
▶ At the beginning of 2011, PHOTON Laboratory inaugurated a new outdoor test facility for modules. Now the yields of more modules can be measured and compared.

# Weak-light behavior counts

Poor performance at low irradiance levels can shave more than 9 percent off a module's annual yield – as PHOTON Lab's 2010 outdoor measurements show

Text: Christian Haase, Christoph Podewils

**o Highlights**

- Among the modules installed at PHOTON Lab's outdoor test facility in 2009, nine performed very well last year – their yields differed by a maximum of only 3.9 percent from the top-ranked device, which was made by Siliken
- The module that ranked tenth, from Isofoton, produced 9.1-percent less electricity during the year than the No. 1 device, due to its substandard behavior under weak-light conditions
- Poor cell quality – specifically, high shunt resistance – is the likely culprit; the problem causes terminals in sections of the cells to short-circuit, and this effect becomes more pronounced at low irradiance levels
- Weak-light behavior is a crucial factor to consider when using modules in less-than-sunny locations

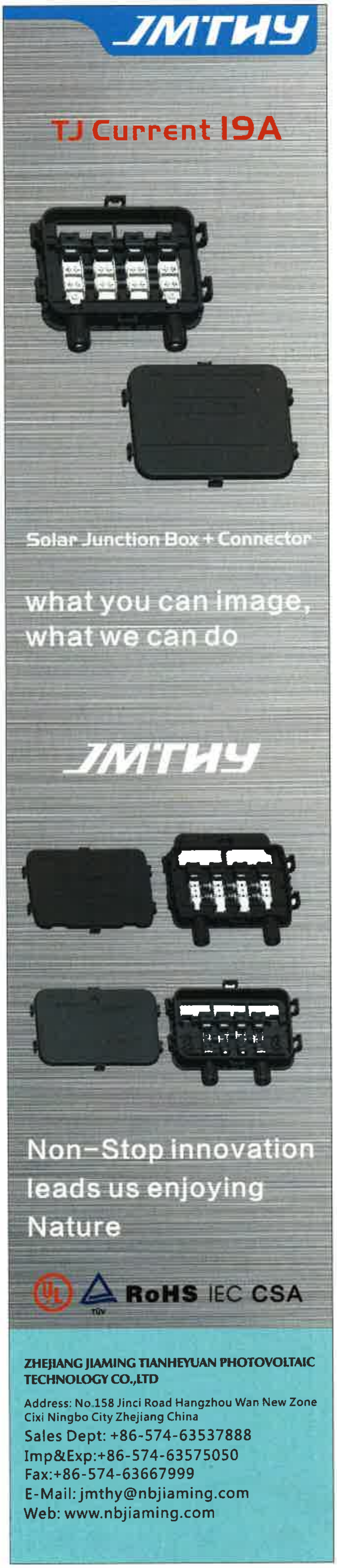
It is obvious what makes a good module – finally it is all about the yield, which should be as high as possible. And PHOTON Laboratory has been measuring exactly that at its outdoor facility for 5 years now. Among the devices tested last year, Siliken SL's 230 W multicrystalline module (model SLK60P6L 230Wp) produced the best results (see table, p. 154). At the lab's test site in Aachen, Germany – not one of the sunniest cities in the European country – the Spanish unit produced 1,044 kWh per kW. Annual solar irradiance at the site measured 1,193 kWh per m$^2$ on the module plane and 1,031 kWh per m$^2$ on the ground. These values were recorded by a model CM21 thermopile pyranometer from Kipp & Zonen BV.

Of the modules installed at the site in 2009, the next seven best-performing devices in 2010 all had yields that came in between 1,022 and 1,016 kWh per kW – or 2.7 to 2.1 percent less than the Siliken module's output. This group includes one multicrystalline module from Austria, two from China, one from India, one from South Korea and one from Taiwan. It also includes a monocrystalline device from China. Sunrise Solartech Co. Ltd. produced the module that ranked ninth, with a yield of 1,003 kWh per kW. The difference between the yields of the top nine modules is relatively small; the output of the Sunrise device is only 3.9 percent less than that of the front-runner from Siliken.

