



Background

Current technology used in On-Grid PV systems has many drawbacks. The purpose of this paper is to discuss and categorize the problems and drawbacks inherent in residential and commercial photovoltaic systems. Typical residential photovoltaic installations suffer from numerous problems that prevent this technology from realizing its full market potential. Many of the present problems stem from power losses – whether due to module mismatch, orientation mismatch, or partial shading. Other problems stem from system design limitations and constraints, lack of monitoring and lack of analysis abilities. In addition, the absence of safety features poses risks to both workers installing or maintaining the system, and to firefighters dealing with fires in the vicinity of PV installations.

For an overview of the SolarEdge distributed power harvesting system, which overcomes the limitations of traditional systems, please refer to the SolarEdge paper “SolarEdge Architecture Overview”.

Typical System Architecture

Current residential PV systems are typically built from ten to a few hundred PV modules connected in a series-parallel connection, as shown in Figure 1. Several panels (10 to 15 typically) are series-

connected in a string of modules so that a voltage high enough for DC/AC inversion (150V to 800V) is achieved. More power can be added to the system by adding strings. Since the strings are connected in parallel, they have to match the other strings in all parameters i.e. type of panels, length and orientation. The entire array is connected to a solar inverter which is responsible for harvesting the electrical energy and inverting it to AC so it can be fed into the grid.

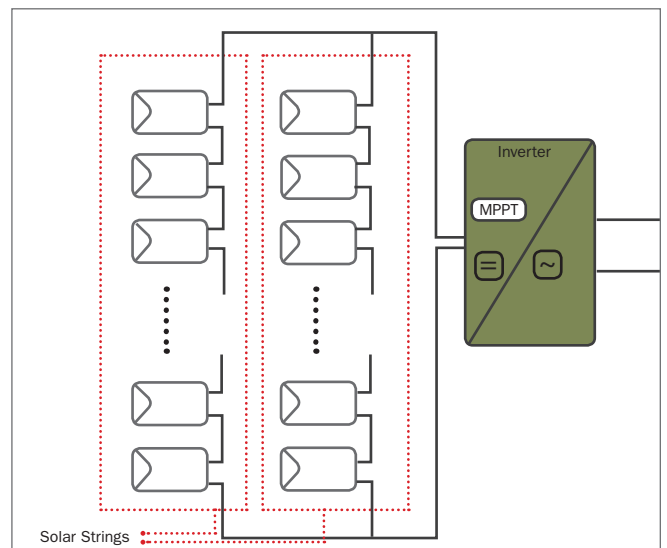


Figure 1



The inverter handles maximum power point tracking for the entire array. This is done by finding the DC working point in which the most power is harvested from the array. The harvested power is inverted from DC into AC power that is fed into the grid. The inverter is also responsible for conforming to the electrical and safety regulation requirements.

PV System Drawbacks

In the following section we will discuss the different causes for power losses in typical PV systems, as well as other key drawbacks of these systems.

Module Mismatch Losses

The manufacturing process of PV cells produces cells with relatively large tolerances in their power output capability. To reduce the difference between cells in the same module, they are sorted during manufacturing to different power categories (bins) and modules are assembled with cells from the same bin. This produces panels with smaller tolerance variances in output power. The panels themselves are not sorted and panels in the market today have a 3% tolerance in output power.

When several modules are connected in series, each one has a slightly different MPP current. The series connection does not allow the optimal MPP current to be drawn from each module. The inverter will select the current which gives the average peak power point of the string or array. This peak power is always less than the theoretical sum of the individual peak power points of every module. Figure 2 shows the I-V and power curves of 3 mismatched modules (3% tolerance). In Figure 3 the accumulated I-V and power curves of these modules are shown. It is clear that the string's peak power point is different from the sum of peak power of the three modules.

