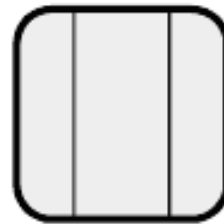


EE 446/646
Photovoltaic Devices III

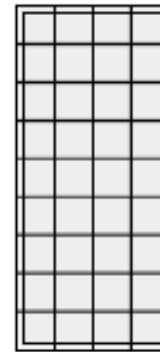
Y. Baghzouz

Cell to module to array

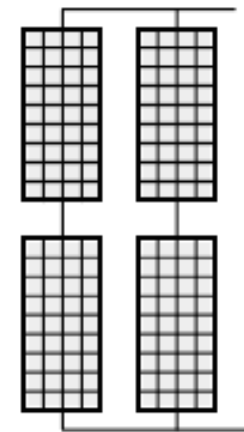
- A single cell produces only a voltage of 0.5-0.6 V and few watts of power – little use.
- To produce a larger voltage, a number of pre-wired cells in series, all encased in tough, weather-resistant package, to form a module.
- A typical module may have 36, 54, 72, or 96 cells in series.
- Multiple modules can be wired in series to increase voltage and in parallel to increase current. Such combinations of modules are referred to as an array.



Cell



Module



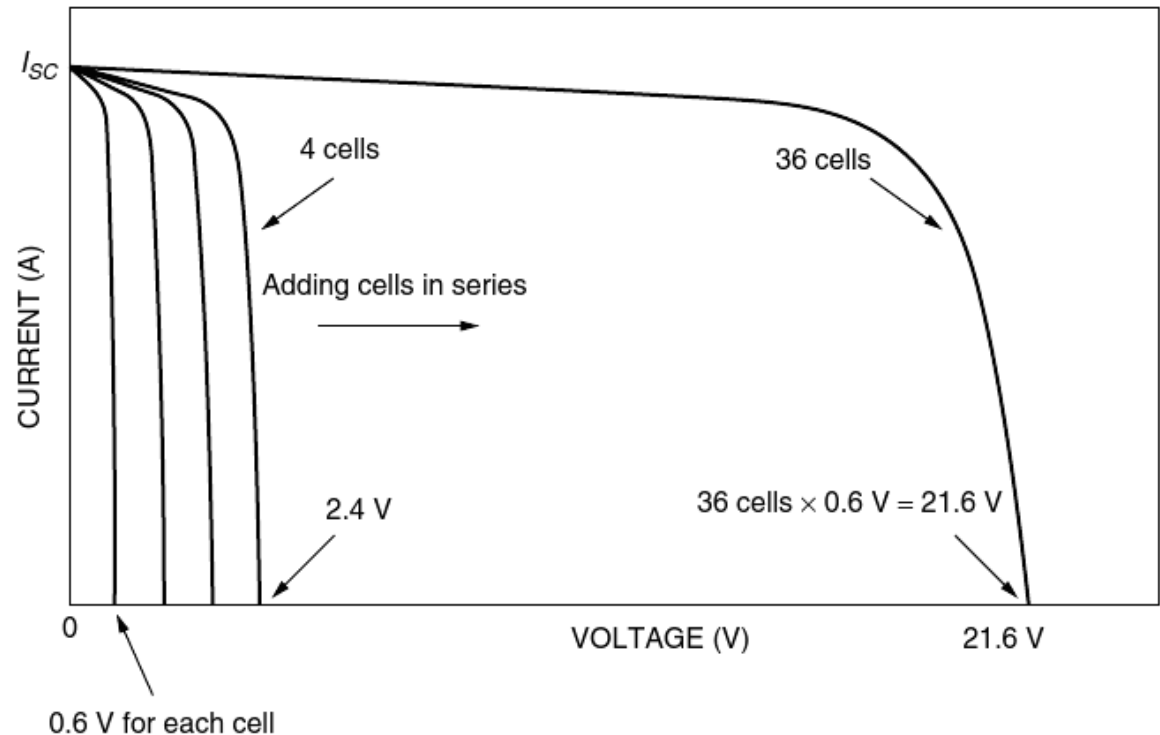
Array

Cells connected in series

- When photovoltaics are wired in series, they all carry the same current, and their voltages add. The overall module voltage V_{module} is found by.

$$V_{\text{module}} = n(V_d - IR_S)$$

where n is the number of cells in series.



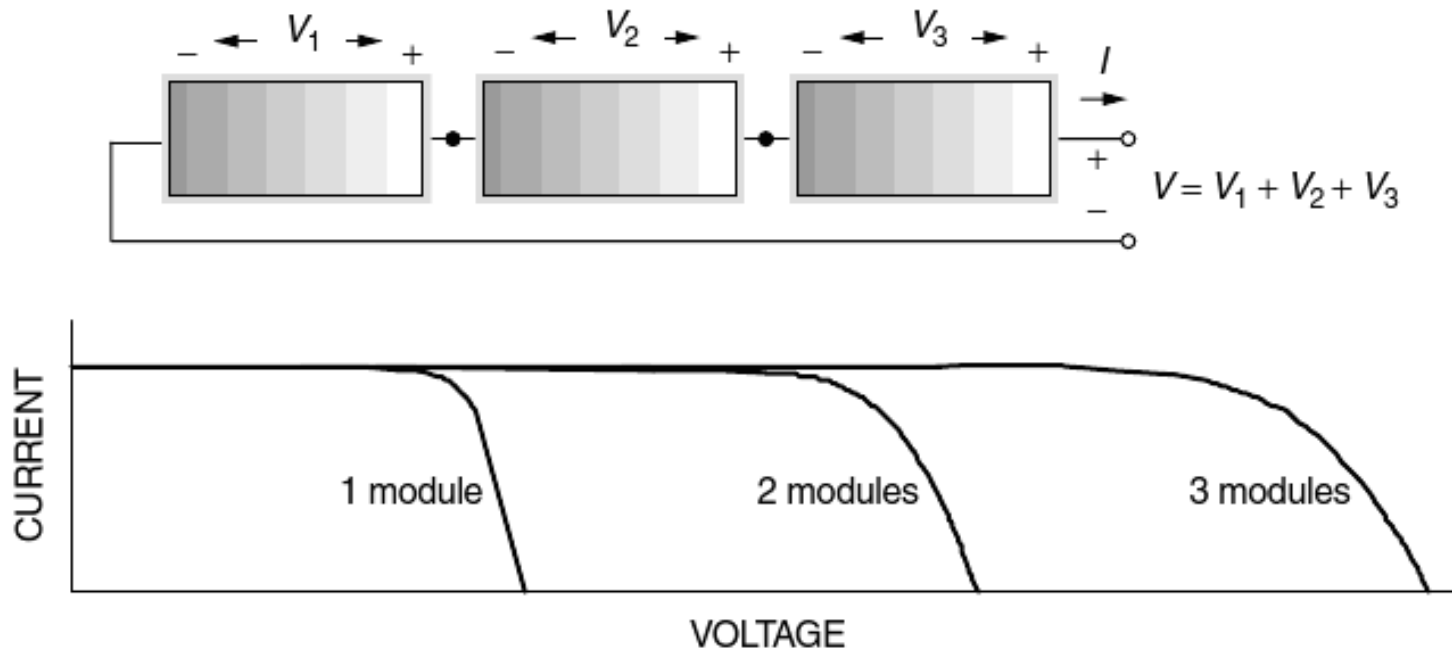
Example

- A PV module is made up of 36 identical cells, all wired in series. With 1-sun insolation (1 kW/m^2), each cell has short-circuit current $I_{SC} = 3.4 \text{ A}$ and at 25° C its reverse saturation current is $I_0 = 6 \times 10^{-10} \text{ A}$. Parallel resistance $R_p = 6.6 \ \Omega$ and series resistance $R_s = 0.005 \ \Omega$.
 - Find the voltage, current, and power delivered when the junction voltage of each cell is $V_d = 0.50 \text{ V}$.
 - Set up a spreadsheet for I and V and present a few lines of output to show how it works.
- Ans. $I = 3.16 \text{ A}$, $V_{\text{module}} = 17.43 \text{ V}$, $P = 55 \text{ W}$

V_d	$I = I_{SC} - I_0 (e^{38.9V_d} - 1) - \frac{V_d}{R_p}$	$V_{\text{module}} = n(V_d - IR_s)$	$P \text{ (watts)} = V_{\text{module}}I$
0.49	3.21	17.06	54.80
0.50	3.16	17.43	55.02
0.51	3.07	17.81	54.75
0.52	2.96	18.19	53.76
0.53	2.78	18.58	51.65
0.54	2.52	18.99	47.89
0.55	2.14	19.41	41.59

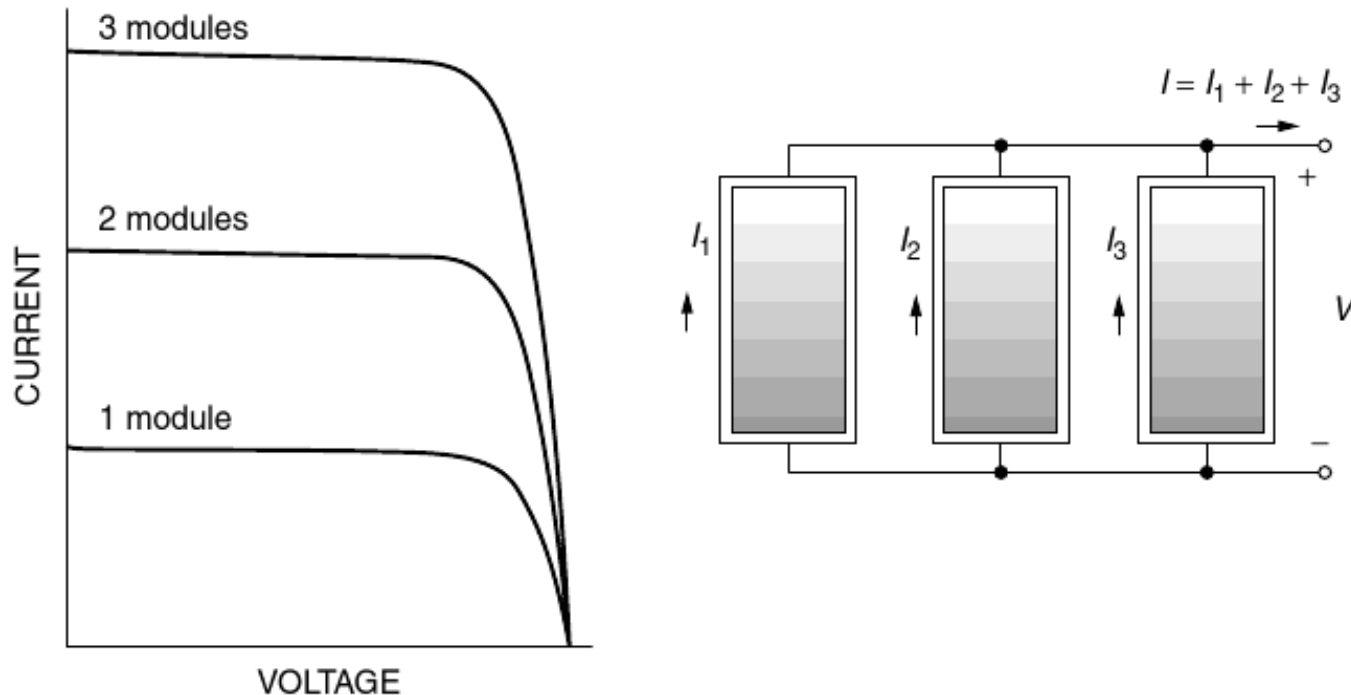
Series connected modules

- For modules in series, the I –V curves are simply added along the voltage axis. That is, at any given current (which flows through each of the modules), the total voltage is just the sum of the individual module voltages.
- The figure below shows the I –V curve for 3 modules in series.