In contrast, the No. 10 module – Isofoton's IS-170/24 – generated significantly less electricity than the top nine, coming in 9.1 percent below the Siliken unit. Taken over the course of the year, this amounts to a difference of 94 kWh per kW. Under standard test conditions (STC) – which are 1,000 W of irradiance per m$^2$ at 25 °C and a spectrum corresponding to the solar spectrum at AM 1.5 – there is much less difference between the yields of the various modules. This is known because the devices installed at PHOTON Lab's outdoor test facility in 2009 were previously flash-tested, both together and individually. Therefore, the variance in yield measurements recorded during outdoor testing must be caused by the modules' reactions to the different conditions that obtain at the site.

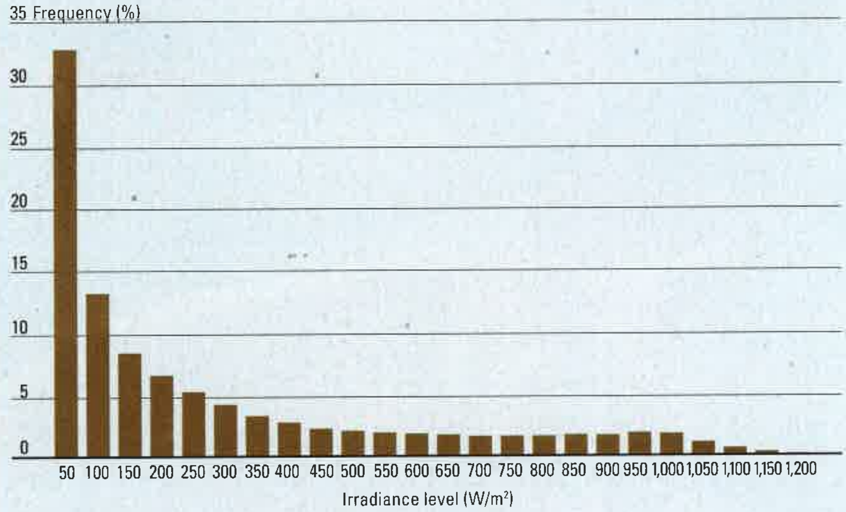
## The temperature coefficient

Two parameters determine the annual yield of a module. The first of these – the temperature coefficient – relates to how much the device's efficiency depends upon temperature. This value is specified in each module's data sheet; it indicates the effect of a 1 °C increase in cell temperature on the device's efficiency

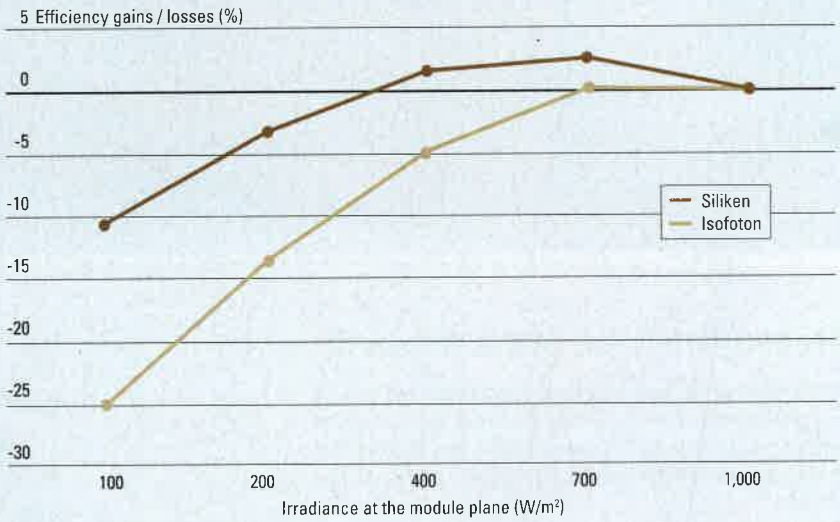



## Weak-light behavior PHOTON module test 2010

### Irradiance levels at the test site in 2010




### Weak-light behavior: Siliken vs. Isofoton modules

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▲ During 54 percent of daylight hours in 2009 (or 2,365 hours), PHOTON Lab's outdoor module test facility in Aachen, Germany, received less than 200 W of solar irradiance per m². The modules received 900 W per m² or more only 7.4 percent of the time (or 324 hours). Thus, in Germany, module performance at levels between 200 and 900 W per m², which occur during 38.2 percent of daylight hours, is especially important for determining annual yield. Modules that can make much of this weak light scored high marks in the lab's tests.