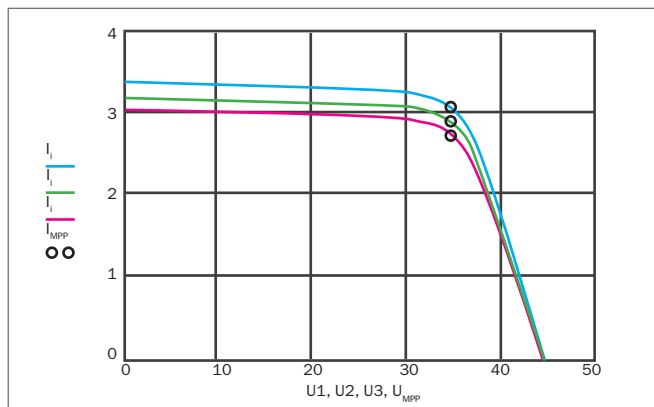


Figure 2

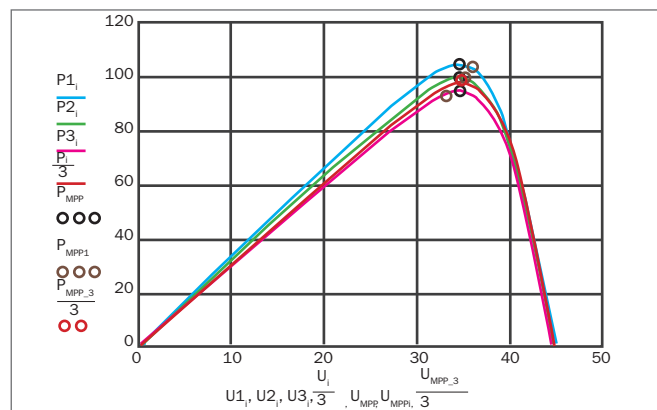
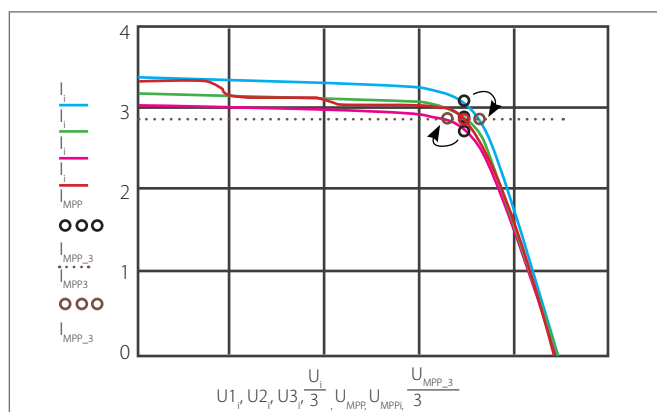
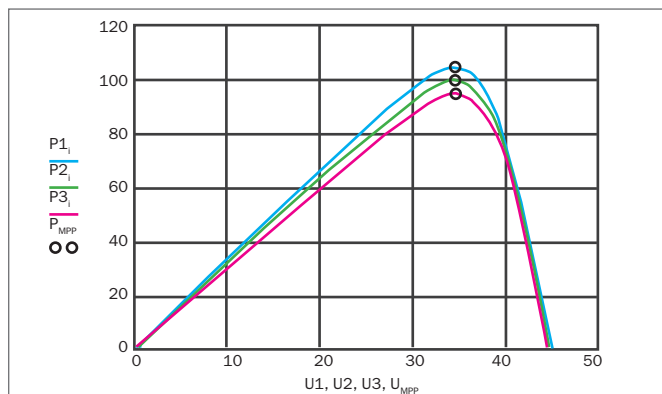


Figure 3

The loss demonstrated here is referred to as mismatch loss. In standard residential and commercial PV installations, it can be as high as 5%.



Partial Shading Losses

Partial shading occurs when part of a panel or panels are shaded, causing different levels of illumination on the cells in the panel. This can happen due to shade from the building itself, light posts, chimneys, trees, cloud fronts, dirt, snow and other light-blocking obstacles.

Shading on any part of the array will reduce its output, but this reduction will vary in magnitude depending on the electrical configuration of the array. Clearly, the output of any shaded cell or module will be lowered according to the reduction of light intensity falling on it. However, since this shaded cell or panel is electrically connected to other unshaded cells and modules, their performance may also be lessened since this is essentially a mismatch situation.

For example, if a single module in a series string is partially shaded, its current output will be reduced and this may dictate the operating point of the entire string. Alternatively, the module's bypass diodes may conduct, causing this module to stop producing power¹. Partial shading of crystalline solar modules will result in dramatic reduction of solar module output. One completely shaded cell can reduce a solar module's output by 40% to 95%.

If several modules are shaded, the string voltage may be reduced to the point where the open-circuit voltage of that string is below the operating point of the rest of the array (under voltage situation), resulting in that string not contributing to the array output.

The reduction of output from an array with partial shading can be significantly greater than the reduction in the illuminated area. This is due to the loss of output from unshaded cells in the partially shaded module, the loss of power from illuminated modules in any severely shaded string that cannot maintain operating voltage and the loss of power from the remainder of the array because the strings are not operating at their individual peak power points².

