Courtesy Michael Pendy

Even a small amount of shading can have a substantial effect on the output of a series string of PV modules. But distributed MPPT technologies are primed to minimize shading's impacts.

New equipment is showing up to address the limitations of standard single-inverter systems. Conventional batteryless grid-tied systems generally use a single maximum power point tracker (MPPT) that is housed in the inverter to condition the energy coming from multiple PV modules. The process tracks one maximum power point from array input, varying the ratio between the voltage and current delivered to get the most power it can.

But each PV module has differences that will cause it to have a *different* MPP than its neighbors. This can be caused by manufacturing tolerances; dust and dirt; different module temperatures; partial array shading; and so on. The result is that the array's MPP becomes a compromise between all the intermodule variances, and additional power that may be available from some modules (i.e., the unshaded, cleaner, cooler ones) is lost.

One solution is distributed MPPT (or "distributed power harvesting") equipment—electronic boxes, wired to individual PV modules, to independently track each module's MPP. This hardware can manipulate the maximum available power to deliver either a higher current or voltage, depending on the configuration of the system (series versus parallel wiring). Included in the category of "distributed MPPT" equipment are specialized DC-to-DC converters, microinverters, and AC modules (i.e., a microinverter packaged with a PV module and UL listed as a single product).

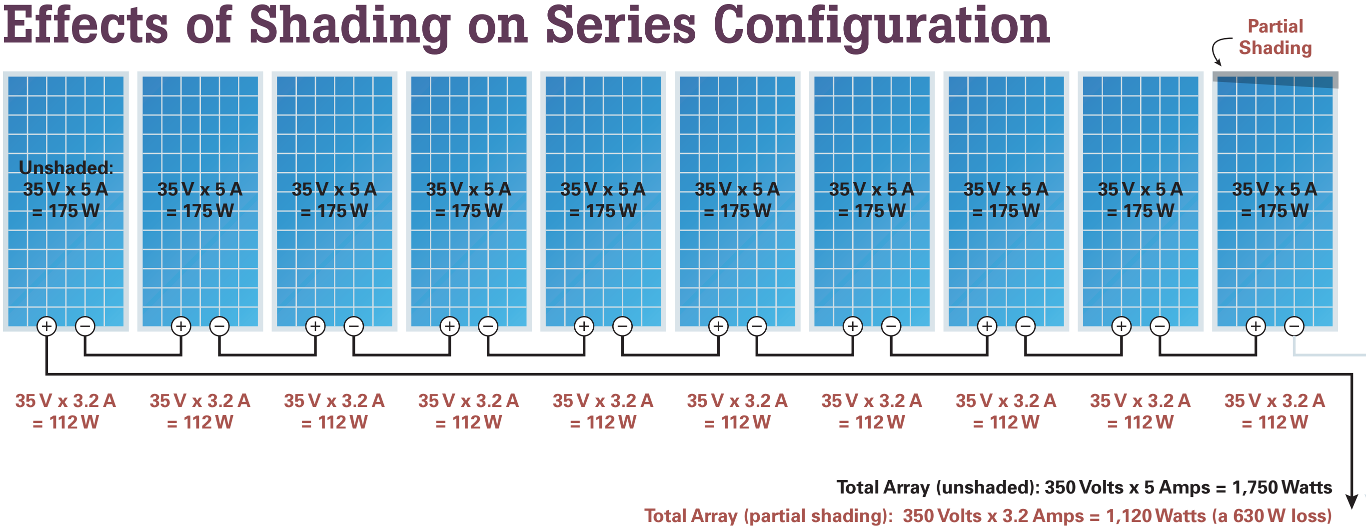
How They Work

To understand how these devices tap into power that might otherwise be lost, we need to understand a few rules about combining PV modules.

Individual, module-by-module power optimizers like this one by National Semiconductor can increase overall PV array production in cases of individual module underperformance.

Courtesy www.solarmagic.com

Effects of Shading on Series Configuration



Series configuration. When modules are wired in series, the voltage of each module is summed to obtain the total voltage of the string. The string's current will remain that of a single module. For example, let's say we have ten 175-watt modules in series—each at 35 V and 5 A.

