

## Application Note 0901

### LIV Curve Analysis: Current Binning

August 4, 2007

#### Introduction

The analysis below is intended to give an overview to the binning strategy employed with multijunction solar cells. Representative current-voltage characteristics under illumination (light I-V curves, or LIV curves) have been used to illustrate the issues involved in determining a proper load point for measuring cells. A load point must be selected so as to provide the best practical indication of how the cells will perform when connected together in series and in parallel.

For high-throughput measurement of solar cells, it is convenient to define a load voltage ( $V_L$ ) at which all cells are measured. A fixed load voltage provides the highest fidelity of measurement by avoiding the data analysis necessary for calculation of individual maximum power points. The load voltage should be selected so as to be slightly lower than the typical maximum power point voltage. This minimizes the incidence of measurements taken beyond the maximum power point. Measurements taken at a voltage higher than the maximum power point voltage fall on the steep “knee” of the exponential LIV characteristic. Such measurements are difficult to reproduce due to the steep slope of the curve; small variations in voltage produce large variations in current. As a result, such measurements are poor predictors of the performance of cells connected in series strings.

Two load points are compared: a now-obsolete 2.75 V load point and the current 2.68 V load point. The 2.75 V load point proved to lie beyond the maximum power point of most cells and therefore underestimated current output near the maximum power point. Series strings of cells binned using the 2.75 V load voltage would produce less power than strings binned using the current 2.68 V load voltage. This will be explained below. The current bins used for each of the respective load voltages are as follows:

$V_L=2.75V$	
Bin	Current (A)
1	6.100-6.299
2	6.300-6.489
3	6.490-6.684
4	6.685-6.879
5	6.880-7.074

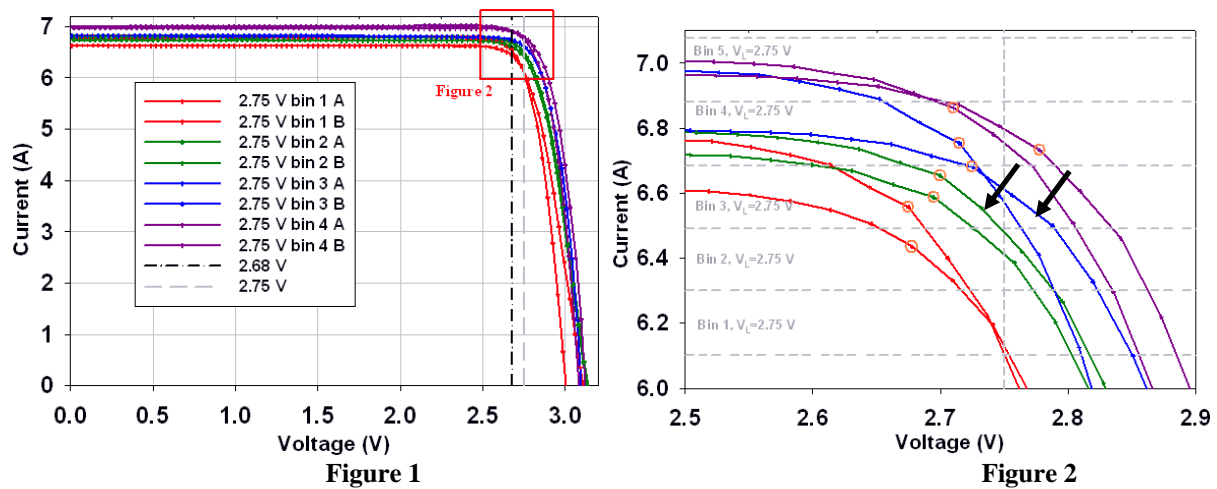
$V_L=2.68 V$	
Bin	Current (A)
1	6.26-6.46
2	6.46-6.66
3	6.66-6.86
4	6.86-7.06
5	7.06-7.26

