Module Shading Guide

The purpose of this document is to provide an understanding of the shading impact on First Solar Series 3 and Series 4 PV modules (hereafter referred to as “FS Series PV Modules”) as compared to c-Si modules and highlight instances of shading that could cause product performance issues. FS Series PV Modules must be installed and operated in accordance with the Module User Guide.

Field Shading Guide and Avoiding Device Damage

First Solar FS Series Modules are tested and certified by an accredited third party laboratory to be compliant to IEC 61215 (*Terrestrial Photovoltaic Modules – Design Qualification and Type Approval*) and IEC 61646 (*Thin Film Terrestrial Photovoltaic Modules – Design Qualification and Type Approval*). The “Hot Spot Endurance Test” (referenced in the aforementioned IEC standards) is used to verify that modules are capable of withstanding certain reverse bias events, caused by localized shading, which may occur in certain field deployment conditions.

The concern of device damage due to shading is unrelated to reverse current, but is driven by localized areas of reverse bias (negative voltage / positive current). This can occur when modules are shaded in very specific prohibited patterns and can result in minor cell level damage in very short durations (seconds to minutes) and under a wide range of irradiance (as low as 150 W/m^2). Reverse bias is generated by one or more series-connected cells being entirely shaded while the rest of the cells are fully illuminated. However, no damage is seen when greater than 45% of series-connected cells are shaded. When evaluating shading impact, series-connected modules within a string should be evaluated as one continuous string of series-connected cells.

The illuminated cells push forward current through the shaded cells. As a result, the shaded cells operate in reverse bias, because they are not generating voltage from sunlight exposure.

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While there exist countless ways to shade a module, typical field scenarios are discussed below to clarify the impact of common behaviors relative to a PV system using First Solar modules.

No Risk Shading

1. **"Row-to-Row" shading, where modules are oriented in landscape** and exposed to uniform shading pattern as a result of low sun angles, poses no risk to long term reliability or performance.
2. **Shading while modules are in Open Circuit (OC)** conditions poses no risk to long term reliability or performance. OC is defined as the condition when modules, strings, or arrays are electrically open and not actively driving current flow. OC conditions are common during storage, unboxed transport, installation, or when inverters (or loads) are off or disconnected. Any shading during these OC conditions, regardless of how many cells are shaded or at what contrast or intensity, will not create reverse bias events because no current is flowing through the module. With no reverse bias, there is no risk.
3. **Diffuse shading (no crisp edge to the shadow) cast as a result of faraway objects** like overhead power lines, meteorological towers, utility towers, et. al poses no risk to reliability or performance.

Low Risk Shading

1. **Repeatedly walking or standing closely in front of operating modules** between rows during highly illuminated times can create highly irregular shading difficult to predict and test. Best practice is to stay as close to the back side of the rack as one walks down a row of operating modules. These irregular actions present very low risk of high contrast shading, and should be systematically avoided.
2. **Repeated parking or driving of vehicles or equipment closely in front of operating modules** can potentially create undesirable high contrast partial shading of complete cells, and should be systematically avoided.

High Risk (Prohibited) Shading

1. **Resting or adhering slender objects (tools, brooms, clothing, wires, tape) on sunny side of operating modules, or nearer than 1.5-2 meters (~5-7 feet) above operating modules**, especially when shadow oriented parallel to cells.
2. **Fixed objects within 1.5-2 meters (~5-7 feet) above operating modules** that cast a shadow over the long dimension of the cell. Close objects like posts, ropes, signs, fences, or equipment can increase risk of partial shading of full cells when nearer than 1.5-2 meters (~5-7 feet).
3. **A support frame or mounting method on the short edge(s) of modules that fully shades the entire length of a cell (either partially or completely)** can create a high risk of undesirable shading.
4. **Working continuously with outstretched arms or tools over operating modules.**
5. **Cleaning apparatuses, including cleaning robots and other mechanisms that traverse the module repeatedly while the system is operating (unless evaluated and approved by First Solar)**.