Theoretically, the array should have 350 V and 5 A, or 1,750 W. However, what if each module's amperage isn't identical to the others, as would result if a module was partially shaded or in a different plane of orientation? When we wire dissimilar modules together in series, voltage will be additive. However, the current will be just above the *lowest* current in the string.

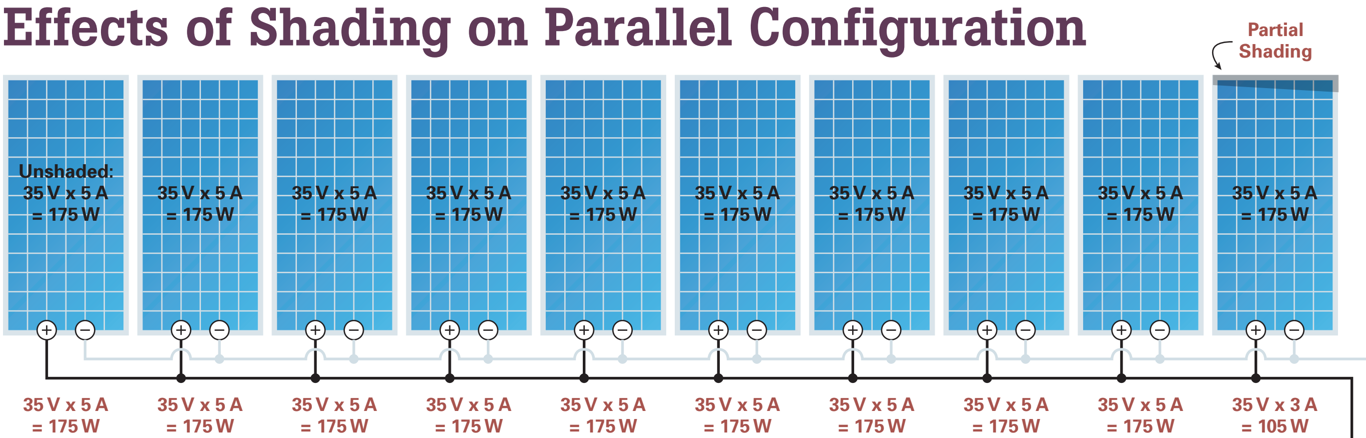
Let's say there were nine modules at 35 V and 5 A, but partial shading on the last module reduced its output to 35 V and 3 A. The resulting array's power would be about 350 V and 3.2 A, or 1,120 W. Notice the loss in the entire string (1,750 W – 1,120 W = 630 W) is much greater than the loss from the underperforming module (175 W – 105 W = 70 W).

Although this example is simplified, and bypass diodes on the array would keep the losses lower (see "Bypassing the Bypass" for more detail), the goal in a series configuration is to keep all the currents as equal as possible (discussed later)—or consider parallel wiring.

Parallel configuration. When modules are wired in parallel, the current of each module is summed, with the array's voltage remaining that of a single module. When dissimilar modules are wired in parallel, the amps add up, and the voltages will average. Wiring the same 10 modules in parallel results in an array that will have 35 V and 50 A, or 1,750 watts. But now, with the last module producing 35 V and 3 A, the resulting array's output would be about 35 V and 48 A, or 1,680 watts—a significant improvement over the series scenario.

Microinverters and some DC-to-DC converters (such as eIQ Parallux vBoost or Tigo Energy's Module Maximizer EP series) accommodate parallel configuration. But instead of leaving the module and array voltage low, they first boost the voltage to several hundred volts, proportionally reducing the current. Then, the high voltage (which has also been converted into AC in the case of the microinverter) and low current is wired in parallel. The result is that the shaded module is still able to contribute its full power, without affecting the rest of the array.

Effects of Shading on Parallel Configuration



Note: This is a theoretical example, as all batteryless grid-tied inverters would require substantially higher array voltage.

Bypassing the Bypass

The main article's simplified explanation of how distributed MPPT devices work left out an important detail: the module's built-in diodes (usually two or three that each control a section of the module) that help mitigate shading effects. While it's true that the lowest current will bog down a string of dissimilar modules in series, bypass diodes will help route power around a shaded module (or module section) once the resistance of the module's shaded section exceeds that of the diode.

