Improved Shade Tolerance of Series-Parallel Interconnected Solaria PowerXT Panels

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THE EFFECT OF SHADING ON PV PANEL OUTPUT

The output power of a PV panel is strongly dependent on the amount of irradiance it receives. Under normal operating conditions, the power increases with irradiance in a more or less linear way. However when the irradiance isn't uniform, as is the case when the panel is partially shaded (see **Figure 1**), the response is usually no longer linear, and the shading of small areas can lead to a large loss in power. The way a given panel responds to shading strongly depends on how the cells in the panel have been connected together. In this paper we'll look at how the series-parallel interconnection in Solaria's PowerXT panels can mitigate power loss under many commonly encountered shading conditions.

Figure 1: Dormer shading, photo courtesy of Mass Renewables (top); shading from partial snow coverage (bottom).

Let's start by considering the shading response of a single solar cell. When a single cell is shaded, its current and voltage is reduced. Since power is the product of current and voltage, the consequence is that the power is also reduced. If this shaded cell is connected to other cells in series to form a string (**Figure 2**), this enforces a restriction on the string current: the current that flows through the string must be the same at every point. Therefore, if one cell is shaded, it will act as the current-limiting cell, and the current of the entire string will be limited to the current of the shaded cell. Moreover, the optimum operating point of the string can occur at a voltage that corresponds to forward bias for the unshaded cells and a large reverse bias for the shaded cell. In such a situation, the shaded cells can heat up considerably - this is referred to as hotspot formation – and result in damage to the PV panel.

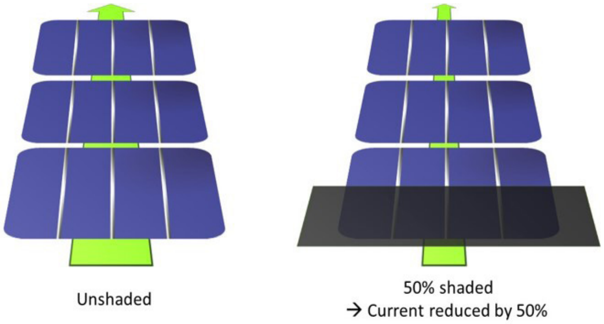


Figure 2: Shading a single cell reduces the current for the entire string.

Conventional PV panels usually contain 60 or 72 series-connected cells. It is clearly an undesirable situation that the shading of just one cell would limit the output of the entire panel and put it at risk of hotspot damage.

This problem is partially resolved by the use of bypass diodes. In conventional panels, three diodes are usually connected as shown in **Figure 3** to divide the string into three sub-strings. Under normal conditions, the diodes are in the 'OFF' state i.e. they pass negligible current and are hence effectively not involved in the circuit. If one sub-string is shaded to such an extent that the corresponding diode becomes forward-biased, the diode will switch to the 'ON' state. In this state, the diode has considerably less resistance than the sub-string, and hence panel current will tend to flow through the diode, bypassing the shade-affected sub-string. This greatly mitigates hot-spot risk and prevents the shaded sub-string from limiting the current from the rest of the panel.