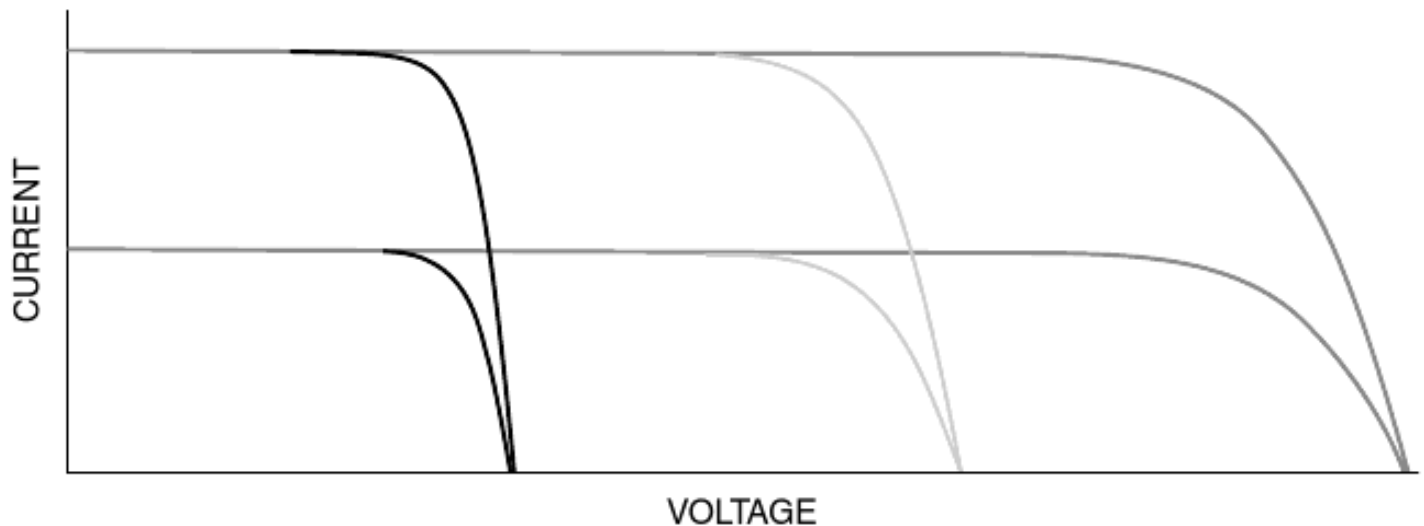
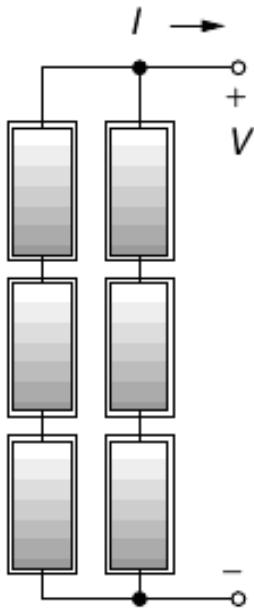
Parallel connected modules

- For modules in parallel, the same voltage is across each module and the total current is the sum of the currents. That is, at any given voltage, the I –V curve of the parallel combination is just the sum of the individual module currents at that voltage.
- The figure below shows the I –V curve for 3 modules in parallel.



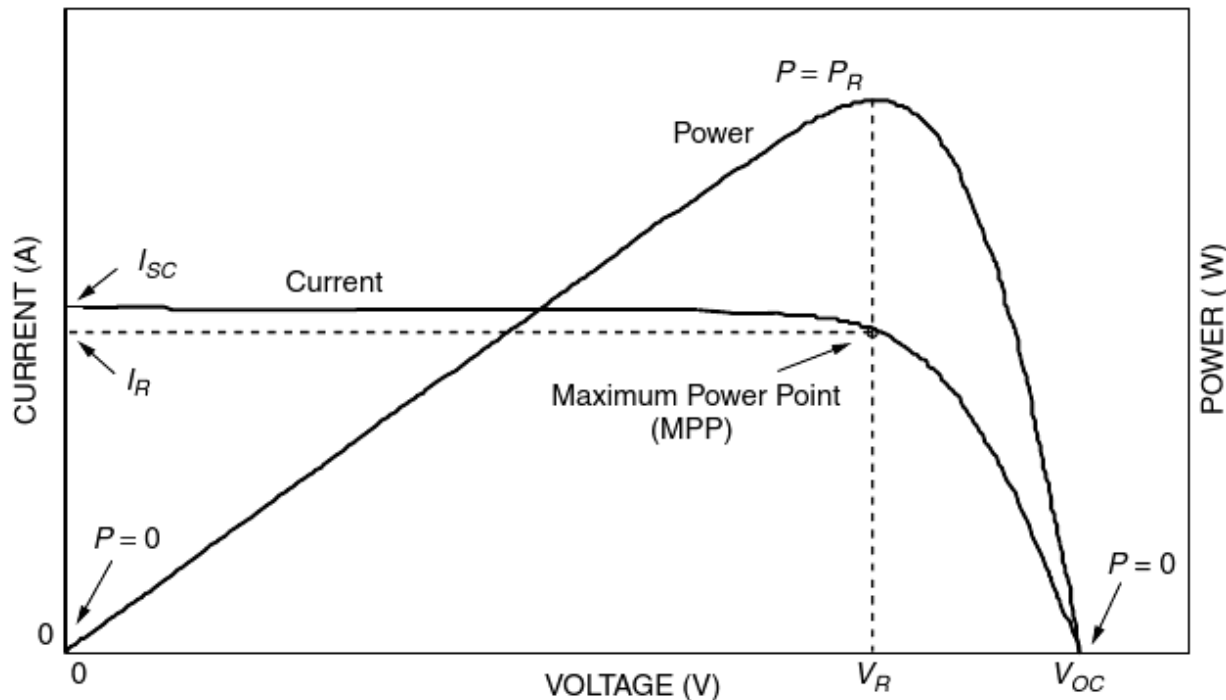
Series-parallel connected modules

- In high power applications, the array usually consists of a combination of series and parallel modules for which the total $I-V$ curve is the sum of the individual module $I-V$ curves.
- The figure below show 2 parallel strings, each of which containing 3 modules.



I-V and P-V Curves

- The figure below shows a generic I –V curve for a PV module, and the product of voltage and current, i.e., power curve of the module.
 - At the two ends of the I –V curve, the output power is zero.
 - The maximum power point (MPP) is the spot near the knee of the I –V curve at which the product of current and voltage reaches its maximum.
 - The voltage, current and power at the MPP are often assigned subscripts (e.g., R, m, mp, max....)

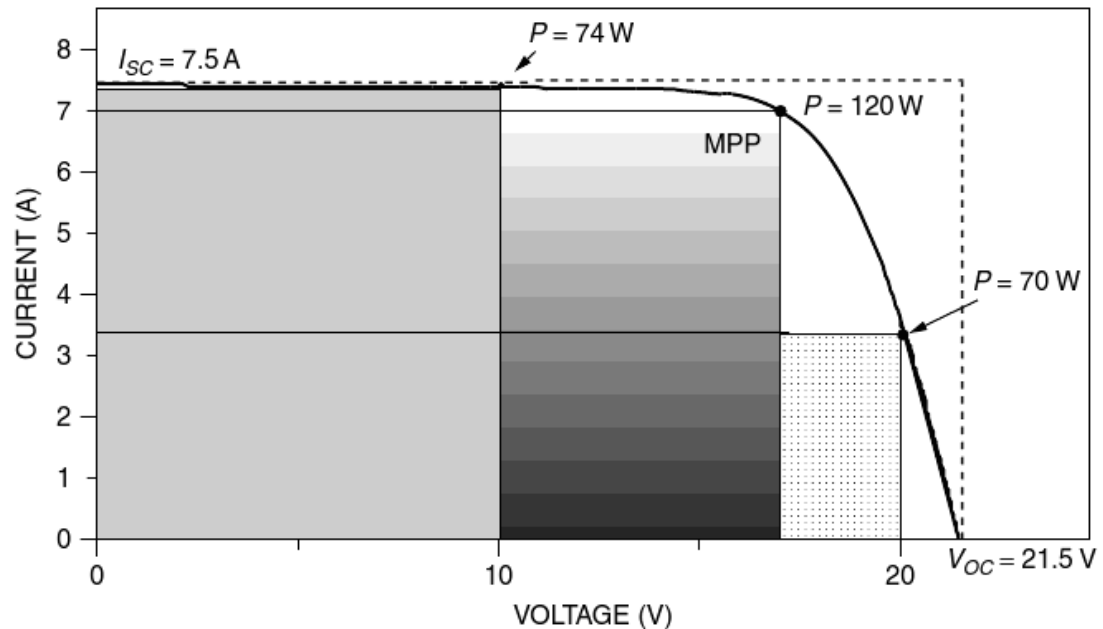


Fill Factor (FF)

- Another quantity that is often used to characterize module performance is the fill factor (FF).
 - The fill factor is the ratio of the power at the maximum power point to the product of V_{OC} and I_{SC} , so FF can be visualized as the ratio of two rectangular areas, as shown below.

$$\text{Fill factor (FF)} = \frac{\text{Power at the maximum power point}}{V_{OC} I_{SC}} = \frac{V_R I_R}{V_{OC} I_{SC}}$$

FF = 70–80%
for crystalline
silicon cells.



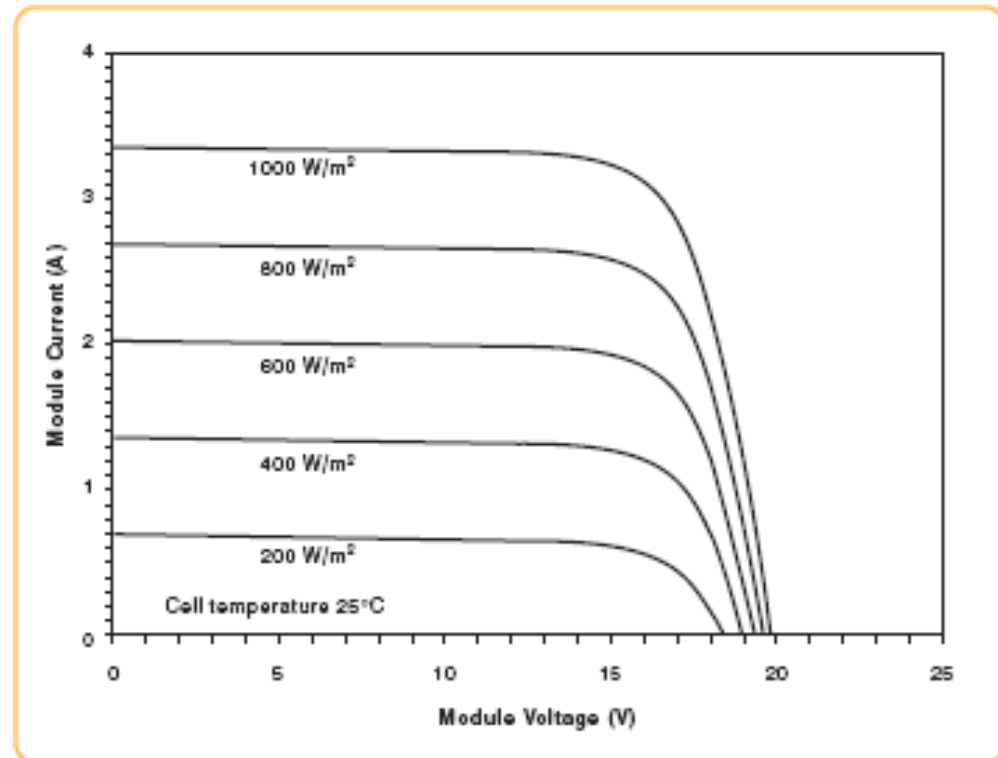
Standard Test Condition (STC)

- Standard test conditions (STC) for PV have been established to enable fair comparisons of one module to another. These test conditions include a solar irradiance of 1 kW/m^2 with spectral distribution shown earlier, corresponding to an air mass ratio of 1.5, and the cell temperature is 25° C .