Batteryless grid-tied inverters actually vary the load on the array to "activate" bypass diodes once the *array's* power loss due to a dissimilar module in series is greater than that module's (or module section's) loss. This is good news for systems without distributed MPPT—otherwise, a shaded cell could shut down an entire array.

Distributed MPPT equipment can recover the power from shaded modules (or module sections) and keep bypass diodes from activating, simply by finding the available peak current and voltage from the partially shaded module, then calculating and placing the required load on the module so that the current will still flow through the shaded portion of the module, instead of the bypass diode. This keeps module sections and entire modules from going "offline" so they still contribute what they can. This can be accomplished either via a parallel configuration where the module voltage is boosted to match the other module voltages and the available current is added to the total, or through a series configuration where the current of the shaded module is increased to match the other modules' currents.

A thin section of tape creates partial shading for testing two arrays—one with distributed MPPT, the other without.

Courtesy www.tigoenergy.com (3)

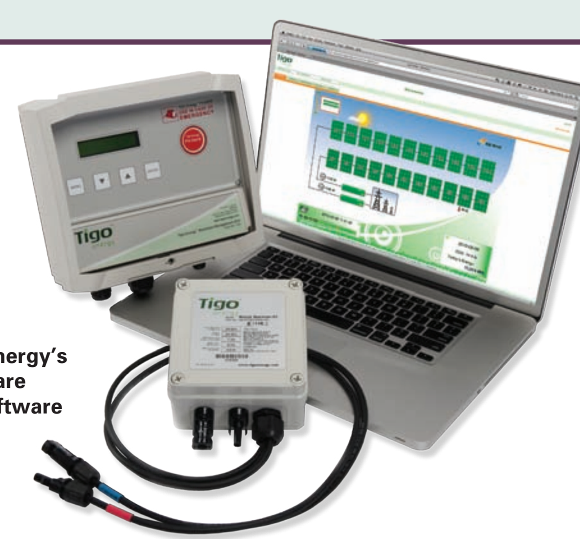
Distributed MPPT gains the bottom array an additional 412 watts (40% more output).

A test compared two rows of 11 modules: the bottom row has Tigo Module Maximizers-ES (series) units installed on each module, and the top row does not (see photo at left and screen shot, above). To mimic a shading scenario on both arrays, the two modules on the right have approximately 50% of the bottom row of cells covered. The screen shot shows the output of all modules under these conditions. The bypass diodes on both shaded modules in the top row (the non-Tigo string) have been activated—showing zero output. The remaining modules on the string have reduced output as well (about 116 W each). When the inverter varies the load on the array to activate the bypass diodes, the string is no longer operating at its maximum power point, reducing each module's output. In contrast, with the assistance of the Tigo devices, the bottom string is getting about two-thirds of the output from the shaded modules, and the other modules are operating at their maximum power (about 141 W each).

The length of time the unshaded modules on the non-Tigo string will operate at the reduced output depends on the inverter's MPPT algorithms. Inverters may scan the string periodically to find a new MPP. Another irradiance change (such as passing clouds) also can cause the inverter to search for the optimal peak power point for the unshaded modules and restore the output of those modules to their MPP. Even with distributed MPPT equipment installed, if entire PV cells have severe shading (opacity at 80% to 100%) and their is high irradiance, bypass diodes may still activate to prevent reverse current in the shaded module sections.