▲ Under standard test conditions of 1,000 W per m², there is little difference between the performances of the top- and bottom-ranked modules last year. However, as the irradiance level diminishes, the efficiency of the 10th place Isofoton module falls drastically, while that of the No. 1 Siliken unit increases at first and dips moderately only later.

(always negative and always expressed as a percentage). For instance, PHOTON Lab found that the two Isofoton modules at the test facility have temperature coefficients of -0.43 and -0.42 percent, which are average values. However, mounting evidence suggests that a module's temperature coefficient is not constant but varies according to the irradiance level. For example, Ralf Haselhuhn of the German Solar Energy Society (DGS) drew attention to this fact at a workshop on module technology last year. A project group at PHOTON Lab is currently studying the matter.

The phenomenon of a variable temperature dependency – one would then have to speak of a temperature characteristic field instead of a temperature coefficient – could explain why, in warm, sunny June 2010, the Isofoton modules delivered only approximately 144 kWh per kW, while the top-ranked Siliken devices, which have poorer temperature coefficients, produced considerably more – namely, 156 kWh.

# The influence of parallel and series resistance on module efficiency

The perfect module would convert 100 percent of the sunlight that strikes its surface into electricity. But that is physically impossible. The efficiency of an average multicrystalline module on today's market, for example, is approximately 14 percent. If a module could continuously convert at least 14 percent of incident sunlight into electricity throughout the course of the day, regardless of the amount of irradiance, things would be fine. But once again the laws of physics intervene. The efficiency of a solar cell – and thus, of a module – fluctuates as irradiance conditions change.

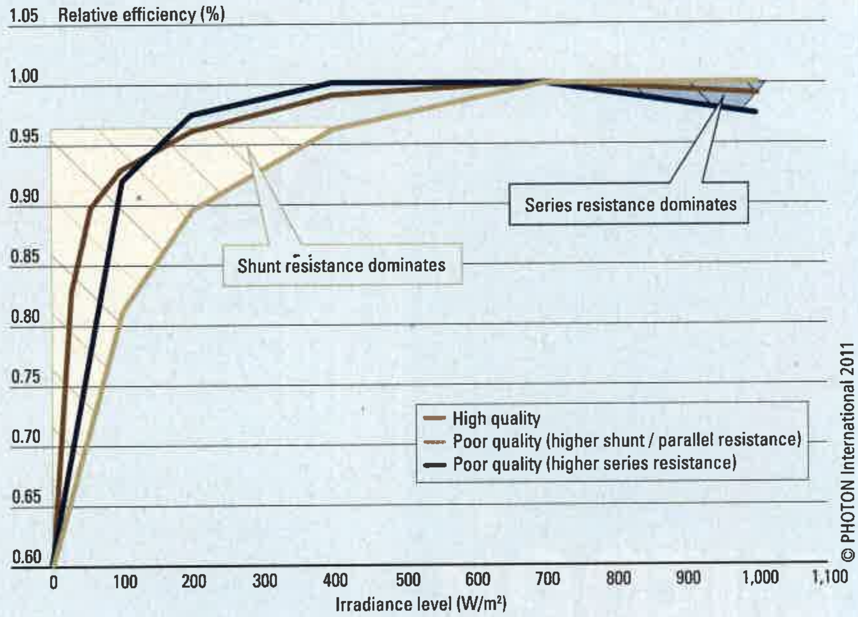
This is caused by two different types of resistance that always occur in solar cells and modules (though in varying degrees): parallel resistance, which occurs between the terminals of each cell, and series resistance, which occurs between the cells themselves.