Standard Test Conditions (STC)					
<i>STC = 1000 W/M² irradiance, 25° C module temperature, AM 1.5 spectrum*</i>					
	KD230GX-LPB	KD235GX-LPB	KD240GX-LPB	KD245GX-LPB	
P_{mp}	230	235	240	245	W
V_{mp}	29.8	29.8	29.8	29.8	V
I_{mp}	7.72	7.89	8.06	8.23	A
V_{oc}	36.9	36.9	36.9	36.9	V
I_{sc}	8.36	8.55	8.59	8.91	A
$P_{tolerance}$	+5/-3	+5/-3	+5/-3	+5/-3	%

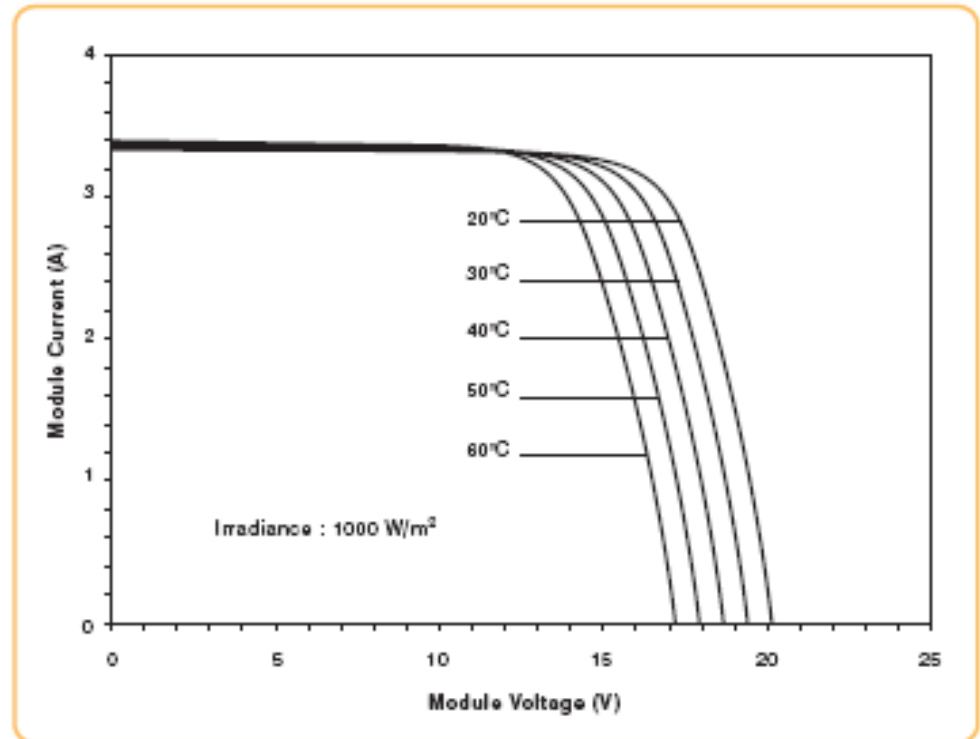
Impact of irradiance

- Manufacturers often provide I –V curves that show how the curves shift as insolation and cell temperature changes.
 - Notice as insolation drops, short-circuit current drops in direct proportion.
 - Decreasing insolation also reduces the open circuit voltage , but it does so following a logarithmic relationship that results in relatively modest changes.



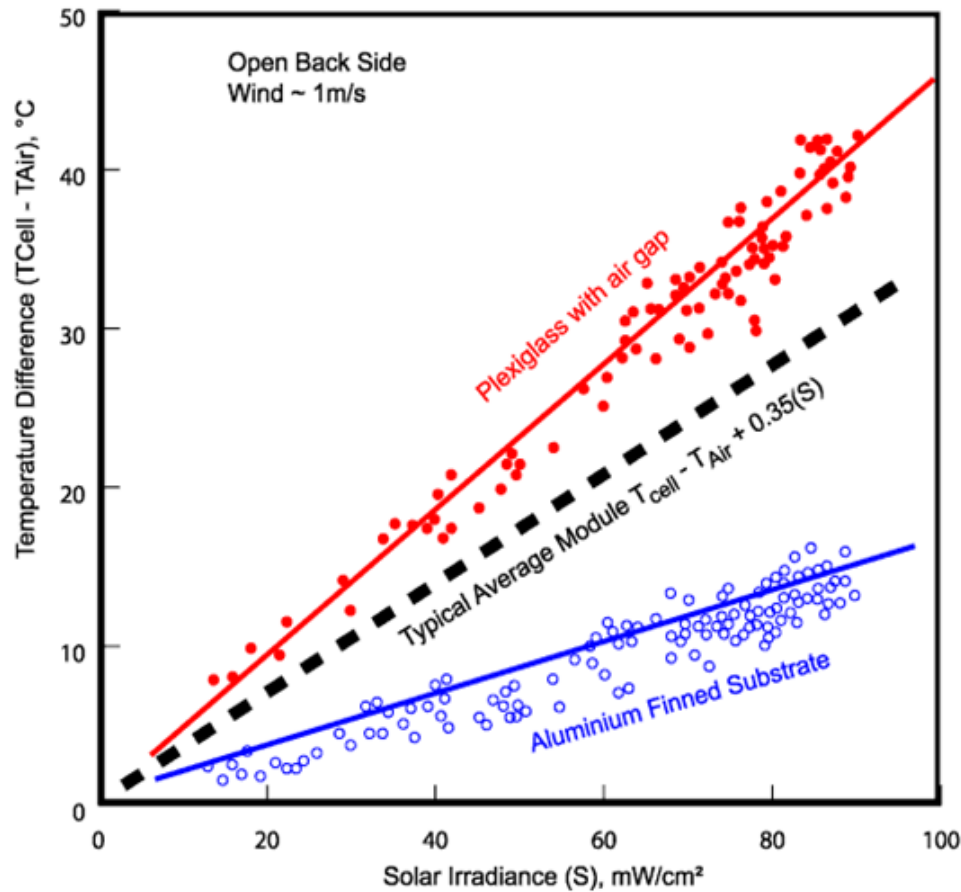
Impact of temperature

- As the cell temperature increases, the open-circuit voltage decreases substantially while the short-circuit current increases only slightly → Photovoltaics perform better on cold than hot days.
 - For crystalline silicon cells, V_{OC} drops by about 0.37% for each degree Celsius increase in temperature, and I_{SC} increases by approximately 0.05%, resulting in a decrease in maximum power available by about 0.5%/ C



Nominal Operating Cell Temperature (NOCT)

- The Nominal Operating Cell Temperature (NOCT) is defined as the temperature reached by open circuited cells in a module under the following conditions: solar irradiance = 800 W/m^2 , air temp. = 20°C , wind speed = 1 m/s , mounting = open back side.



Power rating under NOCT (PVUSA)

- Approximate formula for calculating cell temperature:

$$T_{\text{cell}} = T_{\text{amb}} + \left(\frac{\text{NOCT} - 20^{\circ}}{0.8} \right) \cdot S$$

- PV panels sold in the USA are required to post the panel rating under NOTC.

	KD230GX-LPB	KD235GX-LPB	KD240GX-LPB	KD245GX-LPB	
Nominal Operating Cell Temperature Conditions (NOCT)					
<i>NOCT = 800 W/m² irradiance, 20°C ambient temperature, AM 1.5 spectrum*</i>					
T_{NOCT}	45	45	45	45	°C
P_{max}	165	169	172	176	W
V_{mp}	26.8	26.8	26.7	26.8	V
I_{mp}	6.18	6.31	6.45	6.58	A
V_{oc}	33.7	33.7	33.7	33.7	V
I_{sc}	6.77	6.92	6.95	7.21	A
PTC	208.0	212.6	217.3	219.1	W

Temperature coefficients

- Manufacturers often provide temperature coefficients for maximum power, open circuit voltage and short circuit current.

	KD230GX-LPB	KD235GX-LPB	KD240GX-LPB	KD245GX-LPB	
Temperature Coefficients					
P_{max}	-0.45	-0.46	-0.46	-0.46	%/°C
V_{mp}	-0.51	-0.52	-0.52	-0.52	%/°C
I_{mp}	0.0065	0.0065	0.0064	0.0065	%/°C
V_{oc}	-0.36	-0.36	-0.36	-0.36	%/°C
I_{sc}	0.060	0.060	0.060	0.060	%/°C
Operating Temp	-40 to +90	-40 to +90	-40 to +90	-40 to +90	°C

Examples

- Estimate cell temperature, open-circuit voltage, and maximum power output for the KD230GX-LPB module under conditions of 1-sun insolation and ambient temperature 30°C. The module has a NOCT of 47°C.

Ans. Cell temperature = 64°C, maximum power = 189.6 W, open circuit voltage = 31.7 V.

Estimate the cell temperature and power delivered by a 100-W PV module with the following conditions. Assume 0.5%/°C power loss.

- NOCT = 50°C, ambient temperature of 25°C, insolation of 1-sun.
- NOCT = 45°C, ambient temperature of 0°C, insolation of 500 W/m².
- NOCT = 45°C, ambient temperature of 30°C, insolation of 800 W/m².

Ans.

- T = 62.5°C, P = 81.25 W
- T = 15.6°C, P = 52.35 W
- T = 55°C, P = 68 W

Estimating cell temperature

- When the NOCT is not given, another approach to estimating cell temperature is based on the following:

$$T_{\text{cell}} = T_{\text{amb}} + \gamma \left(\frac{\text{Insolation}}{1 \text{ kW/m}^2} \right)$$

- where γ is a proportionality factor that depends somewhat on wind speed and how well ventilated the modules are when installed.
- Typical values of γ range between 25°C and 35°C; that is, in 1 sun of insolation, cells tend to be 25 – 35 degrees hotter than their environment.

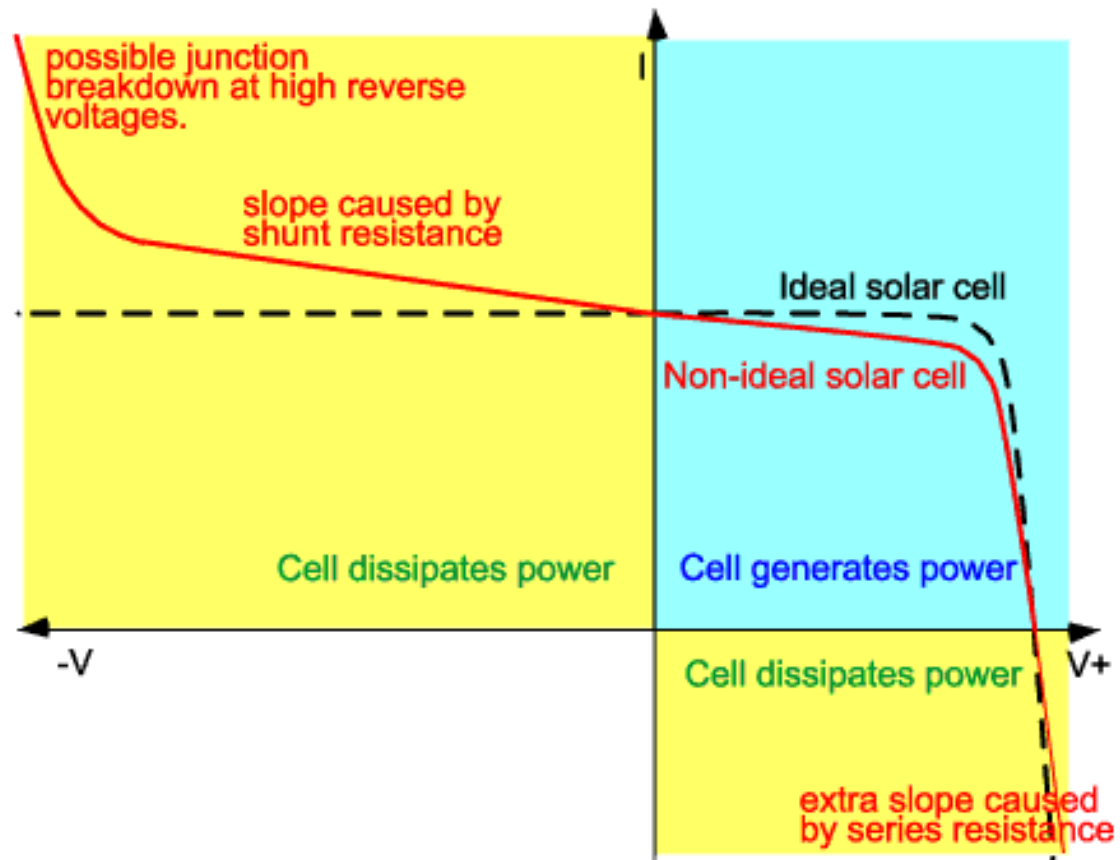
Shading impacts

- The output of a PV module can be reduced dramatically when even when a small portion of it is shaded.
 - For example, when one solar cell is shaded while the remainder in the module are not, some of the power being generated by the “sunny” solar cells can be dissipated by the “shaded” cell rather than powering the load.
 - This in turn can lead to highly localized power dissipation and the resultant local heat may cause irreversible damage to the module.