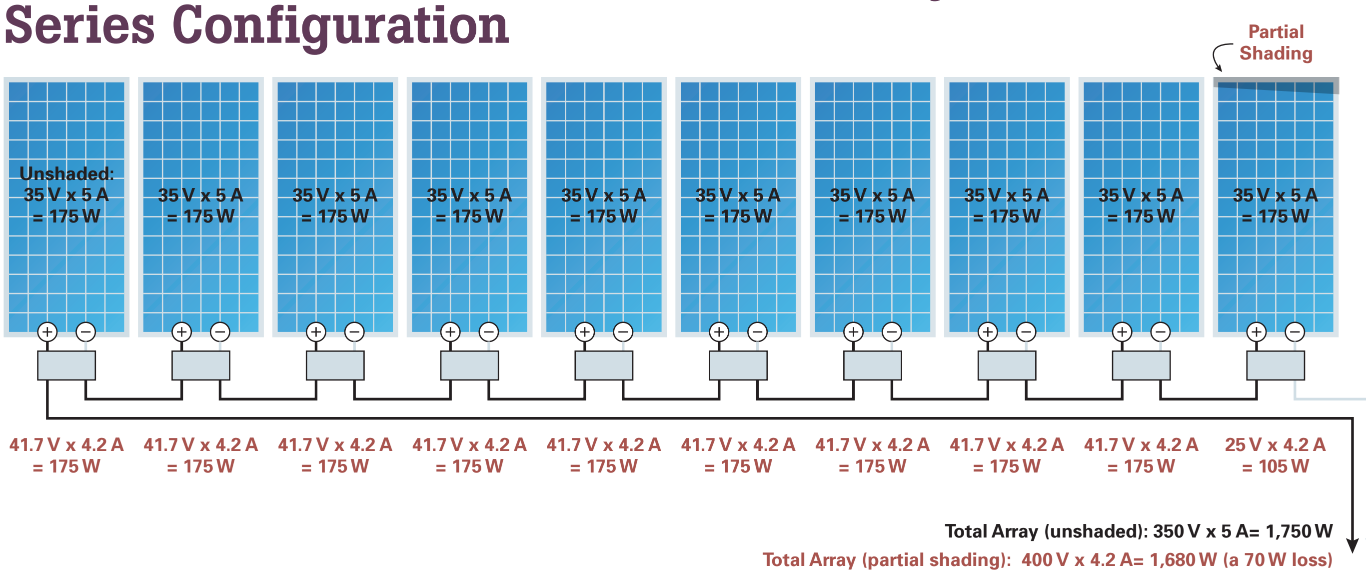
Per-module MPPT & series configuration. A distributed MPPT device wired to each module facilitates tracking the highest power point (voltage and current) for each module, but it can also manipulate that extracted maximum voltage and current to reduce potential string losses.

Although each maximization technology is a bit different for DC-to-DC converters, they all use DC-to-DC conversion circuits ("DC boost" raises voltage and lowers current, while "DC buck" drops voltage to raise current). Some solutions lower the voltage output of the weak modules, raising their current to match that of the stronger ones. Others raise the voltage of the stronger



Tigo Energy's hardware and software suite.

Distributed MPPT Effects on a Partially Shaded Series Configuration



modules, lowering the voltage of the weaker ones (buck/boost) to create a fixed string voltage and current.

In the example system, each module produced 35 V and 5 A (175 W), but the reality is that every module has a slightly different peak voltage and peak amperage. The MPPT adjusts the load for each module to find that per-module peak wattage. Then the maximum available power for the entire array (i.e., the sum of all the individual module's peak watts) can be harvested either in a parallel configuration, or in a series configuration by transforming the voltage to align the string current.

Although other factors, such as module production tolerance or temperature variances, can change a module's peak power output, let's continue with the simplified shading example (9 modules with 35 V, 5 A output, and one with 35 V, 3 A). The theoretical total watts available would be 1,680 W [(9 x 175 W) + 105 W]. Now, we can set the MPPT equipment output voltage to whatever we want and transform the voltage in the DC-to-DC device to set the current as well.

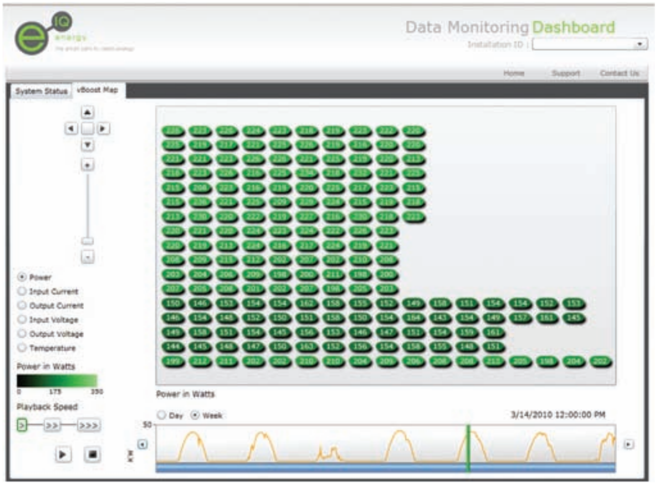
In the case of DC-to-DC converters using a series configuration, the output voltage can be set to one that is efficient for the centralized inverter. For example, the SolarEdge PowerBoxes are typically configured so that the total output voltage of the array (i.e. the inverter input voltage) is 400 V to work with their SolarEdge inverter. The output of each PowerBox is set to have a consistent amperage, and the summation of the voltages will equal 400 V.