#### Analysis: Load Voltage=2.75 V

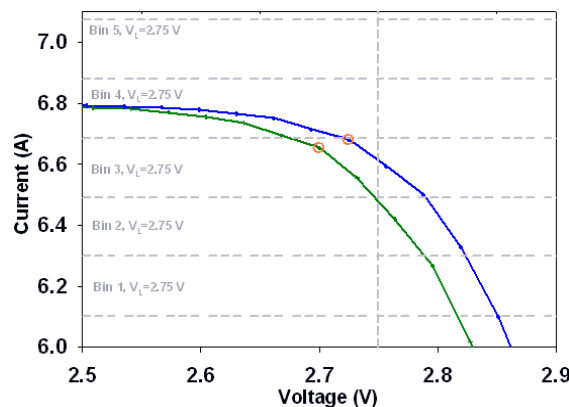
For the purposes of illustration, several typical LIV curves for CDO-100 cells have been selected (Figure 1). Two curves from each of bins 1-4 using the 2.75 V load voltage have been used. A detail showing the knee of the LIV curves is shown in Figure 2. Also shown are the bin thresholds for  $V_L=2.75 V$  and the maximum power points of each cell (orange circles). Since the

load voltage is higher than the maximum power point voltage on seven out of eight of the cells, the load point tends to fall on the steep part of the cells' exponential curves. The current measured at the load point is therefore significantly lower than that at the maximum power point.

This has ramifications at both the cell and CPV system level. At the cell level, cells will be binned lower. Some portion of cells will fall below the minimum bin level and will be rejected. This would reduce yield and drive up the cost per cell. More importantly, on a system level, when cells from a single bin are connected in series, cells binned by a load voltage higher than their maximum power point will be grouped with other cells that can produce only a lower current. As a result, these cells will be forced to operate at a current well below their potential current at maximum power. In high volumes, this will substantially reduce the aggregate power produced.



This is exemplified by the two LIV curves indicated by arrows. These curves are shown separately in Figure 3. The two curves happen to have maximum power points that are almost perfectly current matched (6.65 A and 6.68 A, respectively). Accordingly, these cells, if connected in series, would be able to operate at a *string* maximum power point that would be almost identical to the sum of the two individual *cell* maximum power points. This would produce a near-optimum series string connection. However, since the maximum power voltage for both is less than 2.75 V, using this load voltage causes these cells to be sampled at the steeper region of their LIV curves, causing a wide separation in their current levels. As a result, they end up in different bins.



**Figure 3. Two LIV curves with current-matched maximum power points.**

To get a sense of how the  $V_L=2.75$  V binning strategy translates to power on an assembled panel, hypothetical, two-cell strings may be constructed. For clarity, two-cell strings were used; the method, however, is applicable for series strings of arbitrary length. Cells from bins 2-4 were selected (bin 1 was neglected for reasons explained below). The operating point is chosen using a horizontal line (to represent the condition of current matching) at a level near the midpoint of the two maximum power points (Figure 4). This is likely to be representative of the maximum power obtained, for example, by a maximum power tracker applied to the two-cell string. Results are shown in Table 1. The “residual power” is the power available from cells not used; in this case, the cells from bin 1.