For residential systems, it is impossible to avoid all shading without severely restricting the size of the array and hence losing output at all times (see Figure 4 for examples). In these systems, partial shading

losses are estimated to contribute between 5% to 25% annual power losses.

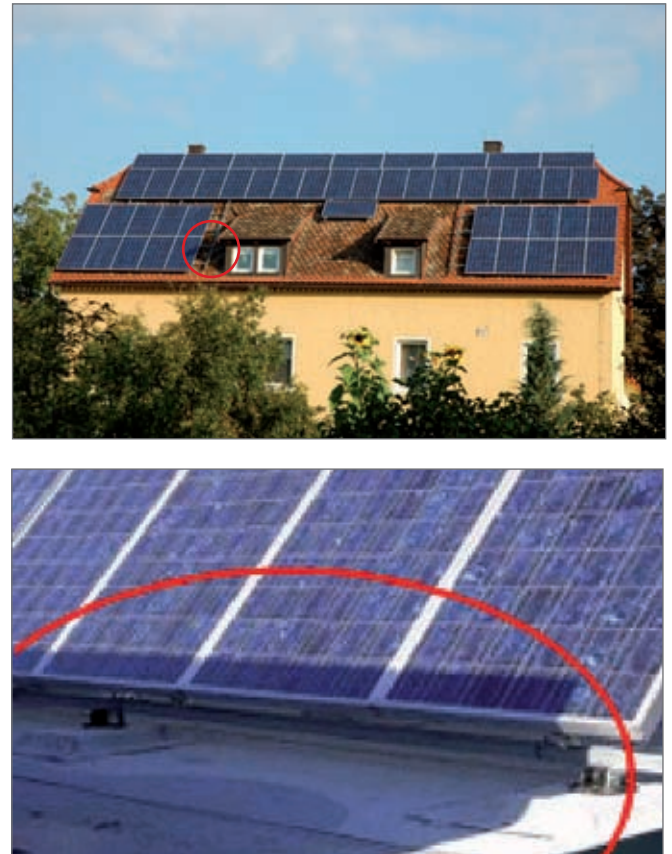


Figure 4

MPP Efficiency Losses

The MPPT performance is a very significant aspect of the characterization of PV systems, since PV systems, like other systems based on renewable energies, must harvest the maximum available energy at every moment from the renewable resource. The global efficiency of the MPPT algorithm depends on its ability to make the inverter operate at the maximum power point (MPP) at every moment. In order to achieve this, the MPPT algorithm has to accurately track the MPP variations, which can be caused by factors such as irradiance, temperature variations and partial shading. Obviously, this accuracy will be strongly influenced by both the amplitude and the dynamics of the variations of the MPP. MPP losses occur due to two main factors:

1. Static losses caused by the inability of the MPP algorithm to locate the array's peak power point. In some cases, the MPPT algorithm can lock itself in local maxima.



2. Dynamic losses caused by the inability of the MPPT algorithm to track changes in the peak power point at the right speed.

The main cause of static losses in PV systems is local peaks in the array's power curve. Shading effects cause the array's power curve to exhibit more than one maximum power point. More specifically, two or more peak power points appear in the curve, where different modules contribute power to different local peaks. Most MPPT algorithms are not designed to handle local peaks efficiently and when the MPPT is locked on a local peak, the MPPT efficiency falls dramatically. Figure 5 shows measured MPPT static efficiency of 4 different inverters in the market³. The results differ showing losses of 1% to 10%.

