Quantifying the Impact of Module Binning

As the solar industry evolves, rigorous analysis and cost-benefit scrutiny are replacing rules of thumb. In this article, we investigate the relationship between *module binning*, or grouping modules based on specified power or current tolerances, and its impact on energy yields.

PV Module Binning

Output current and voltages vary slightly from one module to the next. Even best-in-class manufacturing techniques result in differences in module output values. A North American EPC recently flash-tested 90,000 300 W modules from a Tier-1 manufacturer. The results showed a variation in output voltages of 34.5 V–38.0 V and in currents of 7.89 A–8.73 A.

To account for output variations, PV modules have a power tolerance specification stating the potential deviation in actual power at STC from the module's rated maximum power (Pmax). In addition, manufacturers group modules based on the power or current from each module's flash-test results. This process of module binning groups modules with similar output characteristics based on a specified maximum percent variation. It enables manufacturers—and installers—to further differentiate modules with a smaller percent of variation in output tolerances, which reduces the losses associated with module mismatch.

Current versus power binning. Manufacturers generally group modules based on their power rating, which is also known as *power binning*, although some sort modules based on their maximum power current rating (Imp), which is known as *current binning*. Power binning and current binning are not equal. Figure 1 (p. 16) shows that module output can vary in both current and voltage. Modules connected in series should operate at near-equal current output levels to reduce losses due to mismatch. Within a PV source circuit, variation in current—not voltage—results in mismatch losses.

Within a PV source circuit, different module voltages do not negatively impact one another because the sum of the voltages from each module connected in series equals the source circuit's voltage. When the individual module voltages are normally distributed (as they are in Figure 1), the higher-voltage modules offset the lower-voltage modules in each string. This netting effect results in essentially no mismatch losses due to the voltage differences between modules.

However, binning modules based on their rated power can result in wide differences in module output current. Binning modules based solely on power results in a mix of relatively high-current with lower-voltage modules, and relatively low-voltage with high-current modules. So even the tightest power band of modules can have significant current mismatch. In Figure 1, for example, the entire sample has a power range of 12% and a current range of 6.5%. But as we tighten the power ranges to 1%, that reduces the current range to 3.5%.

Depending on the manufacturer, the *binning tolerance* (the range used to bin modules) typically varies from 2% to 10%. Most manufacturers use a 5% tolerance, meaning they group together modules that are within 5% of each other's output values.

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Modeling Limitations When Estimating Energy Gains from Module Binning

Any good modeling platform has its limitations. When using models to assess the impact of module binning, there are two important considerations: measurement precision and degradation implications.

Flash-test measurement precision. Most commercial flash-testing equipment has a margin of error of approximately ±3%. Developers and EPCs should keep this in mind as they sort modules and in particular should question rebinning modules to tolerances that are smaller than the flash test's margin of error.

If a flash-test machine is always off by exactly +2.0%, then you can trust that sorting the modules tightly is genuinely sorting the good from the bad. However, measurements can drift during operation due to thermal differences, drift in equipment or random variations in operating conditions.

Degradation implications. Modeling the energy gains from binning is based on a static point in time, typically assuming out-of-the-box, STC values. However, modules degrade over time, and energy gain estimates based on modeling results may not hold true.

The key concern is whether the flash-testing results can predict the modules' future degradation rates. If so, then rebinning can mitigate future mismatch losses from degradation, since all of the fast- and slow-degradation modules are grouped together. However, if you do not correlate the flash-testing results with the modules' future degradation rates, a tighter binning tolerance could have less of an effect on production. As degradation sets in, the degraded module outputs may operate outside the binning tolerance. Thus, degradation, not the module binning tolerance, drives the mismatch losses. ●