Following our example: 1,680 watts ÷ 400 V = 4.2 A—this sets the current (amps) goal of each module/MPPT pair (for consistent amperage in series). Each PowerBox will alter output voltage to achieve 4.2 A. With the nine similar modules, voltage will be boosted to about 41.7 V (175 W ÷ 4.2 A = 41.7 V). The voltage of the PowerBox attached to the shaded module will be dropped to 25 V (105 W ÷ 4.2 A = 25 V).

A series configuration would yield 400 VDC at 4.2 A for 1,680 W [(9 x 41.7 V) + (1 x 25 V)], not including conversion losses, which are discussed later. Compare this to the 1,120 W that comes from this series configuration not using distributed MPPT equipment.

The values used in these examples are theoretical and do not account for the impact of bypass diodes (see "Bypass" sidebar). Explanations also are simplified. In reality, there are several ways to achieve this end result: For example, Tigo's equipment uses a technique called "impedance matching" via transistors, rather than directly alternating voltages.

eiQ Parallux vBoost units raise voltage and are wired in parallel to capture maximum power. Because these units can accept up to 350 W, more than one module can be wired to each unit.



Courtesy www.eiqenergy.com (2)

The SolarEdge PowerBox MPPT units are specifically designed to work with the SolarEdge inverter's voltage input window, increasing efficiency.

Courtesy www.solaredge.com (2)

Pros

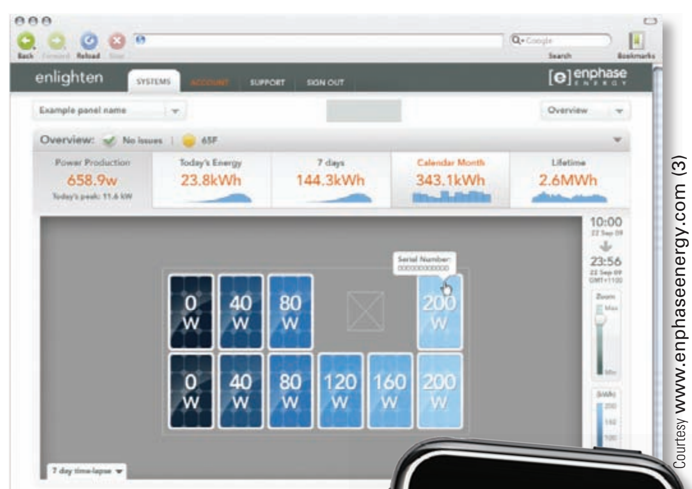
Several of these products have added benefits, such as module-level monitoring (see the "Equipment" table). MPPT hardware attached to each individual module also can capture module performance data for monitoring each module in the array. Typically, this data is uploaded to the manufacturer's Web site via a separate systems communications box that is linked to an Internet gateway.

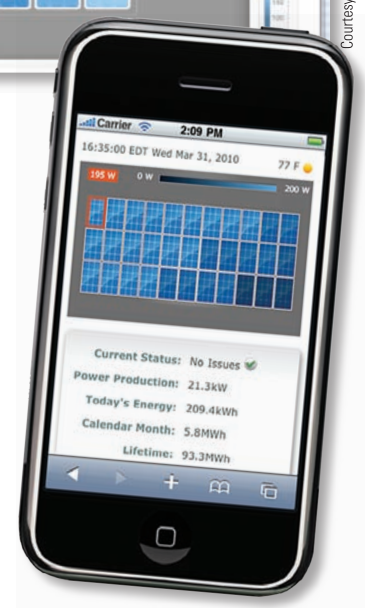
While module-level data monitoring is common for microinverter systems, when included with DC-to-DC converters, this feature also gives centralized inverter systems (for new systems *or* as a retrofit to older systems) the same capability. Monitoring each module's performance can help users quickly spot problems within the array. For example, a module with a bad diode (which can keep an entire section of a PV module from producing power) will be easy to spot. Without module-level monitoring, that problem would likely remain undetected.