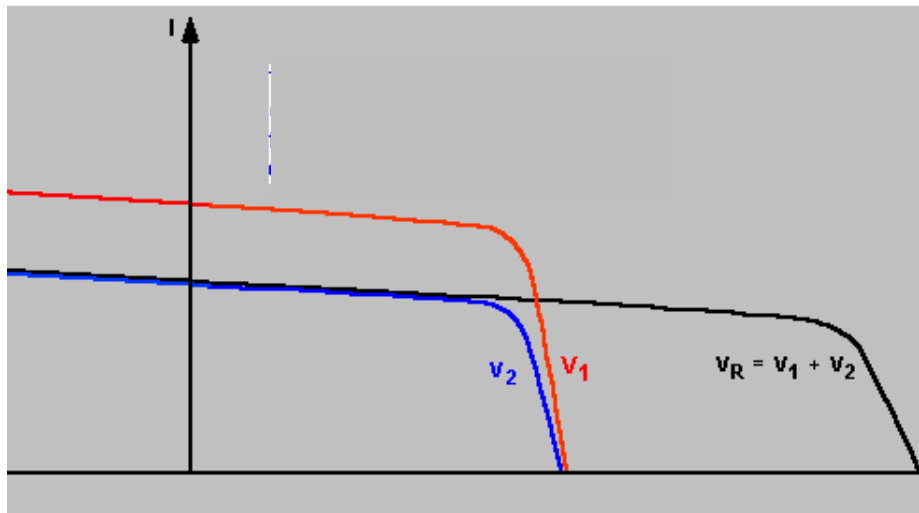
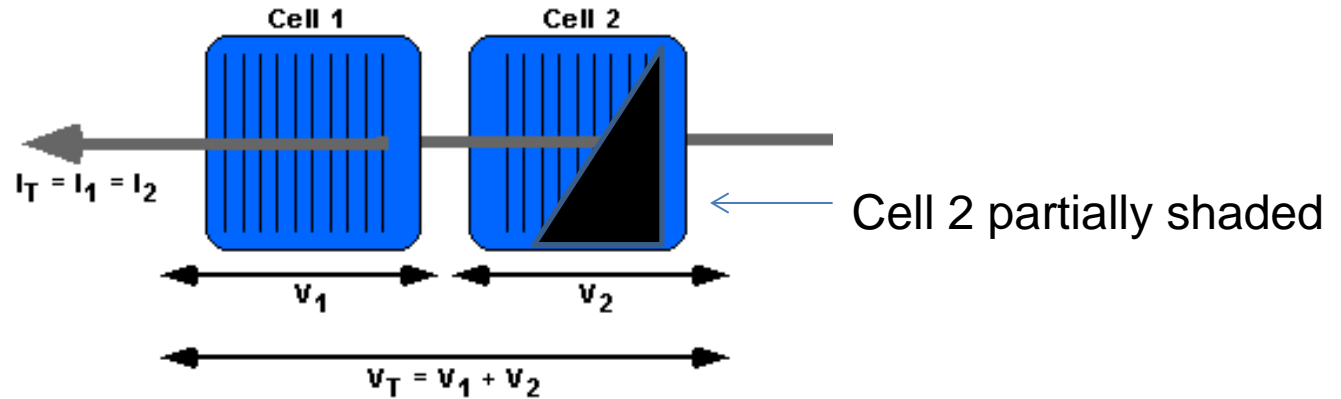


Extended I-V curve of a solar cell

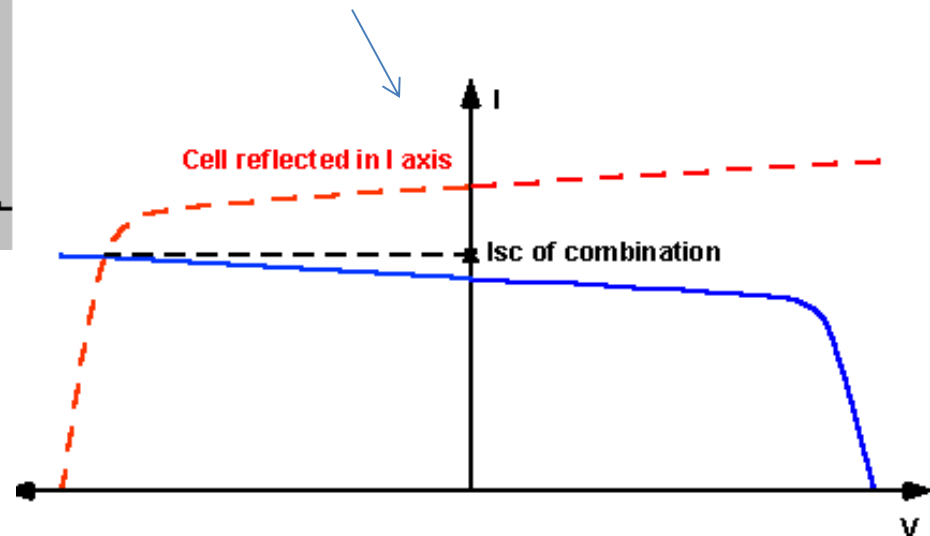
- A reverse voltage (applied by other cells) will cause the cell to consume power. A significant reverse voltage will result in irreparable damage.
- If forward voltage that is greater than the cell open-circuit voltage is applied (by an external source), current starts to flow into the cell. The cell begins to consume power.



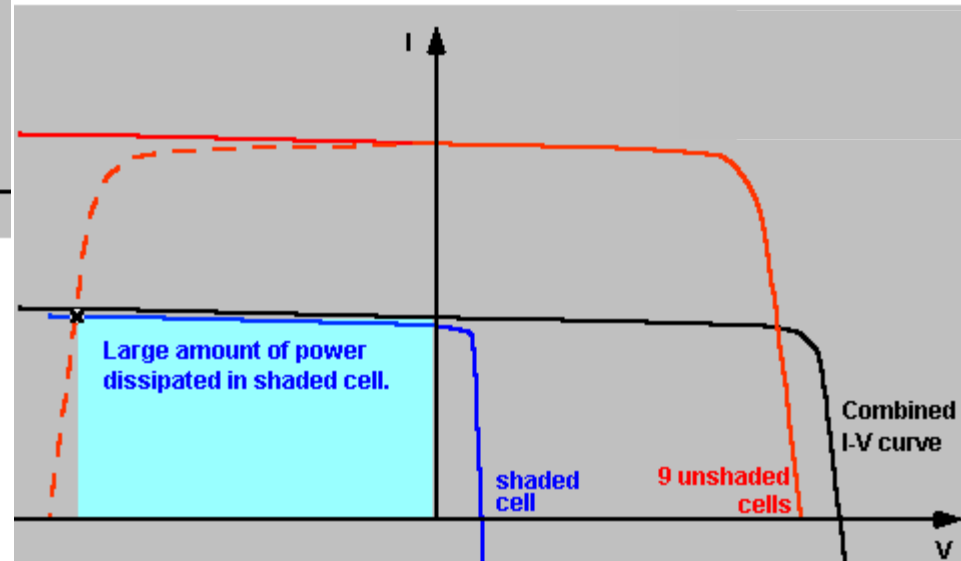
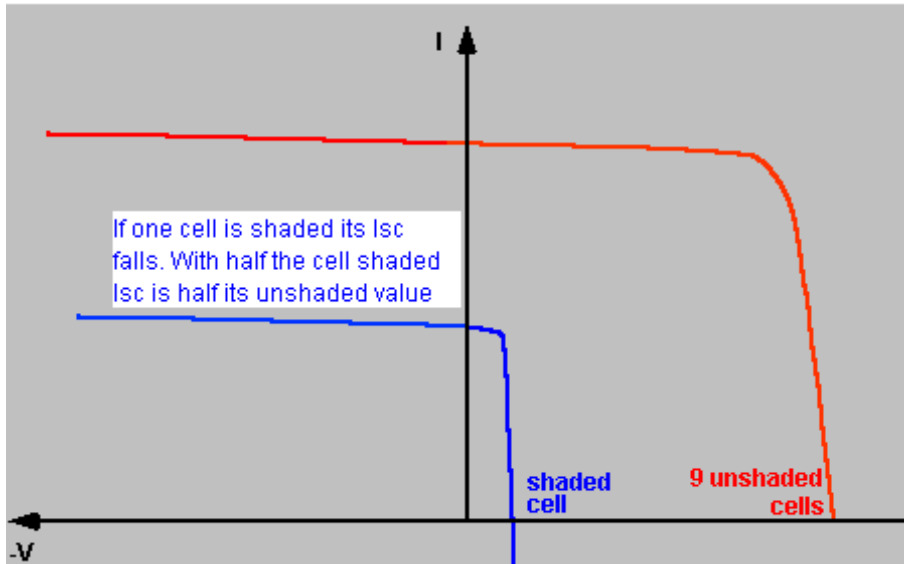
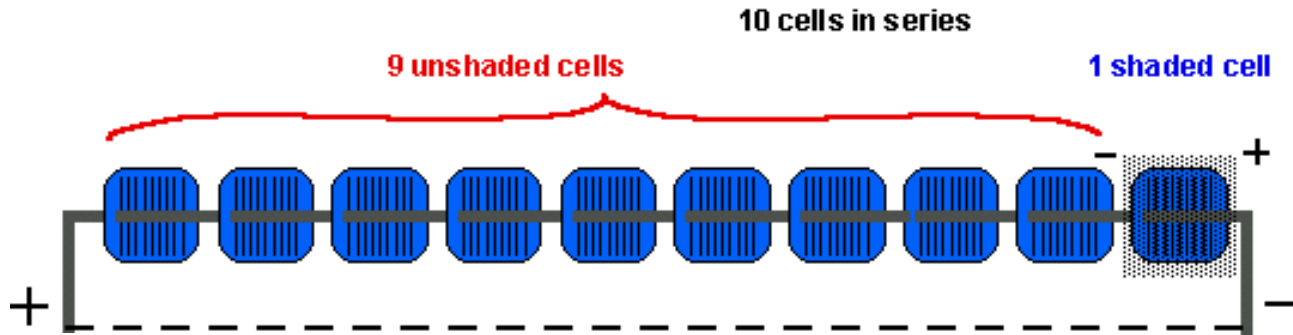
Mismatch of 2 cells connected in series



Determining the string short circuit current.