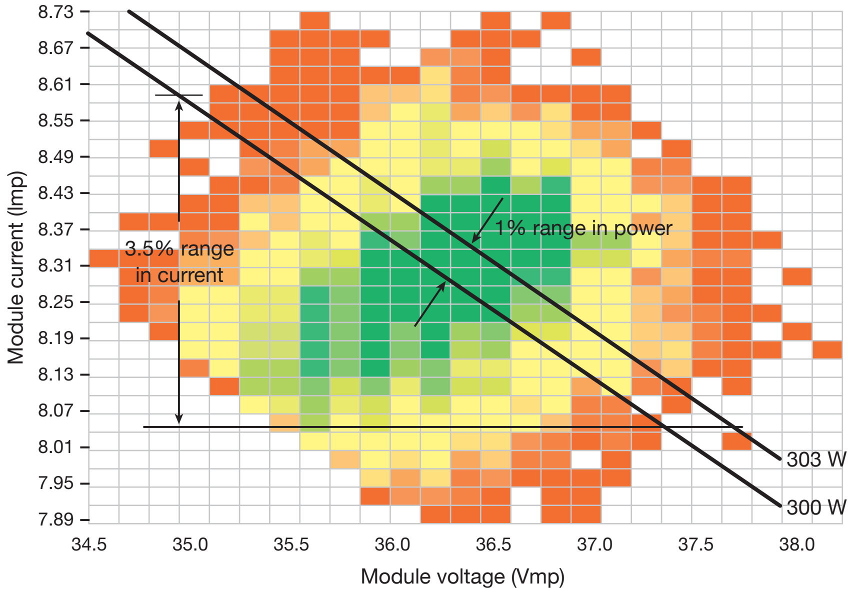


Figure 1 Groups of modules with a 1% power tolerance can have a current tolerance of 3.5%. Think of the 3.5% current tolerance as the current-binning tolerance. Thus, a 1% power-binning tolerance does not reduce losses due to module mismatch as much as a 1% current-binning tolerance does.

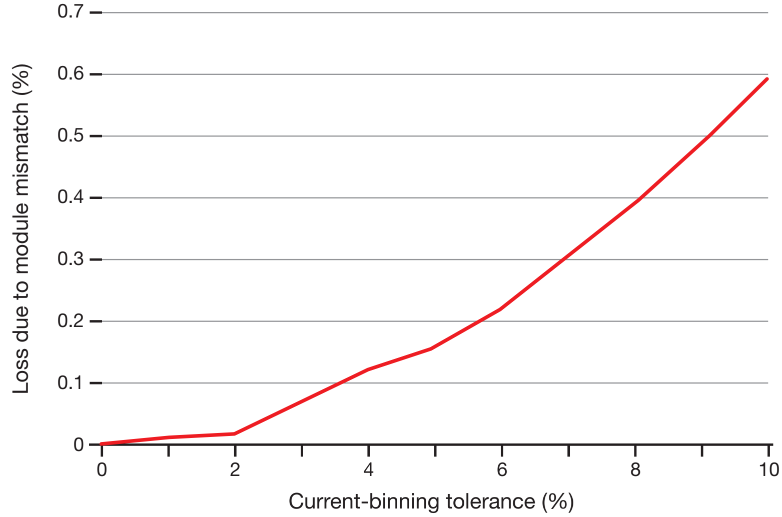
In addition, some manufacturers charge a higher price for modules grouped with narrower binning tolerances. For example, Trina Solar (trinasolar.com) offers current-binned modules that it has binned to a range of 2% for a premium of $0.01 to $0.02 per watt. Some developers and EPCs rebin their modules on the project site to improve array performance. Most installers expect that rebinning modules—for example, from a 5% to a 1% range—will improve system energy yield 1%–2%. However, the magnitude of these benefits should be confirmed prior to paying a premium for smaller binning tolerances or rebinning modules on-site.

Calculating the Benefit of Smaller Binning Tolerances

As manufacturers group modules more closely based on their output characteristics, the losses due to mismatch of these characteristics decrease—but how much? To quantify the energy gains, we used HelioScope, a PV design and performance modeling software tool from Folsom Labs (folsomlabs.com). HelioScope simulates the behavior of each component in the system, including every module, conductor and inverter. The software fully models the system and is capable of predicting the losses associated with module mismatch. Understanding the magnitude of such losses allows project developers to assess whether tight binning or rebinning results in increased energy yields.