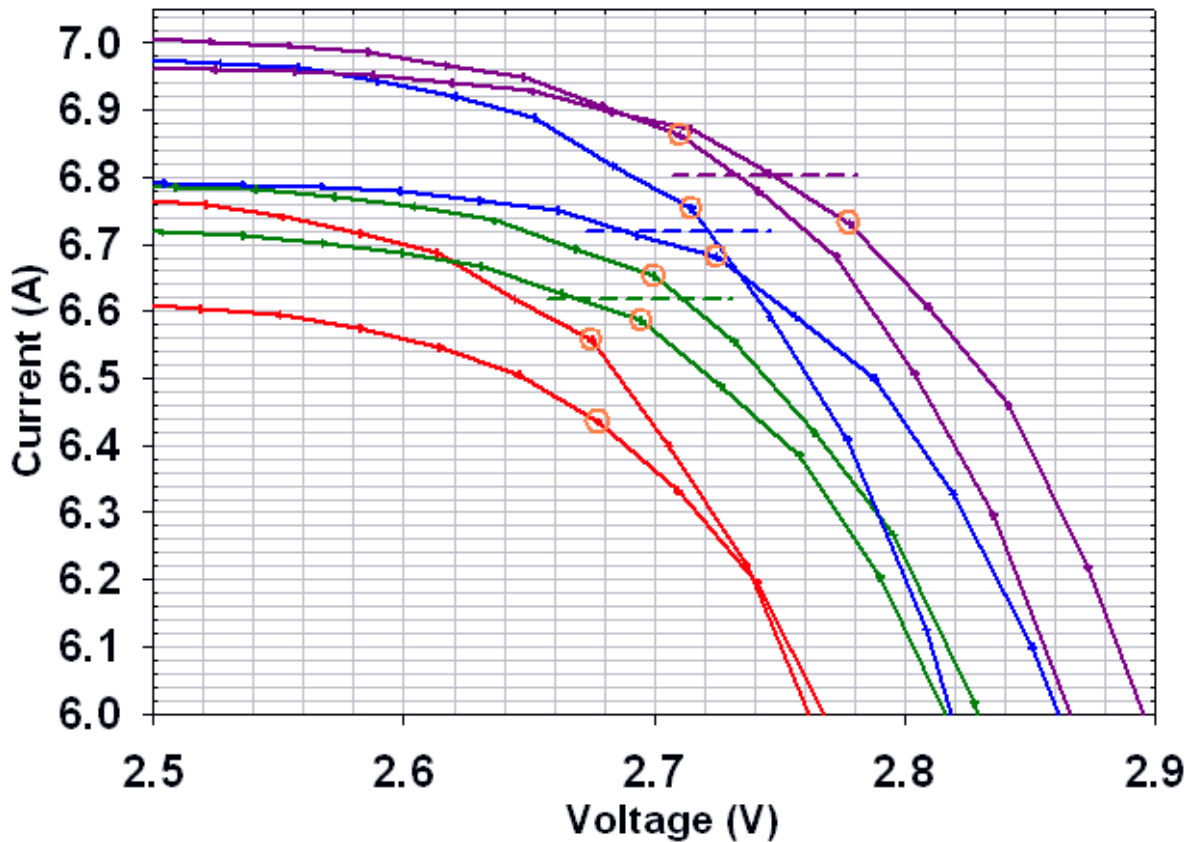


Figure 4. Method for estimating the power output of two-cell strings from bins 2, 3, and 4 using  $V_L=2.75$  V.

Table 1

$V_L=2.75$ V				
	Current (A)	Cell 1 Voltage (V)	Cell 2 Voltage (V)	Output Power (W)
Bin 2	6.62	2.67	2.71	35.6
Bin 3	6.72	2.69	2.72	36.4
Bin 4	6.80	2.73	2.75	37.3
<b>Mean Power Per String:</b>				<b>36.4</b>
<b>Residual Cell Power:</b>				<b>34.8</b>

**Analysis: 2.68 V Load Voltage**

The effect of the current binning strategy using 2.68 V as the load point is shown in Figure 5. In this case, the load voltage is either lower than, or very close to, the maximum power voltage. This allows the load current to be sampled on a flatter part of the exponential curve, resulting in a load current that is more representative of the current obtained at maximum power. Cells are therefore more likely to be binned into groups that will deliver higher overall power when connected in series. This binning strategy results in only one cell in bin 1 and three cells in bin 3. To compare with the  $V_L=2.75$  V case, the hypothetical output power of pairs of series-connected cells from each of bins 2-4 were again calculated (Figure 6). Bin 1 was not used as there was only one cell in the bin. For bin 3, with three cells, the two lower-power cells were used. The resulting power output is shown in Table 2. Due to the new binning strategy, it was possible to produce three strings with a mean power comparable to that of the  $V_L=2.75$  V case (power is 0.6% (0.2 W) lower). Since pairing of cells is closer to optimum, the *residual* power available left over for other strings is now 2.5% (0.8 W) higher; there is a net increase in available power of 1.9%. This reflects the fact that the load voltage is sampling cell currents closer to those at the cells' maximum power points. In high volumes, the  $V_L=2.68$  V case will result in significantly higher system power.