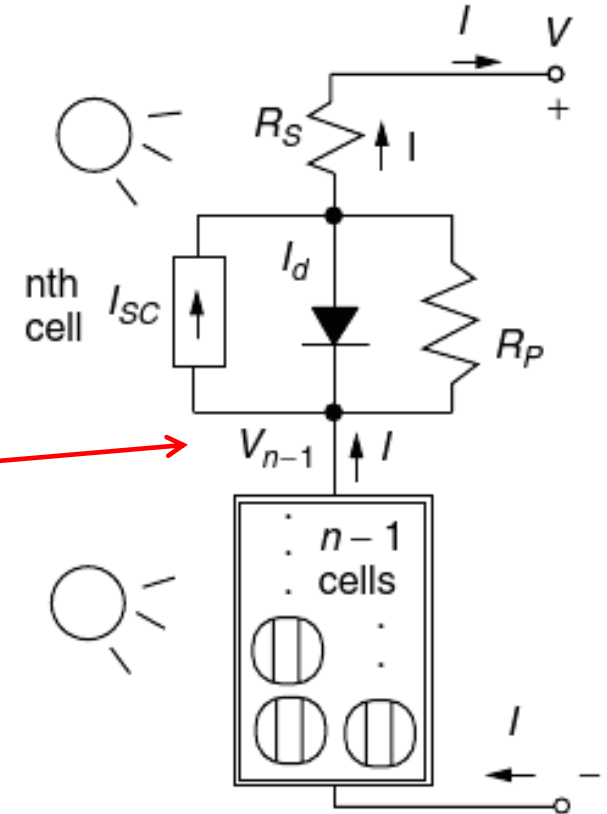
Mismatch of 10 cells connected in series



Mismatch of n cells connected in series

- Consider a module with n cells connected in series, with all the cells in the sun.
- One cell is shown separated from the others. The module is operating at voltage V and current I .
- Voltage generated by $(n-1)$ cells:

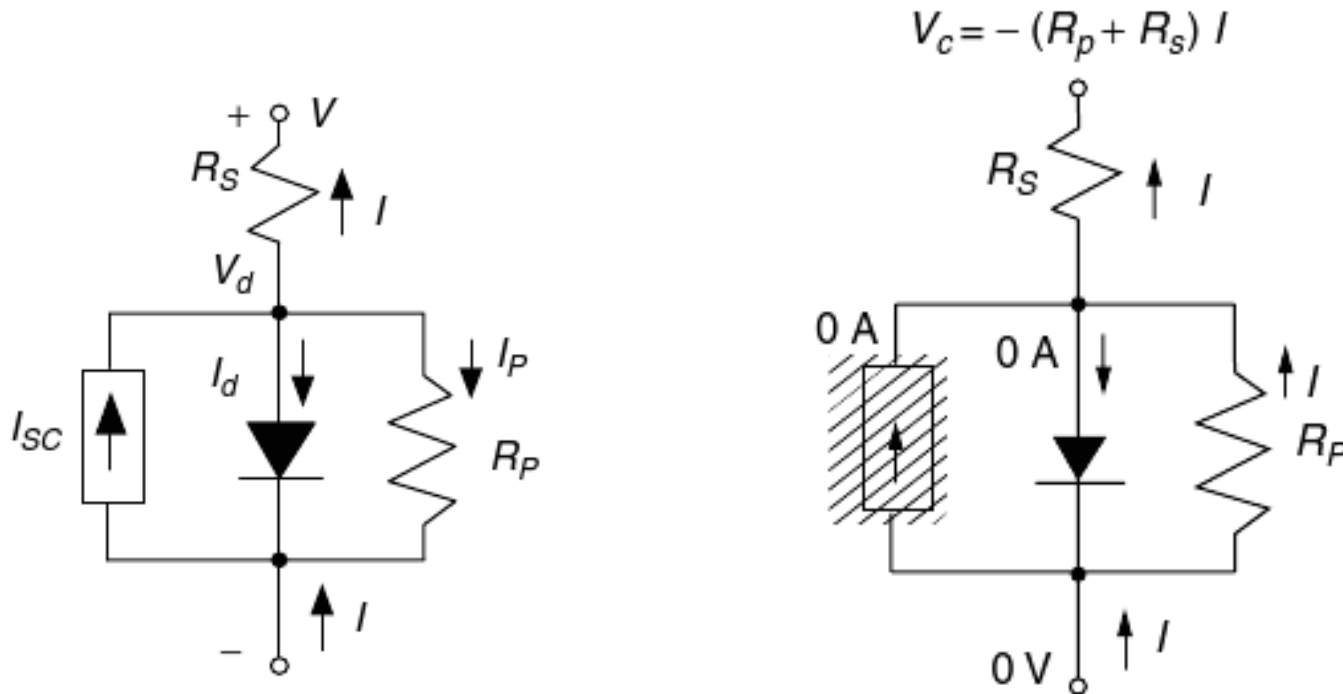
$$V_{n-1} = \left(\frac{n-1}{n} \right) V$$



(a) All cells in the sun

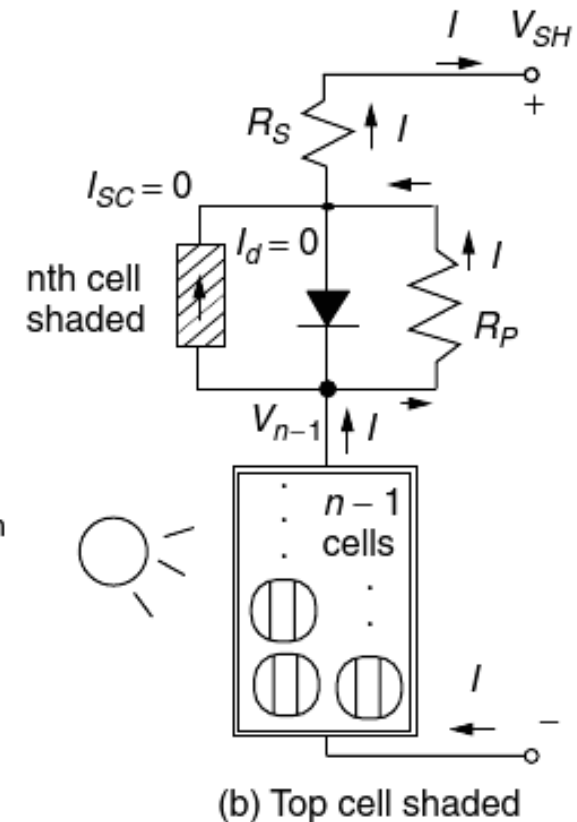
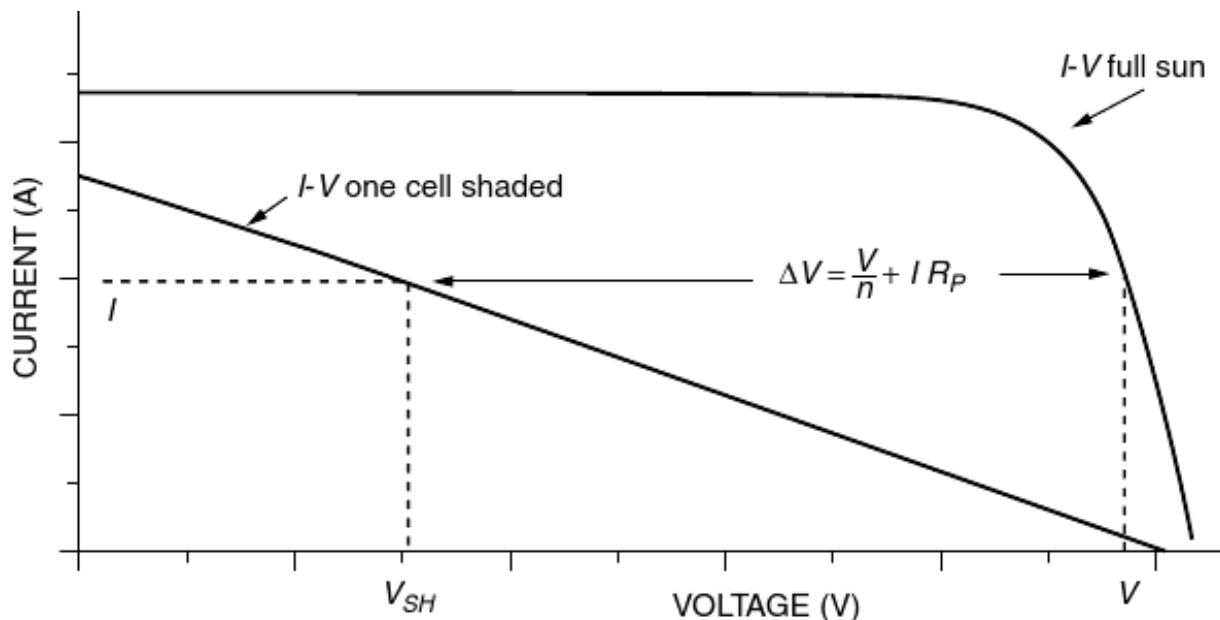
Voltage across shaded cell

- a solar cell in full sun operating in its normal range contributes an increase of nearly 0.5 V in the output voltage of the module.
- A partially shaded cell may generate or consume power – depending on I_{SC} and operating current I .
- A fully shaded cell experiences a voltage drop under any current, The shaded cell will be consuming power.



Physics of shading

- Now consider when the n^{th} cell is fully shaded (i.e., $I_{SC} = 0$).
- Since the current I generated by the non-shaded cells travels through R_p , the shaded cell becomes reverse biased, i.e., negative voltage equal to $-I(R_p + R_s)$ appears across its terminals.



Physics of shading

- The voltage of the module with one shaded cell:

$$V_{SH} = V_{n-1} - I(R_P + R_S)$$

$$V_{SH} = \left(\frac{n-1}{n}\right)V - I(R_P + R_S)$$

- The drop in voltage caused by the shaded cell:

$$\Delta V = V - V_{SH} = V - \left(1 - \frac{1}{n}\right)V + I(R_P + R_S)$$

$$\Delta V = \frac{V}{n} + I(R_P + R_S)$$

$$\Delta V \cong \frac{V}{n} + IR_P$$

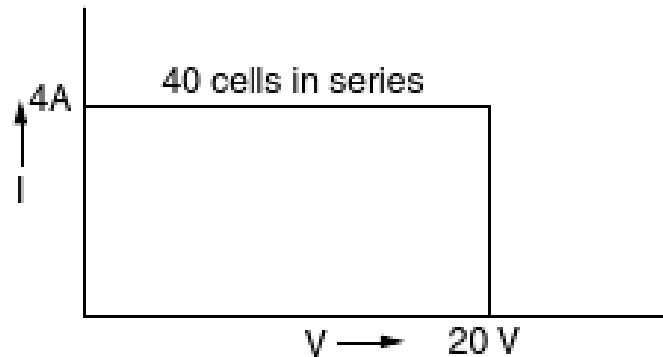
- See the new huge impact on the previous slide.

Shading example

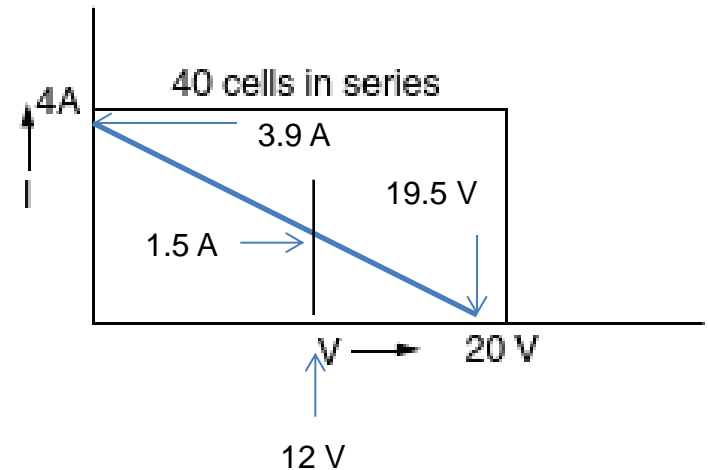
- The 36-cell PV module described ... has a parallel resistance per cell of $R_p = 6.6 \Omega$, and series resistance $R_s = 0.005 \Omega$. Under full sun, and under some load, the current $I = 2.14 \text{ A}$ the output voltage $V = 19.41 \text{ V}$. If one cell is fully shaded and this current somehow stays the same, then
 - What would be the new module output voltage and power?
 - What would be the voltage drop across the shaded cell?
 - How much power would be dissipated in the shaded cell?
- *Ans:*
 - *(a) voltage drop = 14.66 V, new voltage = 4.75 V (compared to 19.41 V), new power = 10.1 W (compared to 41.5 W),*
 - *(b) voltage drop across shaded cell = 14.14 V,*
 - *(c) power dissipated in the shaded cell = 30.2 W – this will likely cause permanent damage to the cell due to excessive heat!*

Another Shading Example

A module with 40 cells has an idealized, rectangular I-V curve with $I_{SC} = 4 \text{ A}$ and $V_{OC} = 20 \text{ V}$. If a single cell has a parallel resistance of 5Ω and negligible series resistance, draw the I-V curve if one cell is completely shaded. What current would it deliver to a 12-V battery (vertical I-V load at 12 V)?