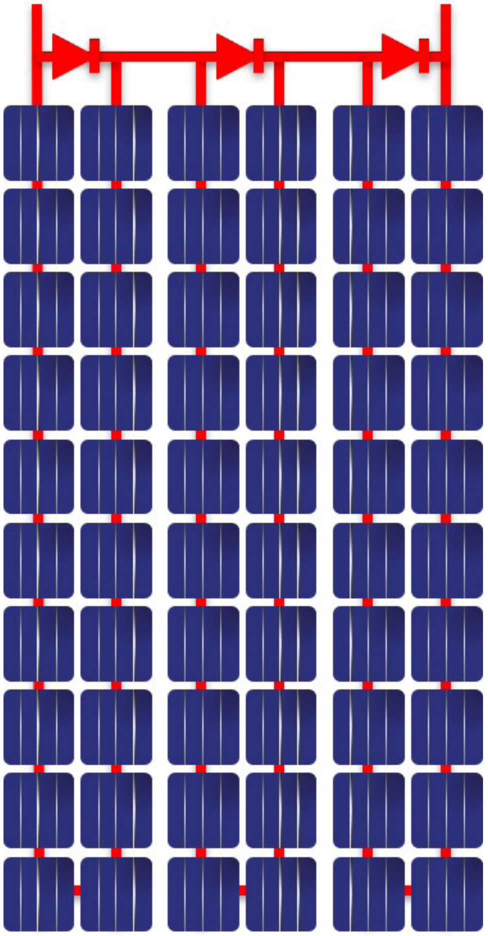
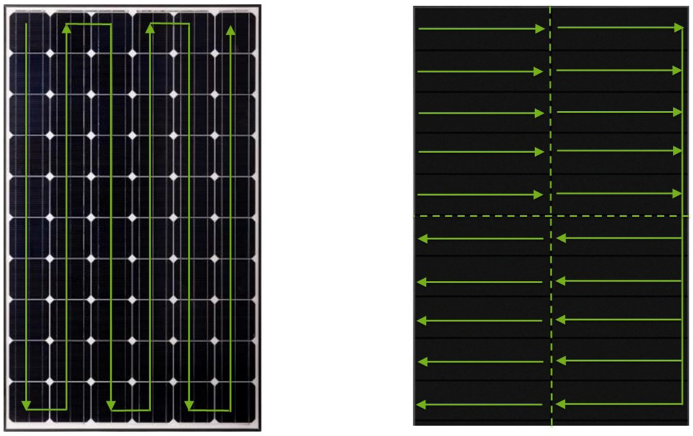


Figure 3: Cell inter-connection in a conventional series-connected panel.

Although the assembly of panels into three sub-strings in this way is a good solution, there is clearly room for improvement. In the next section, we'll describe the series-parallel connection of Solaria PowerXT panels and how it can significantly mitigate losses in power in some commonly encountered shaded conditions.

SOLARIA'S SERIES-PARALLEL CONNECTION

PowerXT panels use shingling, a panel technology in which full cells are diced into strips and reconnected in a way that achieves higher panel efficiency. PowerXT panels are assembled from units of series-connected strips called PowerXT Cells. **Figure 4** shows a panel consisting of 20 PowerXT Cells arranged in four quadrants of five Cells each. Like the sub-strings in a conventional panel, the quadrants are series-connected and fitted with bypass diodes, allowing them to be bypassed if necessary.



Conventional panel

Solaria PowerXT

Figure 4: Current pathways (green arrows) for a series-connected conventional panel and a series-parallel-connected Solaria PowerXT panel.

	Conventional Panel	Solaria PowerXT
# panel segments	3	4
# paths for current flow	1	5 (in each quadrant)

Table 1: Number of panel segments and paths for current flow for conventional panels and Solaria PowerXT panels.

Having four panel segments instead of three gives the PowerXT an advantage over panels with conventional inter-connections for many commonly encountered shading scenarios. The reason for this is simple: when a small object shades a conventional panel such that power from an entire sub-string is lost, the panel can be expected to drop by one third, or 33%. If the same shading causes the power from an entire quadrant of a Solaria PowerXT panel to be lost, the panel power will only drop by one quarter, or 25%.

Another important layer of protection against shading losses is provided by the parallel connection of the five Cells within each quadrant. If a shading object were to reduce current flow for one of the five Cells in a quadrant, the presence of four other current paths can help to mitigate overall power loss.

INDOOR MEASUREMENTS OF POWER LOSS DUE TO SHADING

In the experiment described below, the responses of a conventional panel and a Solaria PowerXT panel are compared for some commonly encountered shading scenarios under controlled indoor laboratory conditions. Panel shading was achieved by adhering pieces of opaque material directly to the glass on the front side of the panels. The pieces were sized based on the dimensions of the cells in the conventional panel to create the following shading scenarios:

i. Half of the top row of cells shaded
ii. Shaded region defined by triangle with edges spanning three cells along the long and short edges
iii. The full left column of cells shaded
iv. The full row top row of cells shaded

The same pieces were used for both panels. The output power was measured using a panel flash tester. The results, expressed as a power loss relative to the unshaded power, are shown in **Figure 5**.

