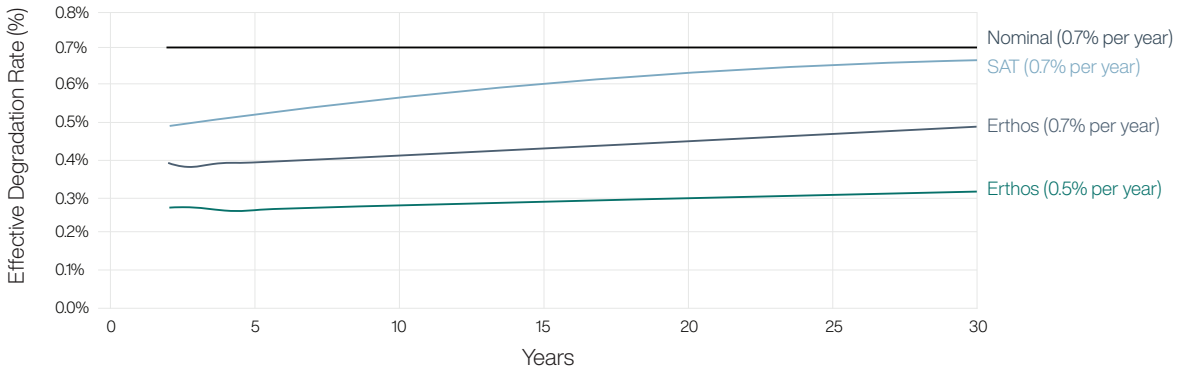

Figure 14 — Effective annual degradation rates for Erthos (1.7 DC/AC) and SAT (1.3 DC/AC)

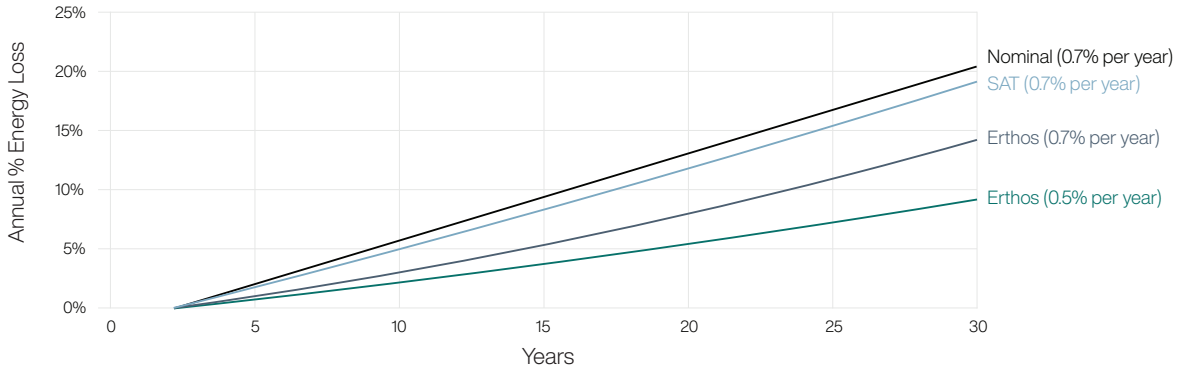

Figure 15 — Annual % energy loss due to degradation for Erthos (1.7 DC/AC) and SAT (1.3 DC/AC)

Summary

The Earth Mount Solar® PV system effectively eliminates or reduces many of the most common and severe degradation modes found in comparable single-axis tracker (SAT) systems. Many of these modes are interconnected, whereby reducing or eliminating one can improve one or more of the others. Reduction of these degradation modes will also reduce mismatch loss, improving system performance further still. For these reasons, Earth Mount Solar® PV systems typically achieve annual degradation rates that are 0.2% lower than comparable SAT systems. Finally, these reduced rates are further improved by Earth Mount Solar® PV PV's high DC/AC ratio, which helps it spend more time above the inverter clipping limit.

When taking all factors into account, the Earth Mount Solar® PV system achieves annual degradation rates up to 50% lower than those found in comparable SAT systems.

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