If the parallel resistance is too low, so-called shunt currents appear, which flow in the cell without leaving it. »Shunt« is the name given to all types of local leakage currents in solar cells. These leakage currents have a local current strength that is considerably higher than the average current strength in the cell. The unwanted currents reduce the fill factor and the open-circuit voltage of the cell. However, the short-circuit current is not affected by parallel resistance. Here, a distinction is made between linear ohmic shunts and nonlinear shunts with a diode-like current-voltage (IV) characteristic. Both types can be detected and located on the cell surface using imaging methods such as lock-in thermography and the electroluminescence technique. In this way, cell manufacturers can draw conclusions as to which process step could have led to the defect. The most frequent causes for these short circuits are poor edge insulation, small cracks in the cell, aluminum particles on the surface or accumulations of contaminants at grain boundaries in multicrystalline cells.

The losses caused by linear and nonlinear shunts accumulate more or less significantly depending on the level of incident irradiance. However, in principle they act as parallel resistances; the efficiency of the cell therefore declines more sharply under weak-light conditions. In contrast, under STC – with an irradiance level of 1,000 W per m² – the effect is minimal, since the current that flows out of the cell is, in that case, many times larger than the shunt current flowing within the cell. There is no excuse for high parallel resistances – they are always caused by deficiencies in cell manufacturing or poor source material (contaminated silicon).

High series resistance cannot be blamed on cell makers (at least not categorically) – it results from poor module design. Cell current faces series resistance from the different conductors through which it must pass: the metal of the contact fingers, bus bars, string connectors, junction box terminals and, finally, the module's connector. The effect of series resistance is the opposite of that of parallel resistance; it reduces the efficiency of the module as the solar irradiance level increases (and thus the strength of the current increases).

### Module efficiencies at different irradiance levels




In scaling the bus bars, contact fingers and other conductors on a front-side contact solar cell, the manufacturer is faced with a dilemma. In order to draw off as much of the electrical current as possible without losses, the strip conductors must be as thick as possible – and in the commercial production of solar cells, in which screen printers are used for metallization, this means that they must be wide. But the wider the strip conductors are, the more shadowing they cause, which also reduces efficiency – at least under high irradiance levels. In other words, in the absence of refinements like back-side contacts or buried contacts, the manufacturer must determine the best possible compromise between the goals of narrower metallizations, on the one hand, and good resistance values, on the other. And this must be achieved without raising materials costs too much.

In practice, the compromise consists of scaling the electrical contacts in such a way that they transmit the maximum current flow through the module without very significant performance losses under ideal irradiance conditions. This means that the losses are diminished under low levels of solar irradiance, and the efficiency of the cell is therefore increased in this range. However, an excessive increase in efficiency under weak-light conditions – more than approximately 5 percent in the 400 to 700 W per m² range – raises questions about whether the cells and module have been designed well. Because in that case, under ideal irradiance conditions of more than 1,000 W per m², the conductors will heat up to a higher degree than is normal. This, in turn, causes an increase in series resistance and a decrease in efficiency. In addition, the heat can cause damage to the cell and module.

However, the assumption that better weak-light behavior under medium irradiance levels, produced by under-scaling the contacts, has a direct influence on the service life of a module has yet to be statistically proven in practice.

Series and parallel resistances have a considerable influence on the course of the IV curve of a solar cell, which determines its performance. If the efficiency curve of a module has a high dependency on the amount of incident irradiance, it usually starts out low at low irradiance levels (when shunt resistance dominates), then climbs steeply to its maximum efficiency around 700 W per m² and subsequently falls off gradually before 1,000 W per m² is reached (when series resistance dominates). High-quality modules have a rather flat efficiency curve in the range above 700 W per m², while the curve falls more sharply in the case of low-quality modules. This has the paradoxical effect of allowing poorly designed modules to perform relatively well under weak-light conditions, compared to their efficiencies at the STC irradiance level of 1,000 W per m².

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