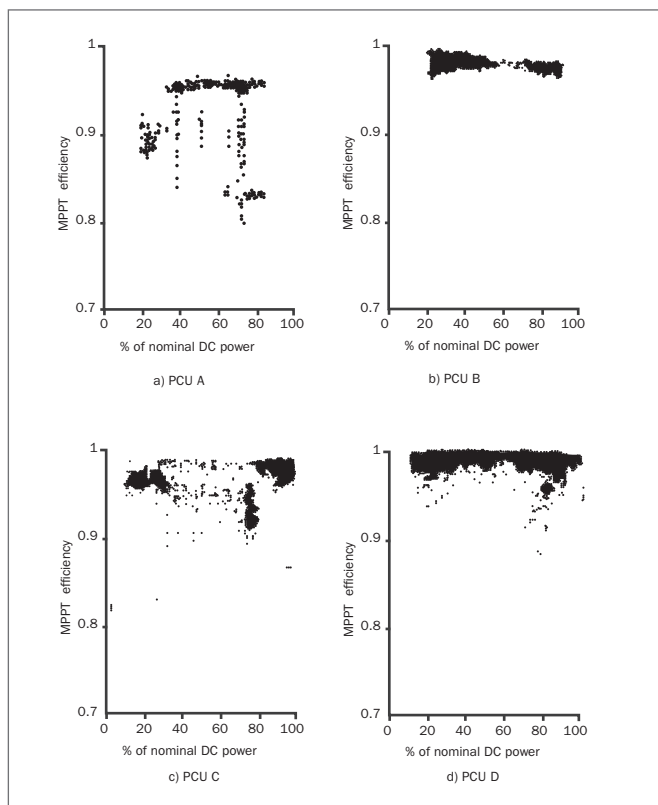


Figure 5

Dynamic losses are directly related to the speed and accuracy of the MPPT algorithm. The peak power point shifts mainly due to changes in the irradiance. While these shifts are slow and often monotonous under clear, cloudless atmospheric conditions, they can also be relatively quick during some atmospheric conditions. Figure 6 shows measurements from two consecutive days in Spain⁴. The first day corresponds to a sunny day that is affected by a partial shading

process at the end of the day. The second day corresponds to a cloudy day in which atmospheric conditions are varying quickly. The figure shows the evolution during both days of the maximum power of the generator, obtained from the measured I–V characteristic curves.

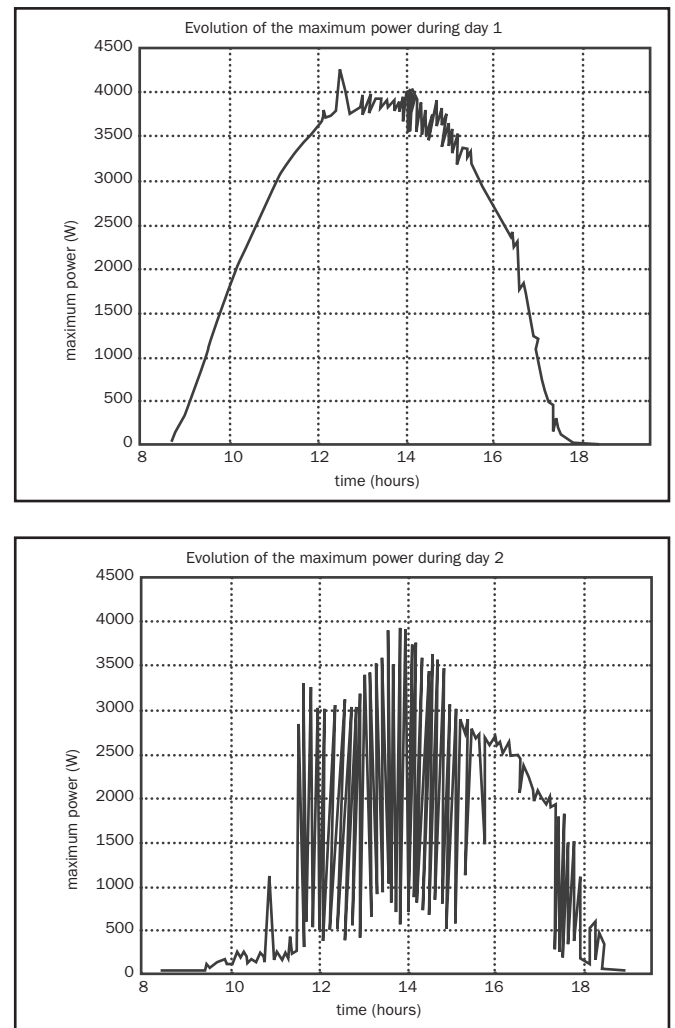


Figure 6

With this information, it is possible to calculate the real maximum energy that could have been obtained with optimal MPPT during these days. This value was then compared with the energy effectively harvested by the leading PV inverters in the market. The comparison of the available energy to that actually harvested in the first (sunny) day is shown in Figure 7.

The graph shows how, during most of the day, the MPPT algorithm tracks the maximum power point quite well. However, during the final part of the day (circled in red), due to the process of partial shading,

the MPPT algorithm fails to track the evolution of the generator maximum power point. During these hours, the performance of the MPPT algorithm in terms of energy harvested from the generator (MPPT efficiency) is 96%, that is, 4% of the energy has been lost due to the fact that the MPPT algorithm is not able to handle this real life scenario.