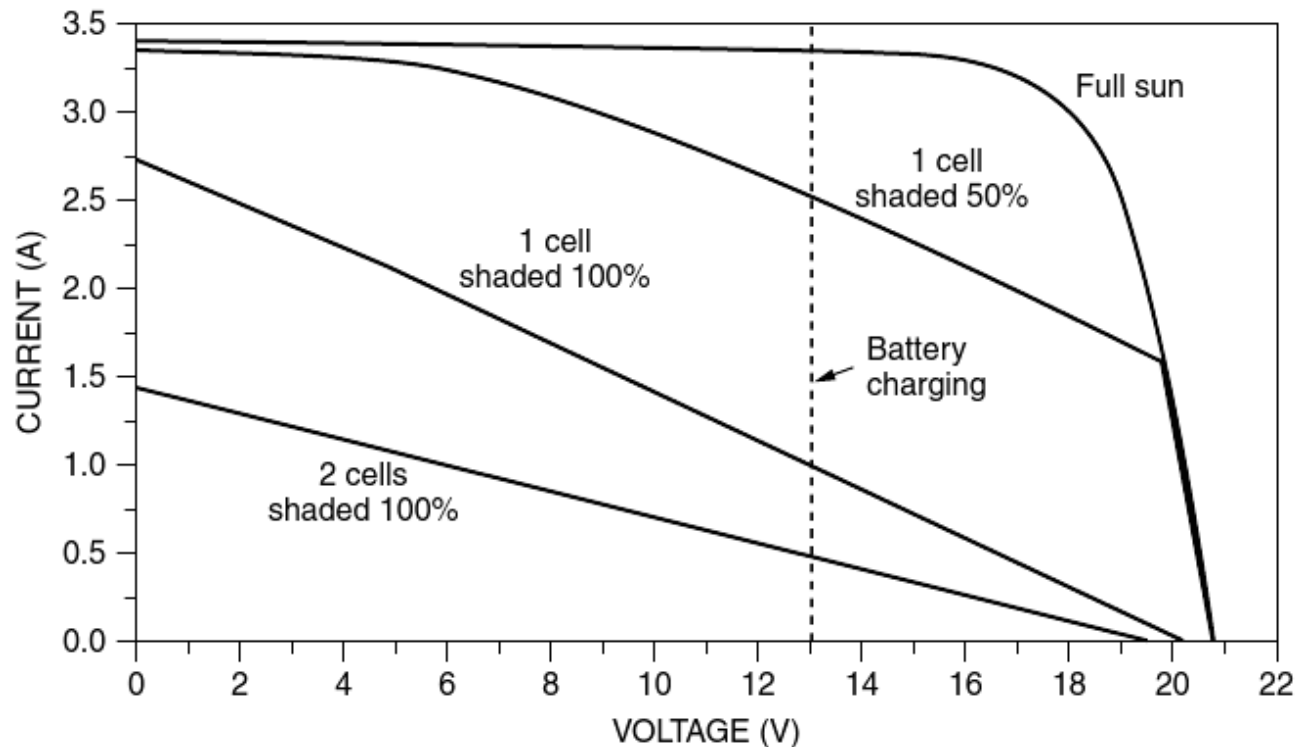
Note: This is not a good problem since on one hand, R_p is assumed to be infinite, and on the other hand $R_p = 5 \Omega$!



Power delivered to battery: 18 W
Power consumed by shaded cell: 11.25 W

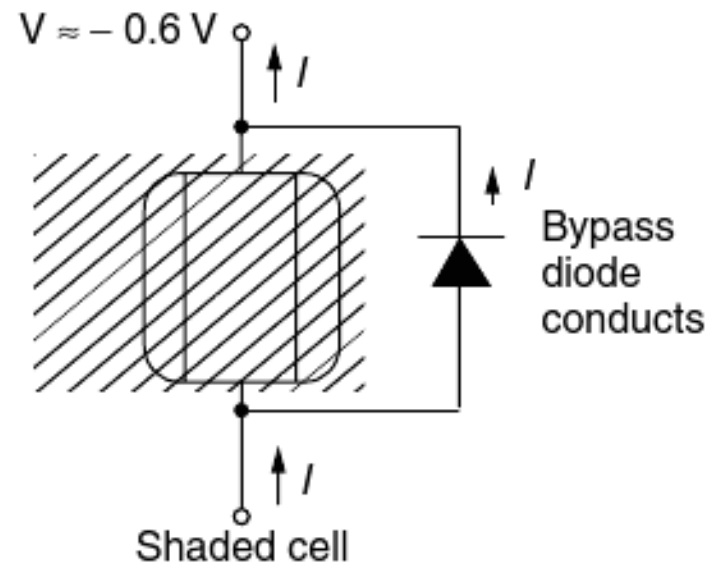
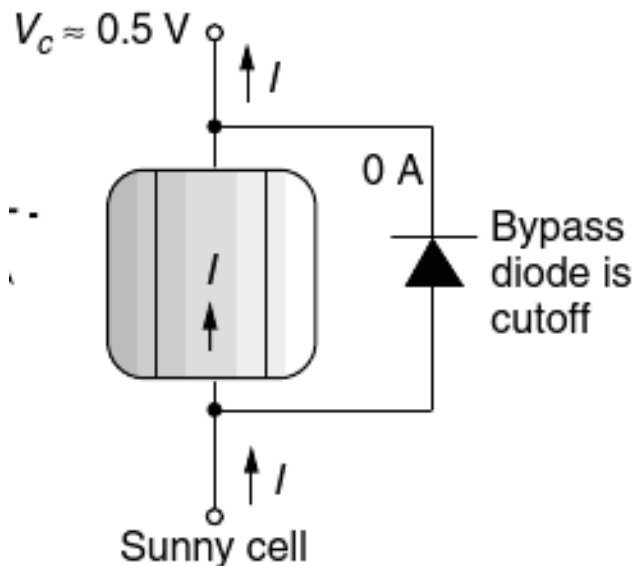
PV shading

- The figure below shows I-V curves (of module in the previous example) under full-sun conditions, with one cell 50% shaded, one cell completely shaded, and two cells completely shaded.
- The dashed vertical line (at 13 V) is a typical operating voltage for a module charging a 12-V battery. Note the large reduction in charging current caused by shading!