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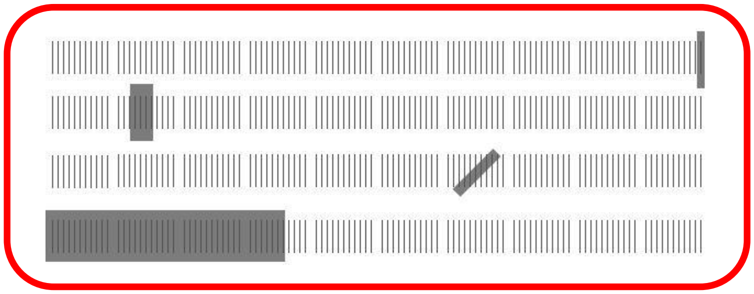
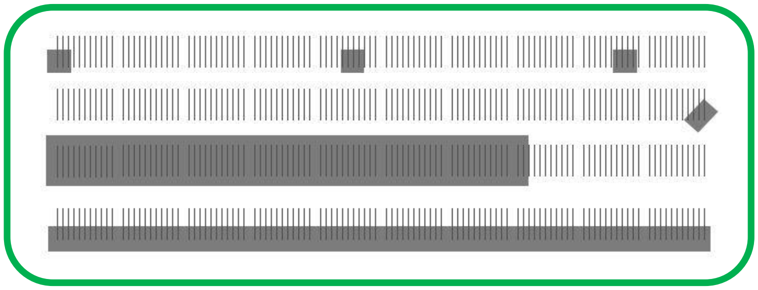
Examples of prohibited risk (red) and low to no risk (green) near-object shading patterns of a 10 module string are depicted below in a typical south facing fixed-tilt structure (rotate 90˚ for single-axis tracker).





Shading Impact on First Solar FS PV Modules Performance

First Solar FS Series PV Modules respond differently to partial shading depending on shading orientation. The data below is intended to support the proper design of systems using these FS Series PV modules as well as the development of more accurate models for energy prediction. The data is representative of all power bins of FS Series PV Modules, although some variation among the modules is normal and to be expected.

Shading Parallel to Cells

Parallel shading of cells is displayed in Figure 1, which in this case, occurred along the 600mm dimension. The I(V) curve of a single FS Series PV Module changes as entire cells are shaded. The response is shown in Figure 2.

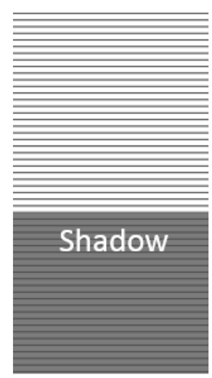


Figure 1: Shading parallel to cells along 600mm dimension

The number of entirely shaded cells increases with the total shading percentage. The shaded cells act to limit the current and power produced by the module. The maximum power (P_{MAX}) and maximum power voltage (V_{MP}) are significantly reduced upon shading of the first 5-10% of the module surface area, but do not vary much as the amount of shading increases from 10% to 30%. In this range, the P_{MAX} value is approximately one half of the value for an un-shaded module. Beyond 30% shading, the output power drops further, eventually reaching zero when more than 50% of the module is shaded. V_{MP} can vary appreciably over the entire range, but remains nearly constant when 10-30% of the module's surface area is shaded.

This effect is also evident in Figure 3, which shows P(V) curves corresponding to the I(V) curves shown which indicates that the module ceases producing power when more than half of the cells are entirely shaded.

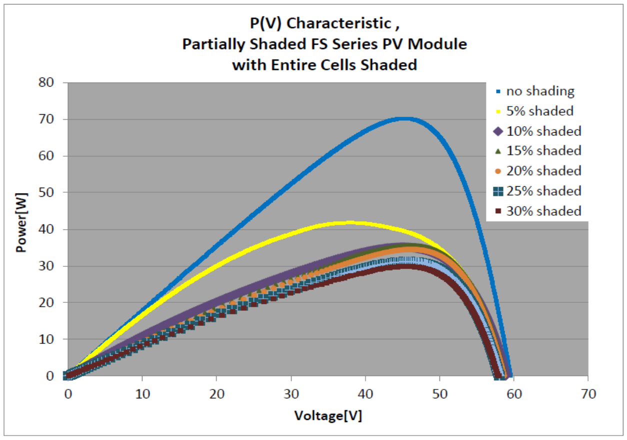


Figure 3: FS Series PV Module P(V) curves with some cells entirely shaded along 600mm dimension