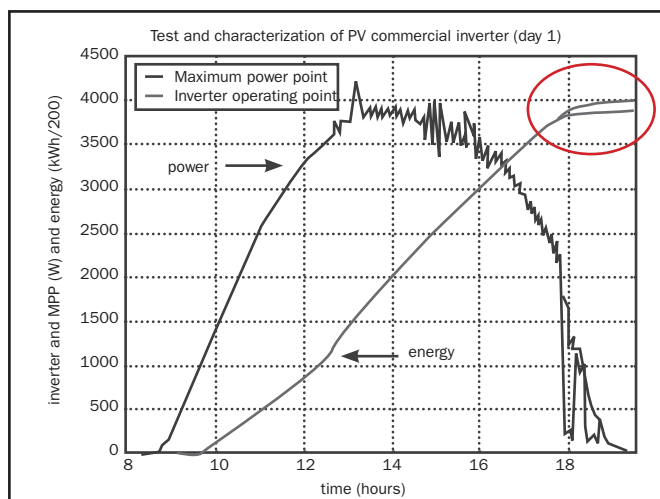


Figure 7

The results for the second day pattern are shown in Figure 8. The day is cloudy with quick variations in irradiance due to atmospheric conditions. The MPPT efficiency of the inverter in terms of energy extracted from the PV generator is reduced to 95% during the entire day.

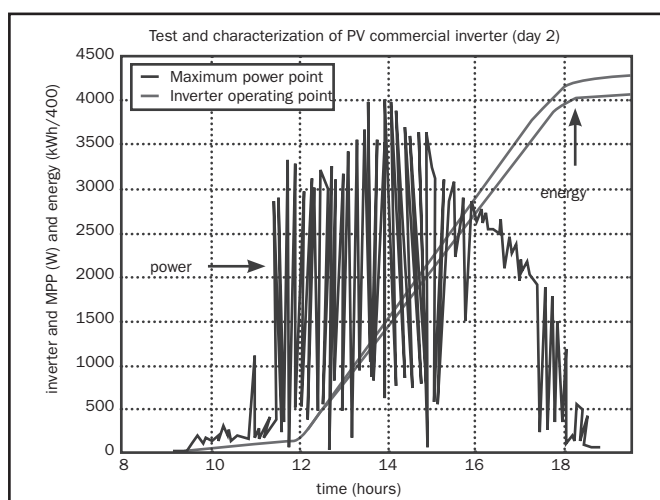


Figure 8

System Design and Roof Utilization

In addition to the power loss contributors previously discussed, current PV system architecture also presents great challenges to installers and system designers. The following factors result in a system which is less optimal and, in many cases, smaller than desired:

- The string's voltage is bound by the specific inverter's minimum and maximum permissible voltages
- The strings are placed in parallel and must be identical in length, combined with the specific geographical and physical constraints of the roof

When designing the system, the installer has to take into account the inverter's maximal input voltage and make sure that in the most extreme open-circuit conditions, the string's voltage won't reach this maximal voltage. This is difficult because many parameters like voltage tolerance, temperature variations and sunlight have to be taken into account. On the other hand, the minimal inverter input voltage must be maintained at all times in order to keep harvesting power. Taking into account the same parameter changes and the possibility of partial shading in the string make things even more complicated. In some cases, these constraints lead to low roof utilization. There are many documented events⁵ where installers elected to use a shorter string in order to increase roof utilization, causing system under-voltage during the summer.

The roof utilization issue is even more dramatic on commercial roofs, where the roofs' irregular shapes and additional obstructions (chimneys, vents, air-conditioning units, etc.) increase the difficulty in selecting just one string length. The average roof utilization in commercial roofs is 65% to 70% due to roof-related problems.

Multi-faceted roofs represent another set of challenges related to PV Systems. In these cases the use of multiple inverters enables better utilization of the roof surface. For example an installation on a roof with 2 facets (south-east and south-west facets) will require two inverters or a multi-input inverter. Both solutions are less cost effective.



It is clear that the serial-parallel architecture puts many constraints on the PV system, preventing the full utilization of the roof and reducing the actual annual energy harvested from the system.

System Feedback and Troubleshooting

Another inherent problem of the serial-parallel connection is the inability to verify the proper installation and operation of every element in the system. The only data points available are measured at the inverter (input voltage, input power) and can only partially assist in evaluating the system performance.