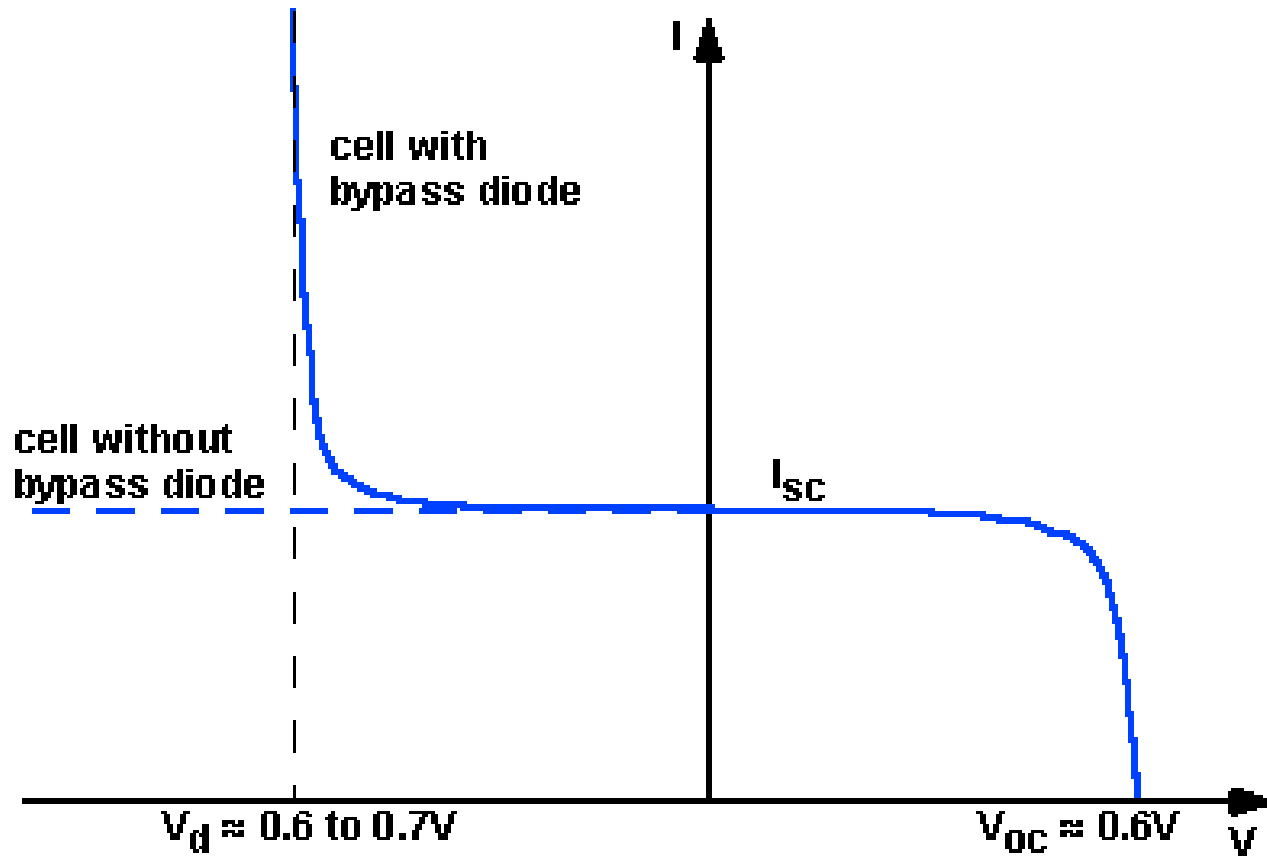


Bypass diodes

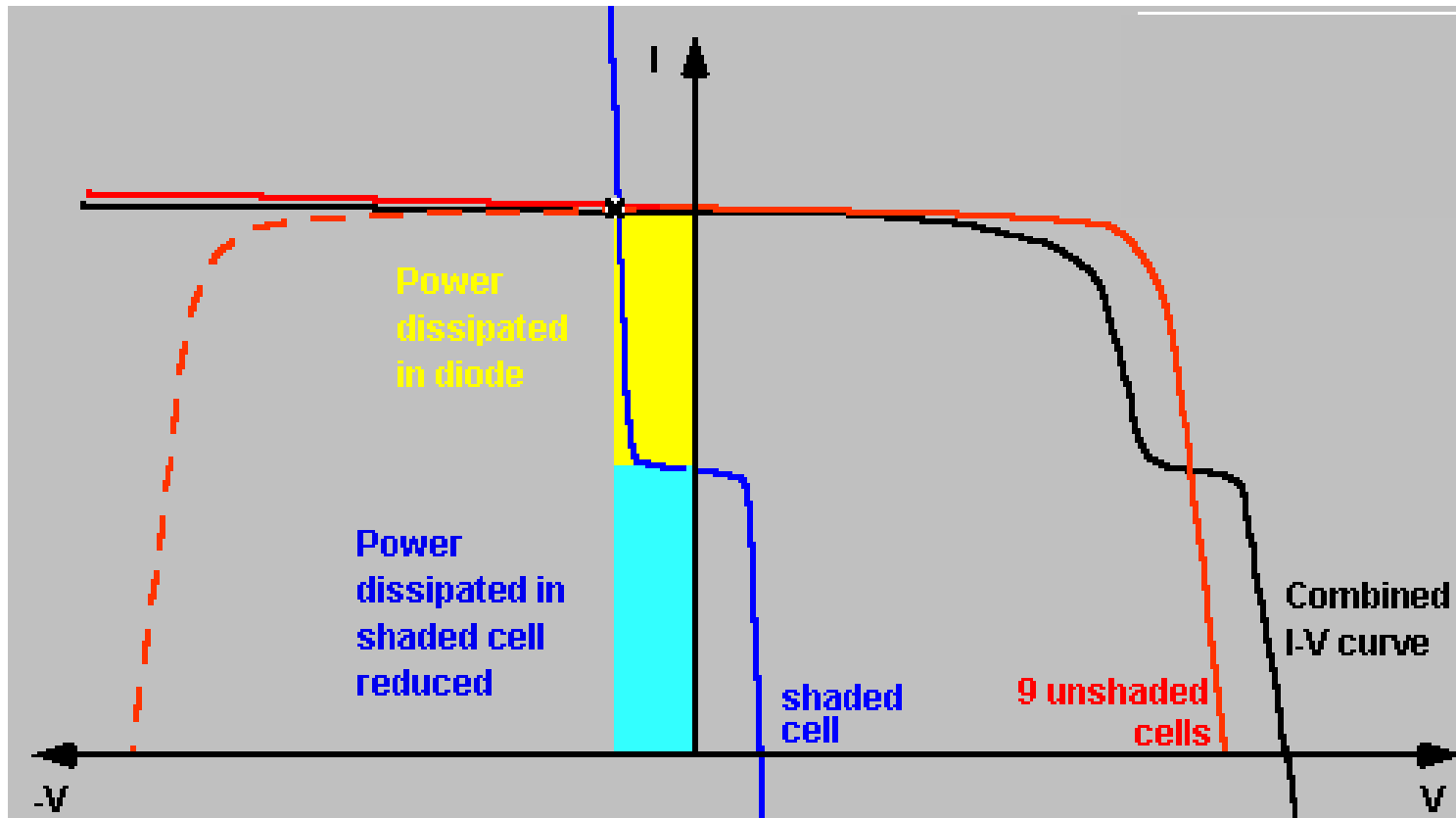
- External bypass diodes are purposely added by the PV manufacturer can help preserve the performance of PV modules.
 - In a sunny cell, there is a voltage rise across the cell so the bypass diode is reverse biased— i.e., it acts as if it is not there.
 - Under shade, however, the negative voltage will forward bias (i.e., turn on) the bypass diode, thus diverting the current flow.
 - When conducting, the bypass diode drops about 0.6 V, thus placing a cap on the negative voltage across the cell.



I-V curve of a cell with and w/o bypass diode

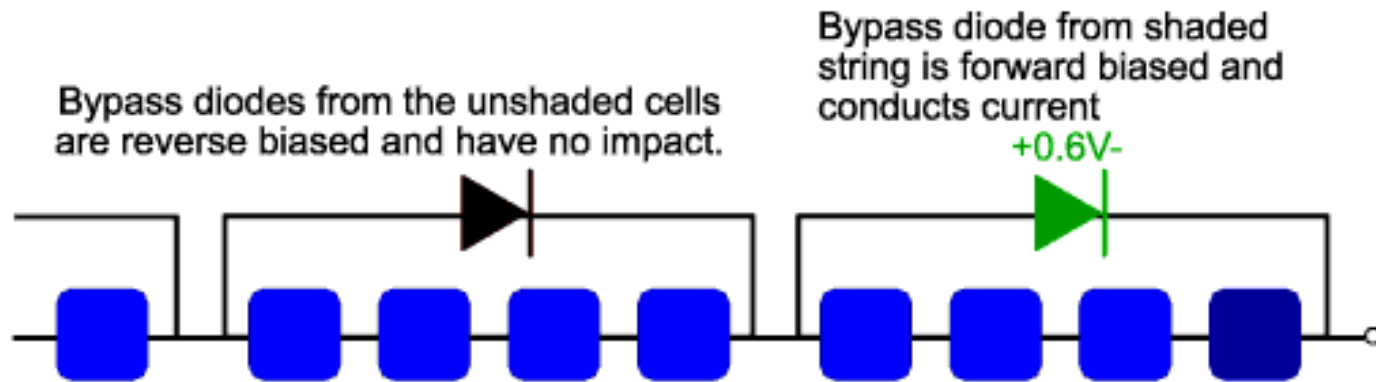


I-V curve of 10 Cells and one partially shaded cell (with bypass diode)



Bypass diode placement (real world)

- In practice, placing one bypass diode across each solar cell is too expensive and not easy to install. Instead, bypass diodes are conveniently placed across a group (or a string) of cells in the back of the panel. A typical number of cells in a string is 16 to 18.



Hidden bypass diodes

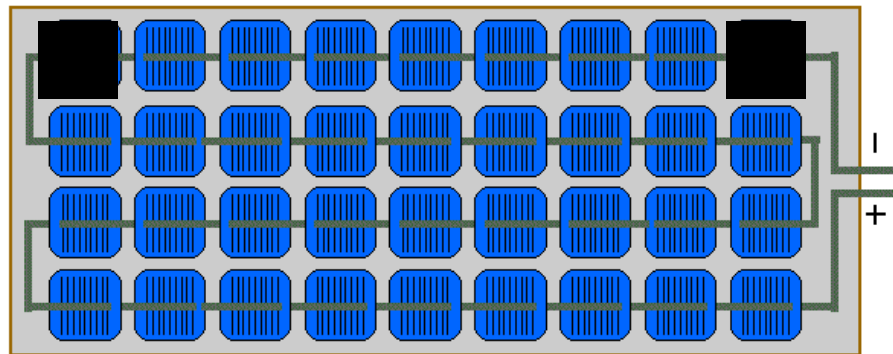


Visible bypass diodes

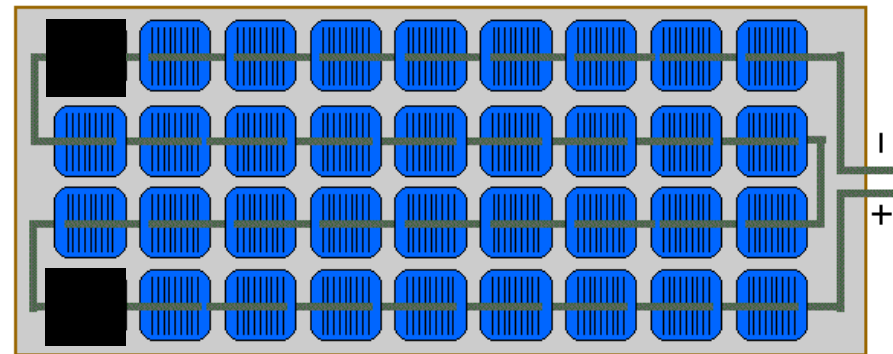


Impact of Partial Shading on a series of strings (module)

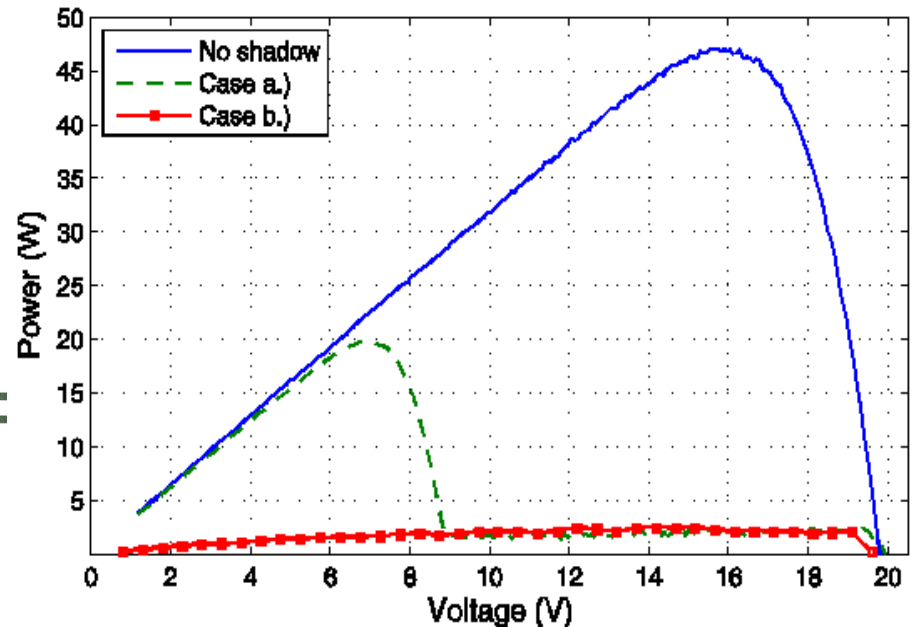
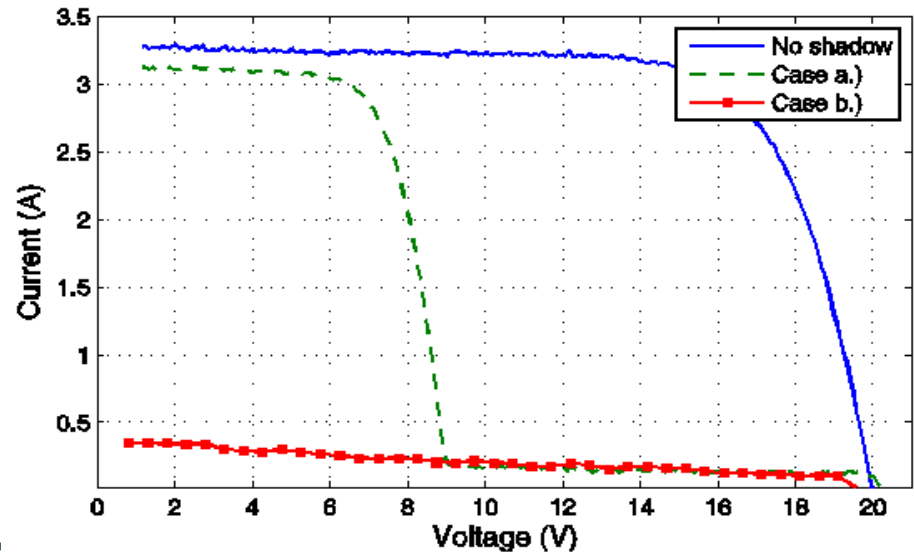
- Panel Model: Kyocera KC70
- Panel Layout: 2 series-connected strings (18 cells each) – one bypass diode per string.
- Two shaded cells belonging to (a) same string (b) different strings.