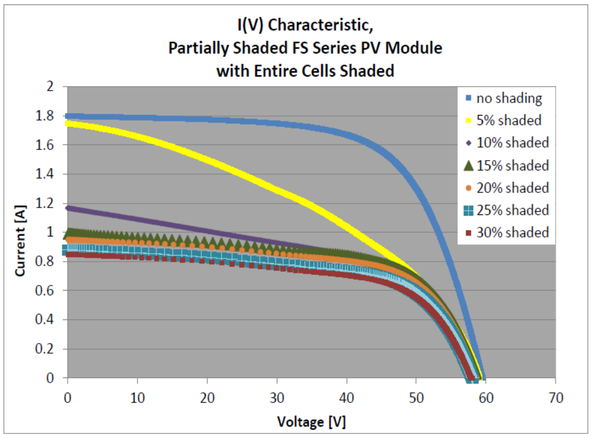


Figure 2: FS Series PV Module I(V) curves with some cells entirely shaded along the 600mm dimension

Shading Perpendicular to Cells

Perpendicular shading of cells is displayed in Figure 4, which in this case, occurred along the 1200mm dimension. All cells of the module remain partially illuminated and the un-shaded portions of the cells function normally. Thus the resulting power loss from shading scales proportionately with percentage of shaded module surface area, the response is shown in Figure 5. The V_{MP} is only slightly affected by the degree of shading, shifting by about 3V (or about 7%) from the fully illuminated case to the 75% shaded case. The weak dependence of V_{MP} on 1200mm shaded area percentage is also shown by the approximate vertical alignment of the maximum power points in Figure 6.

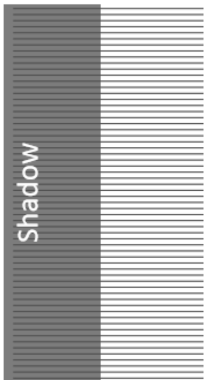


Figure 4: Shading perpendicular to cells along the 1200mm

The maximum power current (I_{MP}) varies directly with un-shaded (active) cell area. Since this dependence is linear, and since the V_{MP} response is only weakly dependent upon shaded area, the resulting dependence of module power is nearly linear with shaded area percentage. This behavior is clearly shown in Figure 7. A linear fit to the relative power versus shading percentage in the 1200mm dimension shows good agreement with the data.

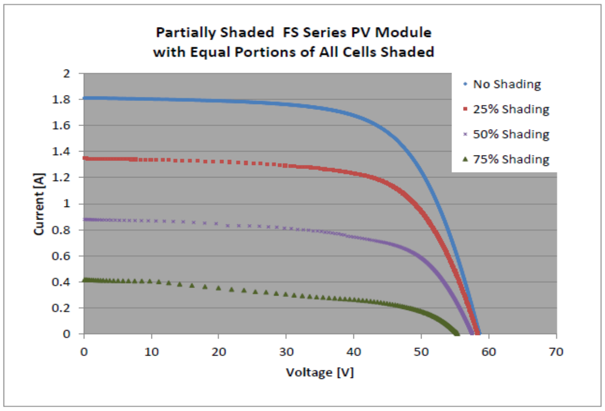


Figure 5: FS Series PV Module I(V) curves with all cells partially shaded along 1200mm dimension

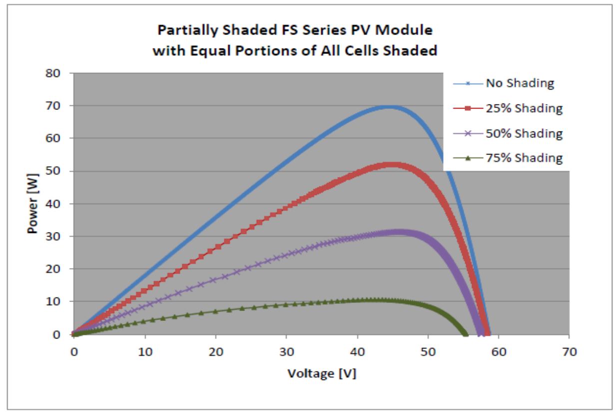


Figure 6: FS Series PV Module P(V) curves with all cells partially shaded along 1200mm dimension

Module power loss due to shading will be minimized when shading can be restricted to occur along the 1200mm dimension of the module (ensuring no cells are entirely shaded). In a typical free-field application where modules might be affected only by row-to-row shading, mounting modules in a landscape orientation would result in minimization of power loss due to shading.