Another feature available on some units is the ability to limit PV power at the array, remotely. Normally, PV arrays cannot be shut down when the sun is shining on them—even if you disconnect the balance-of-system equipment, high-voltage DC will still exist at the PV array, unless the modules are covered. With some distributed MPPT systems, commands can be issued to each box to disconnect each module from the next.

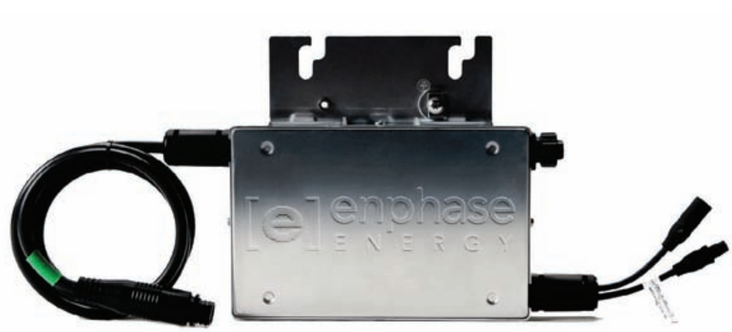
In systems utilizing DC-to-DC conversion, the voltage of an array normally operating at up to 600 VDC can be reduced to the voltage of a single module (from 17 to 70 VDC for crystalline PV modules), or less with some distributed MPPT equipment. The means for accomplishing this varies by product. For example, Tigo uses a "safety" button (via the on-site communications box or activated online, but the communications box requires AC power to do so). SolarEdge units are programmed to switch into "safety mode" whenever the inverter is shut off. In microinverter-based systems, shutting down the AC disconnect (or PV backfed breaker) automatically shuts down each microinverter and thus each module's AC output.

Forthcoming safety requirements could significantly impact the distributed MPPT market. A potential *National Electrical Code* requirement (slated for 2011) calling for "DC Arc Fault Circuit Protection" devices may be implemented. This protection device could be built into distributed MPPT equipment to limit the potential for arc faults in PV arrays. Placing them at the module level increases the protection for the rest of the PV circuit, as opposed to placing that protection further downstream (for example, at the inverter). In anticipation of this new requirement, a few distributed MPPT equipment manufacturers are already including this feature in their equipment (see table).





Courtesy www.enphaseenergy.com (3)



As the only microinverter currently available for the residential PV market, Enphase has been leading the industry in AC MPPT technology.

Online monitoring is now available as an iPhone app.

Products for MPPT of Individual Modules

DC-to-DC MPPT	Model	Retrofit Option (Existing Inverter)	Series / Parallel	Matching Inverter	Module-Level Monitor	Remote Shut-Down	Arc Fault Protection	Unit Required for Each Module?	Efficiency	Cost***	Warranty (Yrs.)
eIQ www.eiqenergy.com	Parallux	Yes	Parallel	No	Yes	Yes	Yes	No*	97–98%	$99, $139	20
SolarEdge www.solaredge.com	Power Box	No	Series	Yes	Yes	Yes	Yes	Yes	98.5%	Kits $3,597 up, incl. inverter	25
National Semiconductor www.solarmagic.com	Solar Magic	Yes	Series	No	Yes	No	No	No	98.5%	$175 + $79 required diode	20
	SM3320	No**	Series	No	No	Yes	Yes	No	99.5%	$75	25
Tigo Energy www.tigoenergy.com	Maximizer ES	Yes	Series	No	Yes	Yes	Pending	Yes	99.6%	$56	20
	Maximizer EP	No	Parallel	Yes (Kaco)	Yes	Yes	Yes	Yes	97.5%	$79	20
Xandex www.xandex.com	Sun Mizer	Yes	Series	No	No	No	No	No	98.0%	$250	20
Microinverters											
Enphase www.enphaseenergy.com	Enphase	—	Parallel	N/A	Yes	Yes	No	Yes	95.0%	$230	15