In scenario **i)** the results suggest that the shading isn't severe enough to bypass entire panel segments in either of the panels. However, the multiple current pathways in the Solaria panel allow it to retain 94% of its power, compared to 60% for the conventional panel. In scenario **ii)** the PowerXT panel loses 26% whereas the conventional panel loses 60% of its power. In scenarios **iii)** and **iv)**, a six-inch strip is used to shade the entire length of the panel along the long- and short-side, respectively. In **iii)**, losses are significant for both panels, and the PowerXT loses somewhat more power (54% versus 36%). However, the short-side shading (**iv**) results in just a 14% loss for the PowerXT while the output of the conventional panel is reduced to virtually zero.

The above results pertain to the shade tolerance of a single panel. Common approaches to mitigate shading losses on a system level include using series-parallel connections between panels, or pairing panels with Module Level Power Electronics such as microinverters and DC optimizers. These approaches can be used with PowerXT panels the same way as with conventional panels. The panel-level advantages of the PowerXT interconnection scheme can be considered to add to the benefits achieved via the use of these system-level approaches.

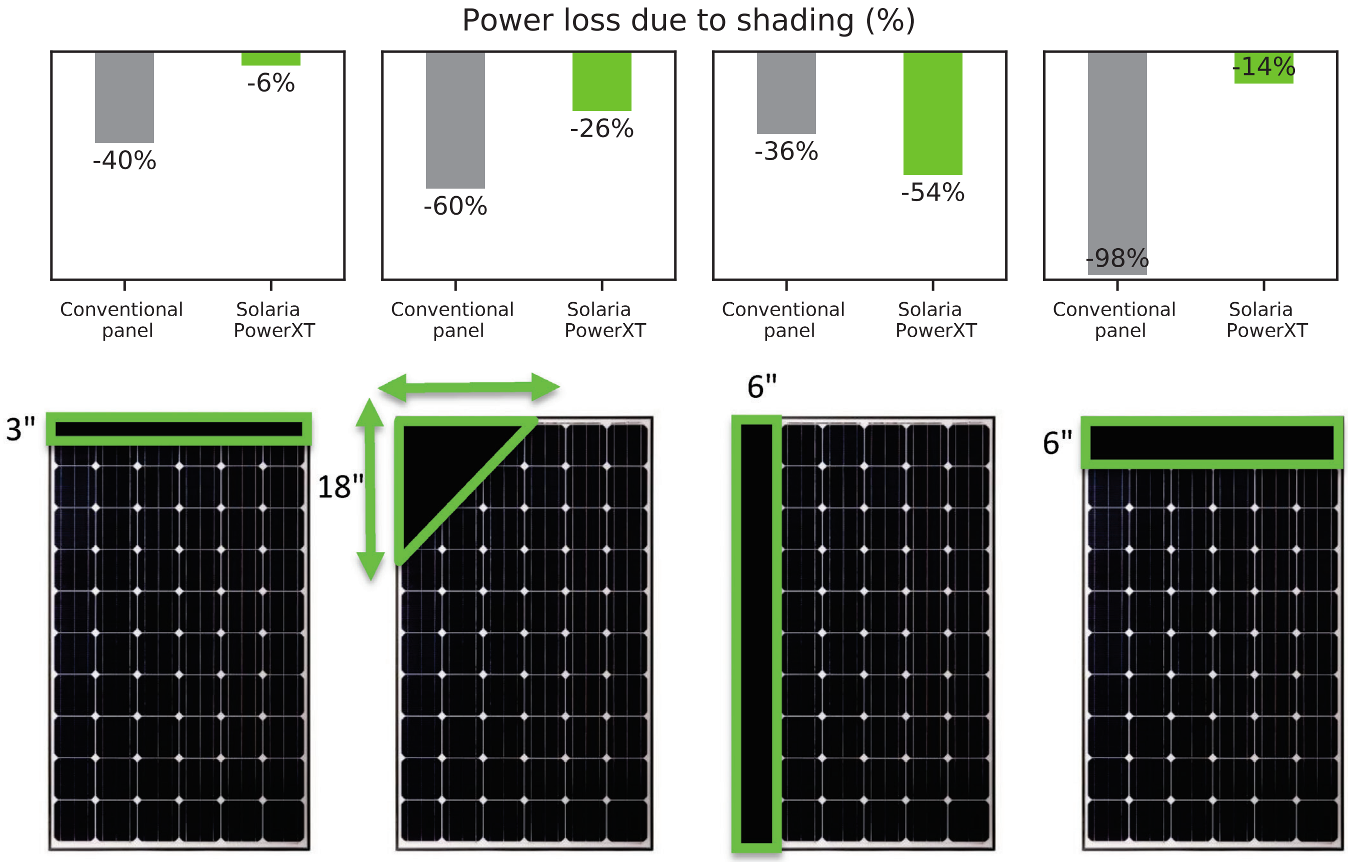


Figure 5: Measured power loss in for four shading scenarios.

OUTDOOR COMPARISON WITH CONVENTIONAL PANELS UNDER SHADED CONDITIONS

To evaluate the performance of Solaria PowerXT panels in real-world conditions, outdoor testing was carried out at a 3rd-party test facility in California. Solaria PowerXT panels were tested against two competitor brands which use a series cell interconnection scheme. For each panel type, an 8-panel, single-string system was installed on a single south-facing mock roof with a 20° tilt. Each system was connected to an identical string inverter. Testing was performed over a 70 day period in late Summer/early Fall.