Impacts of tighter module binning tolerances. To model the impact of tighter module binning, we use a typical small commercial system consisting of 72-cell polycrystalline modules configured in groups of 12 modules per PV source circuit, with weather conditions defined by the Sacramento, California, TMY3 file. The baseline scenario assumes modules with a current-binning tolerance of 5%, compared to 1% for the enhanced system. The results show that the tighter tolerance has a small impact on overall energy production: about a 0.15% increase in system energy yield. In fact, as shown in Figure 2, even if the modules were current-binned at a 10% tolerance, this would result in mismatch losses just under 0.6%, compared to 0.16% for a 5% tolerance and 0.01% when binned at 1%.

Figure 2 The modeled production results of a 600 V polycrystalline rooftop array in Sacramento, CA, show the relationship between current-binning tolerance and the losses due to module mismatch. A 5% current-binning tolerance—a typical distribution—results in losses below 0.2% due to module mismatch.



Low effect. When rebinning polycrystalline modules from 5% to 1% current tolerance, the resulting 0.15% improvement in energy yield is much less than the 1%–2% that most installers and engineers expect. This illustrates a common misperception about module mismatch. While modules connected in series within a PV source circuit should operate at near-equal current levels, the differences in current do not translate to a 1-to-1 power loss. Figure 3 shows the nonlinear relationship between current and power at the peak power point.

When we plot a module's current versus power, the region around the module's MPP is relatively flat. As a result, within a PV source circuit, as the underproducing modules reduce a high-output module's current, that module's voltage increases. Voltages increase in modules with high-operating currents as modules with lower-operating currents effectively decrease their current output. Due to this voltage compensation, small disruptions in a module's operating current have an even smaller effect on its power output. Farther away from their operating point, modules begin to have

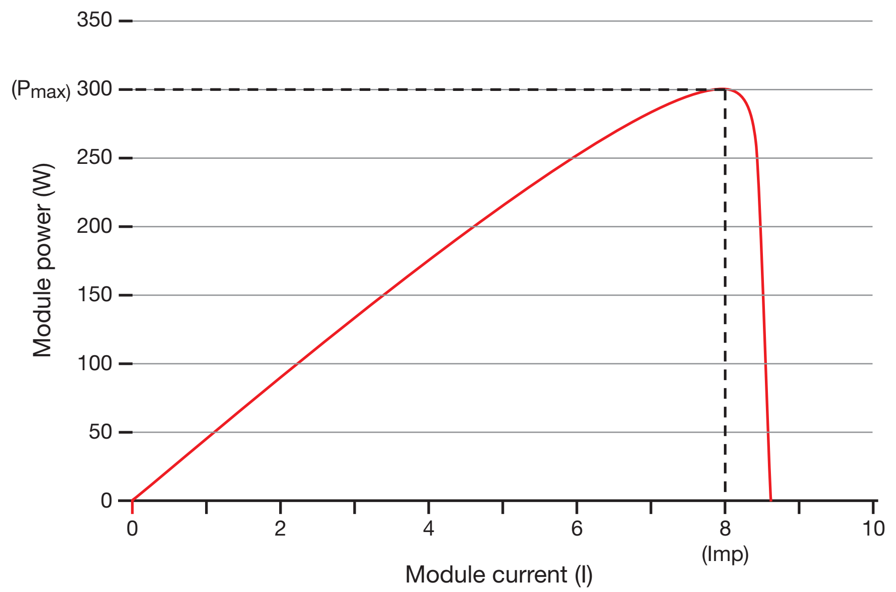


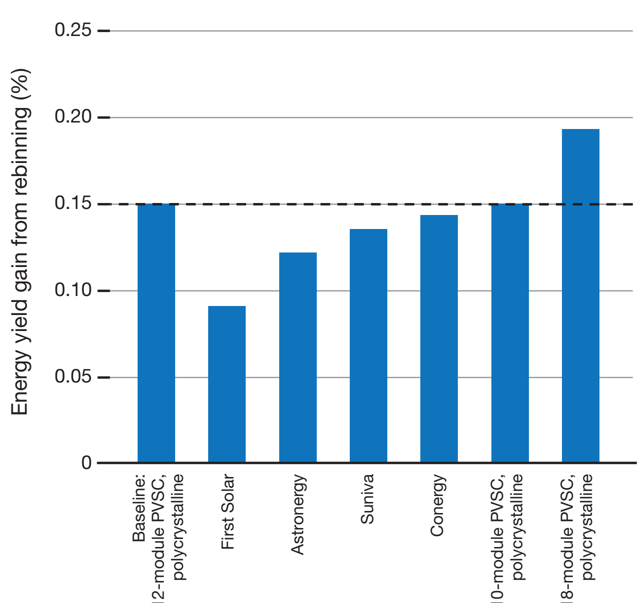
Figure 3 This current versus power curve was derived from a standard c-Si module IV curve. Note that the curve is relatively flat near the peak power point, so small deviations in a module's operating current have very little effect on the module's power.