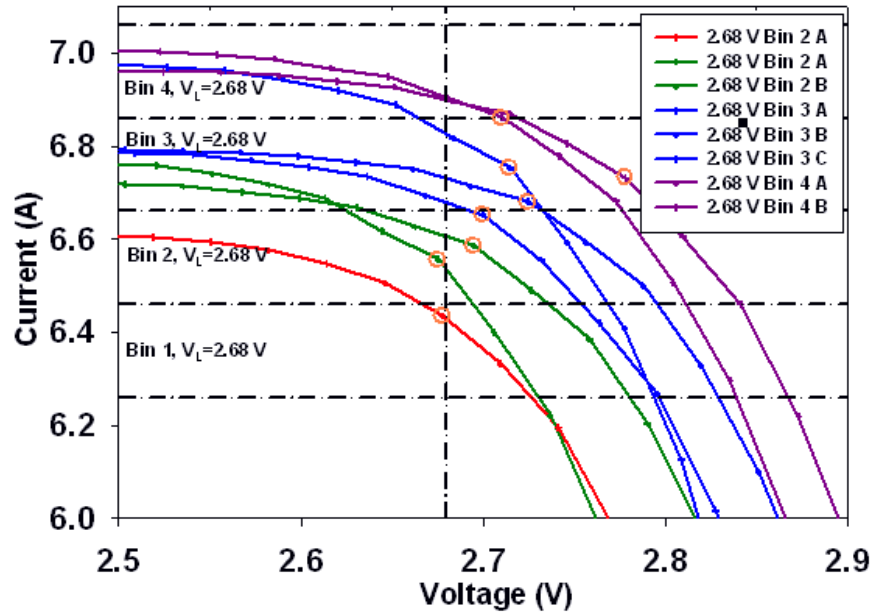


Figure 5. Binning using a load voltage of 2.68 V. The LIV curves have been re-colored to indicate their new bins.

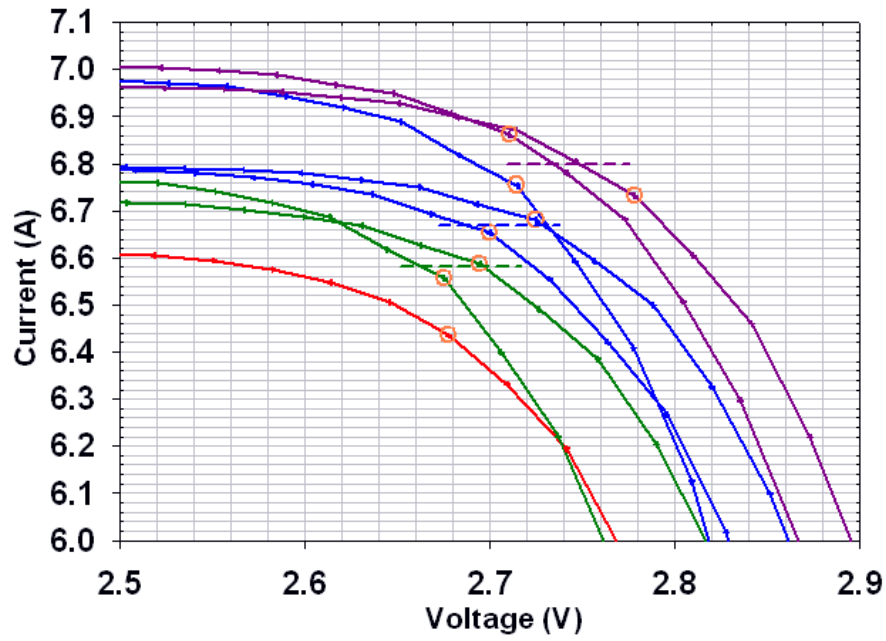


Figure 6.