Since usually only overall power output is monitored, significant problems with an installation can go undetected yet cost the owners 10% or more of their energy payback. Without actionable diagnostic information, the only alternative when operating problems are suspected is to deploy technicians to the site to search for the problem with little direction or guidance. This search becomes more difficult as the installation size increases. The average commercial solar site installed in California in 2004 had 1,000 solar modules, making this difficulty very real.

The parallel connection of strings prevents the detection of defective modules and in some cases the detection of a disconnected string. For example, in a system with 8 strings, the detection of 12.5% power loss, which is equivalent to one string, is not trivial, especially since the system's expected power output is dependant on all the other criteria mentioned above.

Even when a fault is suspected and technicians are sent to the site, maintenance is expensive because it requires the deployment of skilled technicians to the solar site. Once on-site, their only recourse is to dismantle the system and search for the cause of the failure. The same lack of feedback also increases the initial installation time due to lengthy verification and debugging.

Retrofit and Long Term Fault Tolerance

Another drawback of PV systems is the difficulty of retrofitting and replacing faulty modules throughout their life cycle. If a PV module breaks in an installation (due to extreme weather conditions or accidents), it has to be replaced with a module with similar electrical characteristics, and since PV modules are improving all the time, it is not possible to use a new PV module in an old installation. For this reason, PV module companies keep an inventory of cells and modules for 25 years as a supply for old systems. The same reason prevents the gradual retrofit of old systems—you are essentially stuck with old technology.

System Safety

The safety of PV systems has always been an issue of concern. Over the years, many codes and standards were devised and discussed to improve the safety of these systems. Two main safety issues remain:

1. The risk of electrocution while installing the system. Even the series connection of two PV modules exposed to sunlight generates an unsafe voltage with enough power to kill whoever touches the exposed contacts. Many work procedures and safety precautions employed during the installation processes slow the work but maintain employee safety.
2. The risk to firemen during a fire. The first thing firemen do in a building fire is cut the power. This enables them to spray water and use axes to cut holes in the roof to let smoke out. These actions are dangerous when PV systems are installed on the roof. Firemen are trained to cut the power to the building. After doing so, they believe that there is no power source that can endanger them. In PV installed buildings cutting the power does not eliminate the dangerous voltages present at the string ends. Firemen preparing to chop a hole in the roof or to use water could be electrocuted⁶. Regulatory bodies and firefighting officials are pushing for new regulations that will ensure the shutdown of PV modules in case of fire.

Conclusion

We described the structure of PV systems and several drawbacks and disadvantages in the way these systems are designed and built. Though previous works focused on improving different aspects of photovoltaic systems, no single holistic approach was presented that could solve many of the current problems present in PV installations. SolarEdge Technologies distributed power harvesting system is the only power harvesting system and architecture that offers a full, robust solution that harvests up to 25% more energy and resolves the issues described in this paper.

¹ “Effects of Reverse-Biased PV Cell in Panels”, SolarEdge Technologies (2006)

² “Photovoltaic Modules, Systems and Applications”, Nicolla M. Pearsall & Robert Hill (2001)

³ “Performance Assessment of the Inverter based Grid Connection of Photovoltaic Systems”, Gianfranco Chicco, Roberto Napoli, Filippo Spertino (2004)

⁴ “On the Testing, Characterization, and Evaluation of PV Inverters and Dynamic MPPT Performance Under Real varying Operating Conditions”, Pablo Sanchis, Jesús López, Alfredo Ursúa, Eugenio Gubiá and Luis Marroyo (2007)

⁵ “PV Installations, A Progress Report”, John C. Wiles, Bill Brooks, Bob-O Schultze (2002)

⁶ “Commercial Building Product Magazine”, (2007)



About SolarEdge

SolarEdge provides next generation power conversion electronics that effectively remove all known system constraints across the photovoltaic energy space. Our Smart DC technology enables increased production of clean, grid-ready energy at a lower cost per watt than any other competitive offering.

SolarEdge technology marries traditional photovoltaic workflows and installation methods with a groundbreaking holistic system approach. It is a quiet revolution that is at once disruptive because of its profound benefits in changing the manner in which energy is harvested, deployed, managed and delivered and complementary because it fits into the current photovoltaic workflow.

At SolarEdge we believe the PV delivery chain is ultimately only as strong as its weakest link. By adopting a “system first” philosophy that identifies and eliminates the Achilles heel in each step in the process, we enable a constraint-free delivery of sun harvested energy.

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