greater mismatch loss, as seen in Figure 3 (note that the slope increases with larger ranges).

Sensitivity analysis. Figure 4 shows the energy gains due to rebinning from a 5% to a 1% tolerance for various system designs and components. In each scenario, the impact from module binning on energy production is small. There are two scenarios worth noting. A PV source circuit with 18 polycrystalline modules connected in series—such as in a 1,000 Vdc array configuration—incurs a 0.19% increase in energy yield from rebinning. Alternatively, we see that First Solar's CdTe modules benefit the least from rebinning from a 5% to 1% tolerance—only about 0.09%.

The more modules per PV source circuit, the more likely the circuit is to experience losses due to module mismatch: The modules in series must have identical current, and more modules means more data points. The lower fill factor of CdTe modules makes them more tolerant to mismatch, since the module's power does not change as much based on changes in current near its maximum current point. For both CdTe and crystalline-based modules, the current-power curve is flat near a module's MPP, and it is even flatter for a CdTe module.

Figure 4 Comparing the energy gains for various scenarios shows the minimal impact that rebinning from a 5% to a 1% current tolerance has for many common system designs and technologies used in the industry today.



Financial Implications of Binning

The bottom line is that tighter module binning can lead to a slight improvement in a system's energy production, but not as much as expected. Although module type and the number of modules per PV source circuit have noticeable effects on the amount of energy gained by rebinning from 5% to 1%, our analysis indicates an increase in energy production of only 0.09%–0.19%. Understanding the energy impacts from binning enables developers to assess how much they should be willing to pay for a tighter module binning tolerance.

A common industry guideline is that a 1% improvement in system energy yield is equivalent to an up-front net present value of $0.03–0.04/Wp. If we apply this to the modeled 0.15% energy increase from rebinning, the up-front net present value would be $0.006/Wp. While this is slightly lower than the $0.01–$0.02/Wp that Trina Solar charges for current-binned modules, it is close. For a 1 MW array with 4,000 modules, this 0.15% of energy yield would be worth $4,500–$6,000 per year. At $40 per labor hour, this total provides a maximum budget for 100 to 150 hours of labor. It seems unlikely that an on-site installation team could test and sort 4,000 modules in that time.

Ultimately, the benefit of rebinning modules depends on kilowatt-hour value for PV generation and the labor cost to test and sort modules. As the prices for PV systems decrease, the benefits of tighter tolerances become harder to justify economically.

Informing Module Choices

Understanding the minimal impact that module mismatch has on energy losses is also valuable when selecting a module. For example, is a module with a 0% to +1% power tolerance preferable to one with 0% to +5%?

When module power tolerances are positive, the average module power is higher than the datasheet rating. While both examples above have the same lower end of the range, the +5% modules have a midpoint of +2.5%, compared to +0.5% for the alternative module—resulting in a 2% net difference. Given that systems with modules with a current-binning tolerance of 5% produce 0.15% less energy due to module mismatch than a system with 1% current-binned modules, we expect the modules with the 0% to +5% power tolerance to outproduce those with a 0% to +1% power tolerance by 1.85% (2.0% – 0.15% = 1.85%).

Conclusion

As the industry matures, PV developers are looking for ways to improve their ROI by reducing costs and increasing production. However, in the case of rebinning modules, it is very unlikely that the improvement in energy production justifies the labor cost, particularly if the testing and sorting is done in the field. Binning practices are just the first of many PV design strategies that must be put to a more comprehensive cost-benefit scrutiny.

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