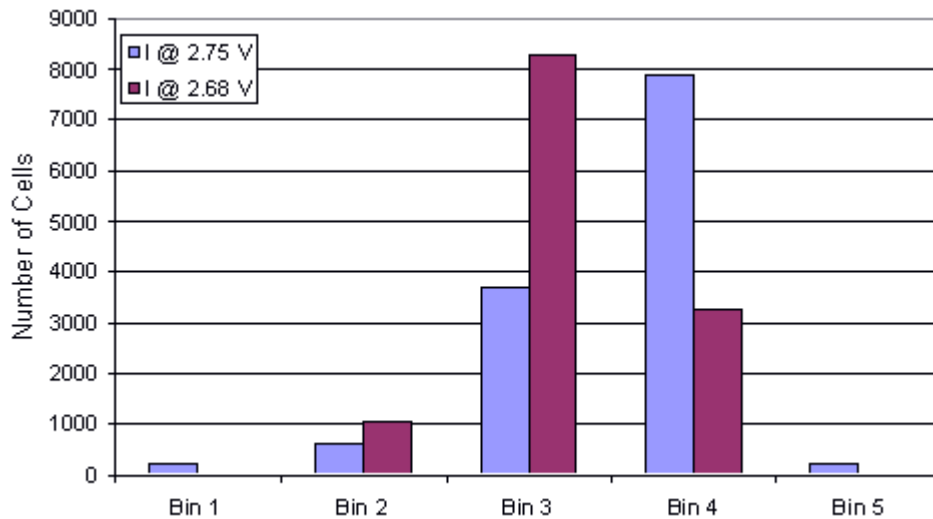
Table 2

V <sub>L</sub> =2.68V				
	Current (A)	Cell 1 Voltage (V)	Cell 2 Voltage (V)	Output Power (W)
Bin 2	6.58	2.66	2.70	35.3
Bin 3	6.66	2.69	2.73	36.1
Bin 4	6.80	2.73	2.75	37.3
Mean Power Per String:				36.2
Residual Cell Power:				35.6

### Appendix

The plots below provide a comparison of the obsolete ( $V_L=2.75$  V) and current ( $V_L=2.68$  V) binning strategies. The new bins allow for a tighter distribution and better correlation within each bin with respect to the maximum power point.

#### 1. Current at load ( $I_L$ ):



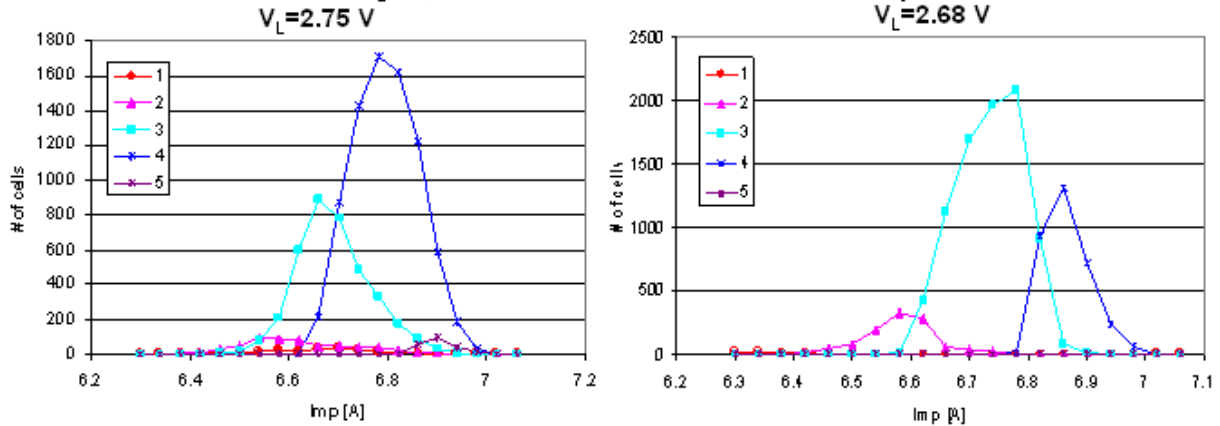
#### 2. Cell quantities in each bin:

- This table shows how cells from 2.75 V bins would be distributed into 2.68 V bins
  - Cells from low bins tend to move to higher bins, sometimes much higher.
  - Cells from high bins tend to stay put or move down slightly

	Bin 1 @ 2.68 V	Bin 2 @ 2.68 V	Bin 3 @ 2.68 V	Bin 4 @ 2.68 V
Bin 1 @ 2.75 V	13%	68%	18%	0%
Bin 2 @ 2.75 V	2%	66%	32%	0%
Bin 3 @ 2.75 V		13%	84%	2%
Bin 4 @ 2.75 V			62%	38%
Bin 5 @ 2.75 V				100%

### 3. Current at maximum power ( $I_{mp}$ ):

- Using  $V_L = 2.68$  V tightens the current distribution within lower and upper bins (e.g., bins 2 and 4 shown below)
  - This implies more optimal matching of cell power when binned cells are connected in series
  - Width of bin 3 is unchanged, but it contains more than 2x as many cells



### Voltage at maximum power ( $V_{mp}$ ):

- Shape of  $V_{mp}$  distribution within a bin becomes more similar among the different bins (i.e., the  $V_{mp}$  distribution for bin 2 becomes more like the  $V_{mp}$  distribution for bin 4)
  - This reduces power losses when placing cells from upper bins and lower bins in parallel