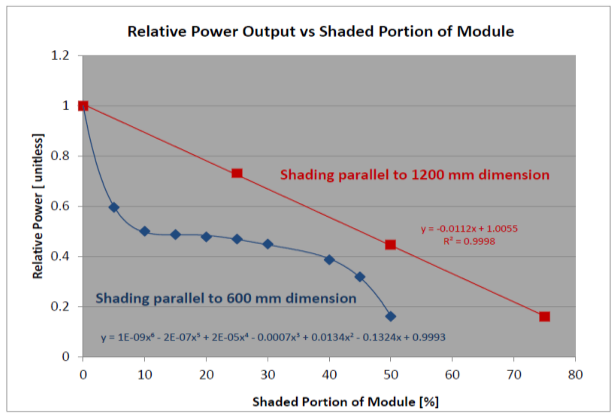


Figure 7: Relative Module P_{MAX} as a function of shaded module portion for both shading orientations

System Shading Performance without Bypass Diodes

FS Series PV Modules differ from typical c-Si PV modules in a number ways that drive the design of a module without a bypass diode. Figures 8 and 9 display the cell structure of a typical c-Si module and FS Series PV Module, respectively.

1. The cells in FS Series PV Modules are interconnected in-line by an advanced monolithic laser-scribing process. In contrast, typical c-Si modules use soldering to interconnect adjacent cells.

2. The electrical configuration of FS Series PV Module cells are defined such that each cell runs the entire width of the 600mm side of the module, and each cell-to-cell interconnection spans the entire width of the module's active area parallel to the 600mm side of the module. Conversely, typical c-Si modules have cell-to-cell interconnections that span only a small portion of the active area and are oriented both lengthwise and widthwise.

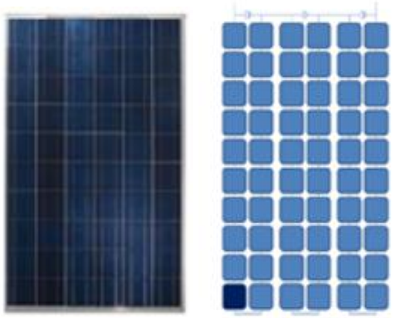


Figure 8: Typical c-Si module (left); electrical configuration and one highlighted cell (right)

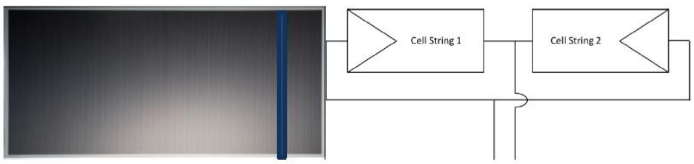


Figure 9: FS Series PV Module and one highlighted cell (left); electrical configuration (right)

Module electrical configuration and row-to-row shading

Row-to-row shading typically observed in utility scale PV systems is partial shading of a string of modules connected in parallel with other module strings, shown in Figure 10. Typically this shading happens during dawn or dusk at low irradiation conditions.

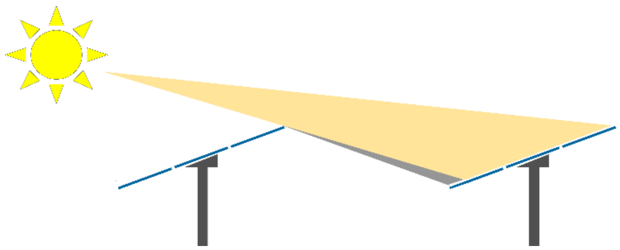


Figure 10: Typical row-to-row shading

FS Series PV Modules

FS Series PV Modules are typically comprised of two parallel strings of cells interconnected by a shared (shorted) cell and bus ribbons that terminate in the potted junction box. Figure 9 shows the electrical circuit representation of the FS Series PV Module. This cell configuration, in typical applications, results in a linear response to uniform row-to-row shading without any requirement for bypass diodes. This is due to the fact that all cells within each string are shaded equally, preventing mismatch in cell currents. Additionally, the connection of the two multi-cell series circuits in parallel, not in series, makes a bypass diode an ineffective means to isolate each power-producing string of cells. In this case, due to the way the cells are defined on the FS Series PV Module, all the modules in the string will be operating at the same voltage and current. Thus, no current mismatch within the partially shaded string of modules will occur.

The net effect for the PV system would be that the I_{MP} of the partially shaded string would be less than that of the fully-illuminated strings in parallel. This poses insignificant mismatch system losses, since the currents of parallel-connected strings can vary independently and do not interact. Figure 11 below illustrates this situation.