*More than one module can be wired into a single unit; **Module-integrated; ***Communications equipment and online system monitoring access costs not shown

Cons

So, what are the drawbacks? The most obvious is increased up-front cost compared to the traditional centralized inverter approach. But does the increased energy production and access to additional features (monitoring and safety) pencil out with the additional equipment purchase and installation time? It depends on the PV system's specifics: the amount of array shading (the more shading, the more likely increased energy can be harvested with these devices); various orientations/tilt angles; or different models of PV modules within the same system. Chances are, if your system does not fit into these categories, the additional cost of the equipment will not balance out with the increased energy yield. However, the desire to add module-level system monitoring or the safety features included may be enough to tip the scales for some system owners. Several manufacturers are taking steps to integrate their MPPT devices into the modules to decrease overall system cost and installation time. National Semiconductor's SM3320 unit is one example.

Another consideration is that these devices use some energy to perform their functions. The question is, then, does the increased energy harvest exceed the energy lost in the device? If so, by how much? Again, the answer depends on the PV system's specifics, such as the amount of shading and any module mismatch. DC-to-DC converter efficiency ranges from about 97.0% to 99.6%. Parallel configurations are on the low side of that range, due to the significant voltage boosting that they must perform. To fairly compare these systems against microinverter-based ones, you'll also need to account for the centralized inverter's efficiency.

These products are new to the industry—there is not yet a track record. All claim to have performed some field-testing and "accelerated life testing" on their products, but it is difficult to predict if the thermal cycling these units endure will take a toll on their electronics—yet most carry 15- to 25-year warranties.

Comparing Your Options

Currently available, UL-listed DC-to-DC converters and microinverters are compared in the table, including the following:

- **Retrofit option**—Can the product be installed on the existing system with an existing inverter? Most of the DC-to-DC converters can be used with an existing system that has a central inverter. Microinverter systems will generally only be installed on new systems, since most folks will not want to get rid of an already purchased and installed central inverter. In either case, make sure your modules' voltage and amperage are compatible with the equipment you are using.

- **Parallel or series configuration**—All microinverter systems will connect to each other in a parallel configuration (voltage stays constant; current is additive).

Xandex's SunMiser units only need to be installed on modules that have shading, reducing up-front costs.

Courtesy www.xandex.com

DC-to-DC converters are designed for either, but not both, parallel or series (voltages are additive; current stays the same).

- **Matching inverter available**—Some DC-to-DC converters can be matched to specific inverters, which are altered and optimized for use with this equipment, further increasing system efficiency. (Currently, SolarEdge PowerBoxes can only be used in systems with a SolarEdge inverter.)

- **Units required**—Is one unit needed per module, or only needed on shaded modules? Can multiple modules connect to one unit? If you do not need to install a unit on every module in the string, you can reduce your up-front cost. However, other benefits, such as tracking MPPT individually for all modules, module monitoring, and array safety features, may not be available.

- **Cost per unit**—If one unit is required for each module, you will need to multiply this times the number of modules in the array, and add any other desired/needed components expenses (such as communications equipment, online monitoring/subscription contracts, etc.) to calculate the full cost. SolarEdge pricing is for kits, which include several power boxes and their inverter.

Out of the Shade

Sage solar advice is to install PV arrays on shade-free, south-facing rooftops. While good counsel, what about sites that have a little shading, multiple module types, or multiple orientations? The boom in residential grid-tied systems is pushing manufacturers to devise solutions, since shading, module variations, and using various roof planes are a reality for many installations. Distributed MPPT products are one solution, yet viability for *your* installation depends on the circumstances.

Another indicator that this technology is on the rise is the many more manufacturers—in addition to those listed here—that are in various stages of developing their own distributed MPPT products, including Enecsys, Exeltech, Greenray, SMA/OKE, Direct Grid, and SolarBridge. In the years to come, it will be interesting to see which products will ultimately be standing out in the sun—or rather, under the shade of the modules.

Access

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