A dormer-like shading object was positioned over the panels such that it created approximately 12 inches of shading on the top row of panels at solar noon on the first day of the test (**Figure 6**).

Figure 6: One of the three systems installed at the test site. Top: front-on view, around midday. Bottom: view from ground, early morning. The overhanging dormer was installed (visible at the top of each image) to partially shade the top row of panels.

As expected, all three systems generated less than they would have had they been operating in unshaded conditions. However, the Solaria panels, with cells assembled in a series-parallel connection scheme, achieved significantly better performance than the competitors. **Figure 7** shows the total specific energy yield for each system. By the end of the 70-day test period, the Solaria system had generated 37% more energy than Competitor 1 and 45% more energy than Competitor 2.

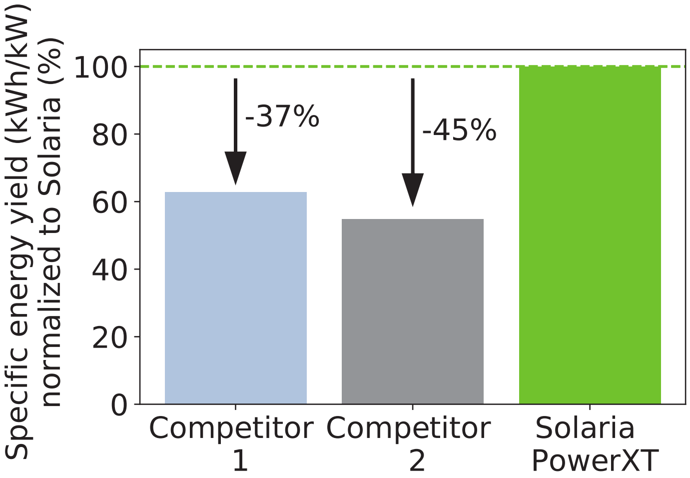


Figure 7: Total energy generated by each system after the 70-day testing period. Results are expressed in kWh/kW, normalized to Solaria's energy yield.

In principle, these results could be predicted with performance prediction software tools. However, at this time, Solaria is not aware of any tools capable of capturing the shade-tolerance benefits of PowerXT panels experimentally measured above.

SUMMARY

As shown in this paper, the Solaria PowerXT series-parallel connection can effectively mitigate shading losses under many commonly encountered shading conditions. These conditions were produced in a controlled environment to quantify the effects clearly. In actual field conditions where shading is present, the shading losses compared to other system loss factors and their resulting effect on system power may vary depending on various factors such as system location, configuration, and shading conditions. The results set forth herein are not intended to represent or guaranty actual performance levels.