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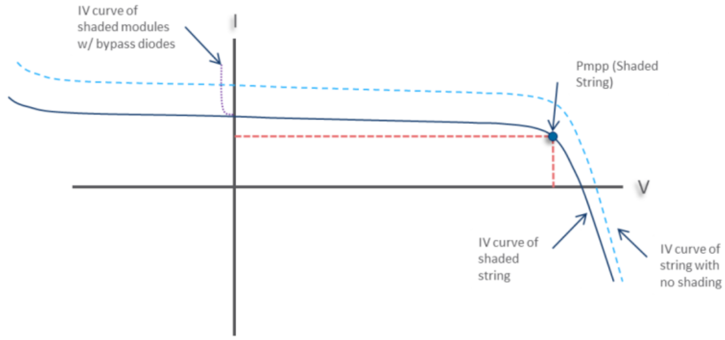

Figure 11: IV Curve of row-to-row shading

Typical c-Si Modules

Under normal unshaded operation, each cell in the module will operate in forward bias. When a typical c-Si module is exposed to normal row-to-row shading conditions, regardless of module orientation, complete rows of cells may be partially or fully shaded. This condition creates a mismatch in current between cells and shaded cells may become reverse biased. Left unprotected, this reverse bias condition could create cell or module damage due to the hotspot heating effect. Bypass diodes used in c-Si modules will limit current in reverse bias conditions, and will therefore protect the module against hotspot heating.

Only a small amount of shading is sufficient to activate the bypass diode and isolate the illuminated cells from the rest of the module. This reduces the module's power output disproportionally and annual energy loss due to shading will be greater than simply the loss due to the physical shading event. This reduction in cell count is the same across all modules in a single row, thus creating a voltage imbalance versus the other fully illuminated module strings compounding mismatch losses. Given the geometry of the cell layout and the natural movement of the row-to-row shading as the sun travels its normal trajectory, it is not possible to avoid these partial cell string shading conditions unless adjacent module rows are spaced sufficiently to result in zero shading. As a result, row-to-row shading of a c-Si module in either portrait or landscape orientation will cause disproportionate energy loss, even when module designs include bypass diodes.

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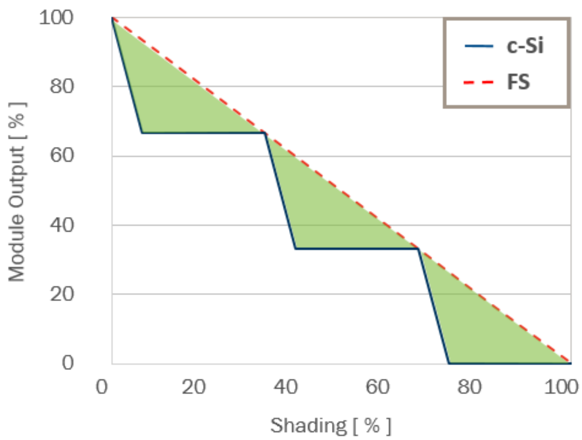

Figure 12: Landscape shading response

Landscape FS Module vs Landscape c-Si Module

FS Series PV Module linear power loss:
10% shading = ~10% output power loss

c-Si Module power loss:
10% shading = ~30% output power loss

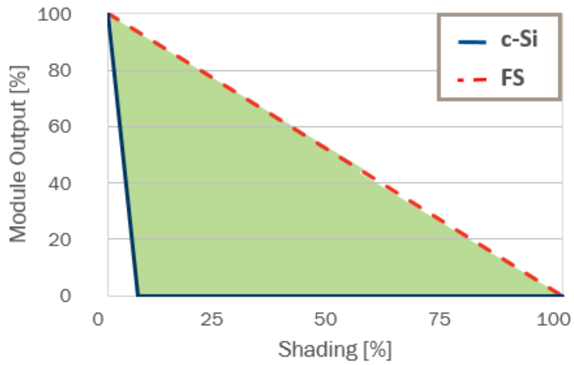

Figure 13: Landscape FS module vs portrait c-Si module

Landscape FS Module vs Portrait c-Si Module

FS Series PV Module linear power loss:
10% shading = ~10% output power loss

c-Si Module power loss:
10% shading = ~100% output power loss

The advanced design features and electrical configuration of FS Series PV Modules prevent module damage and disproportionate power output losses in typical row-to-row shading situations without requiring bypass diodes.

Contact

For further information on appropriate system design, or information about FS Series PV Module features, please contact First Solar at technicalsales@firstsolar.com.