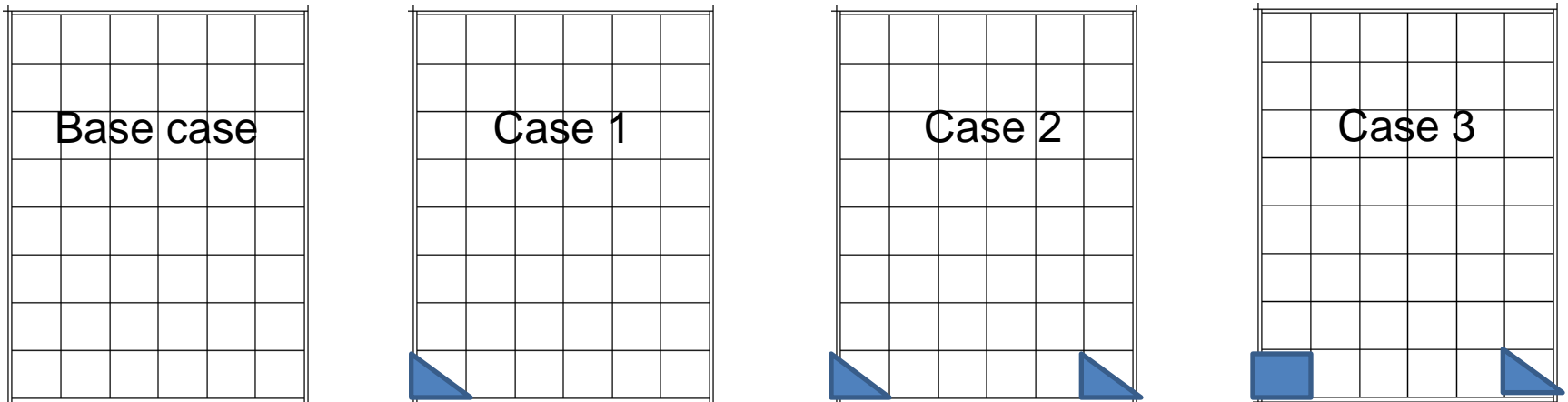
Case (a)



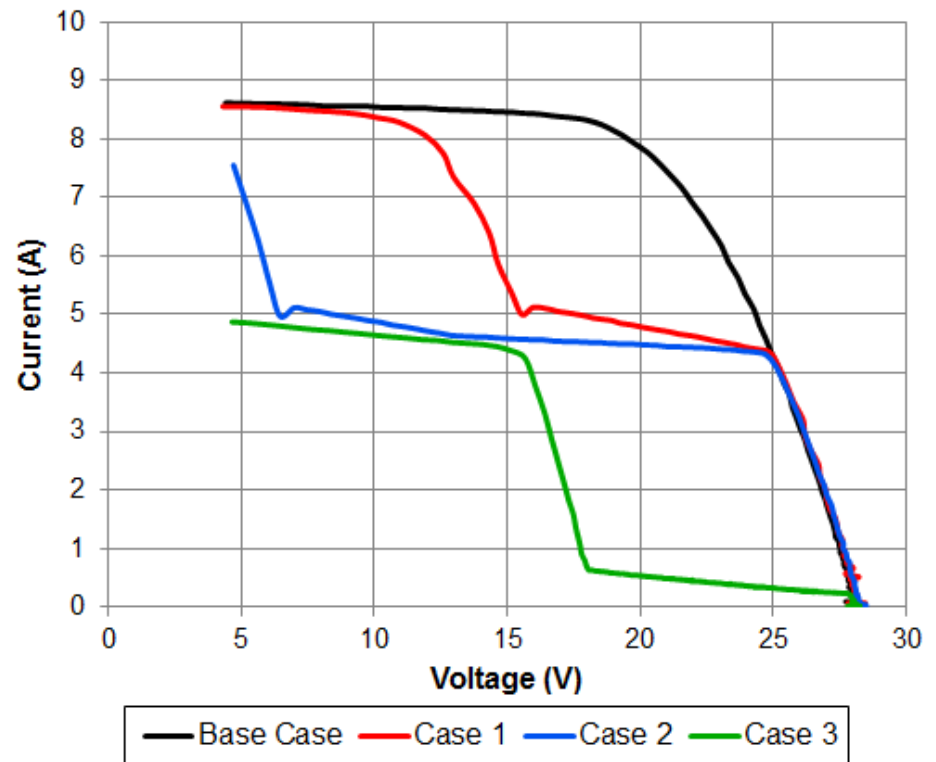
Case (b)



I-V Curve of partially shaded PV module

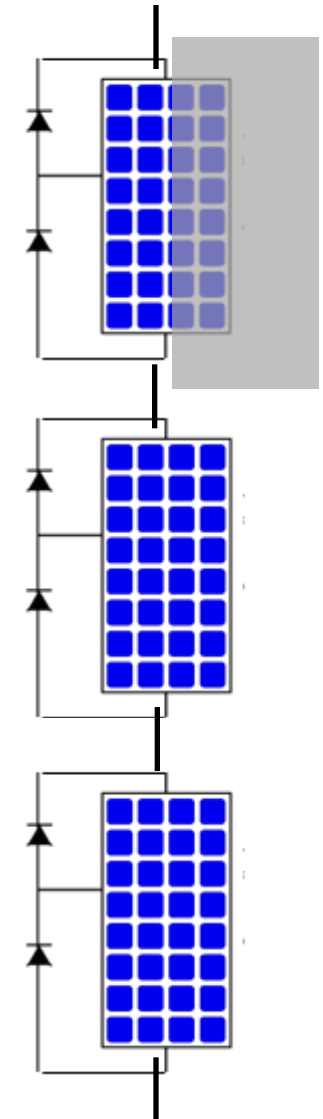
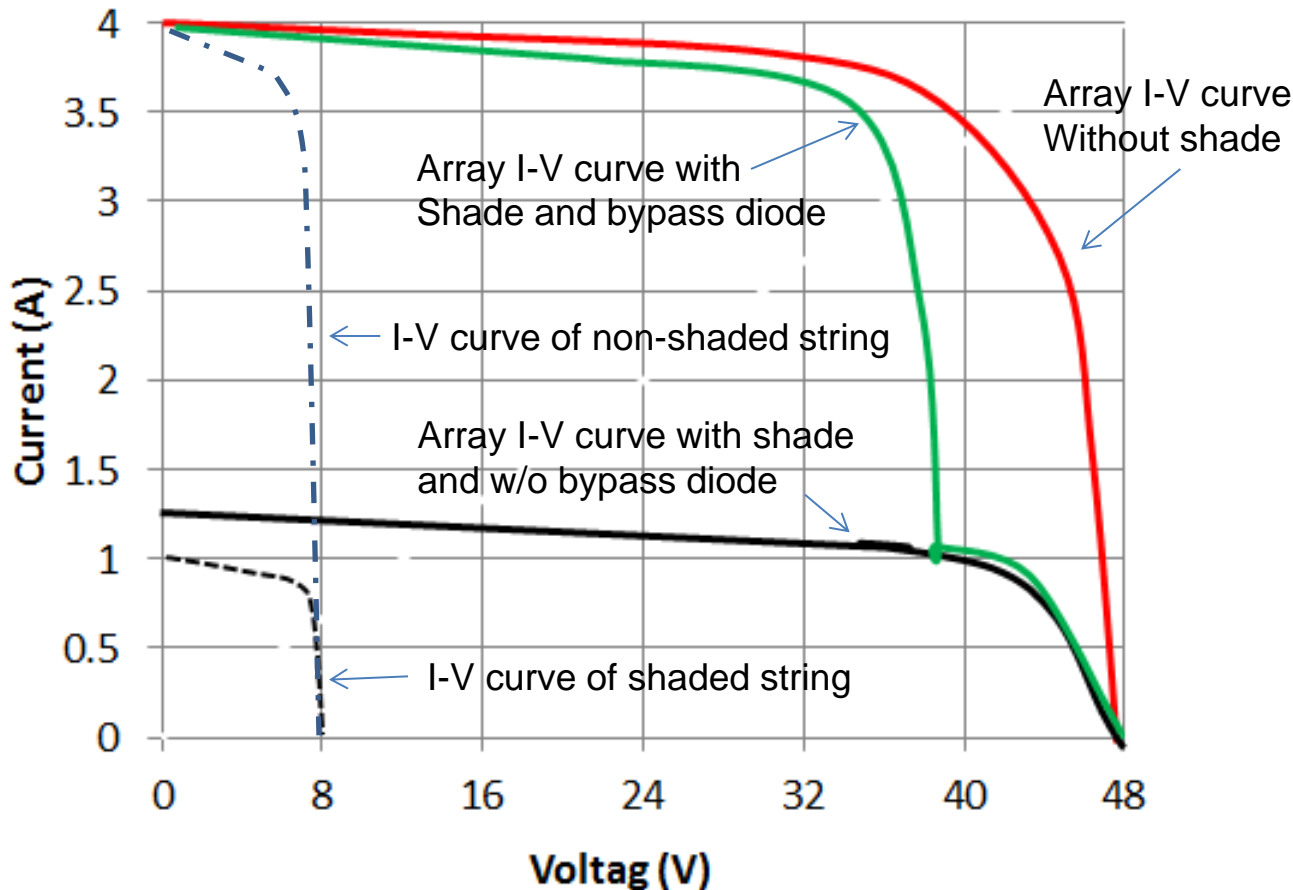


Pane Model: KD205GX-LPU
Power Rating: 205 W
Number of cells: 48
Number of bypass diodes: 3
(each across a sting of 16 cells)



Bypass diode effectiveness in PV array

- Cell characteristic: $I_{sc} = 4 \text{ A}$, $V_{oc} = 0.5 \text{ V}$
- String Characteristic: $I_{sc} = 4 \text{ A}$, $V_{oc} = 8 \text{ V}$
- Array Characteristic: $I_{sc} = 4 \text{ A}$, $V_{oc} = 48 \text{ V}$
- Partially shaded string: receiving 25% of sunlight.



Example

Suppose a PV module has the 1-sun I-V curve shown below. Within the module itself, the manufacturer has provided a pair of bypass diodes to help the panel deliver some power even when many of the cells are shaded. Each diode bypasses half of the cells, as shown. You may consider the diodes to be “ideal;” that is, they have no voltage drop across them when conducting.

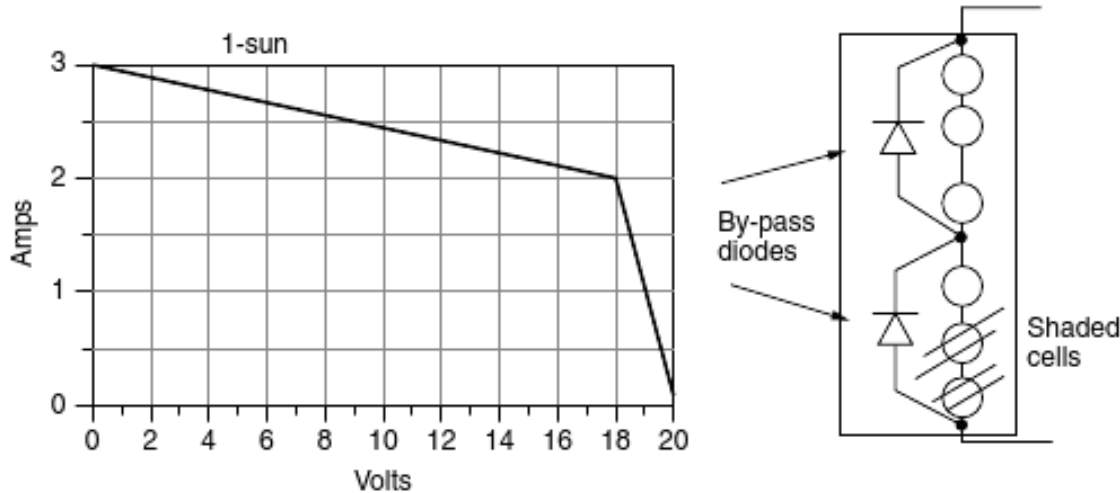
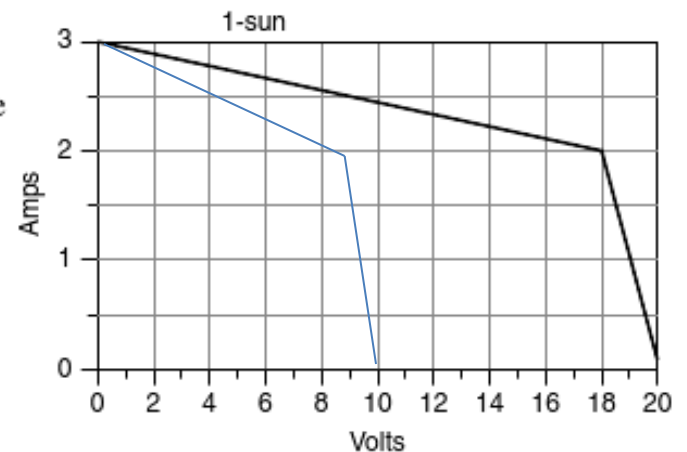


Figure P8.9

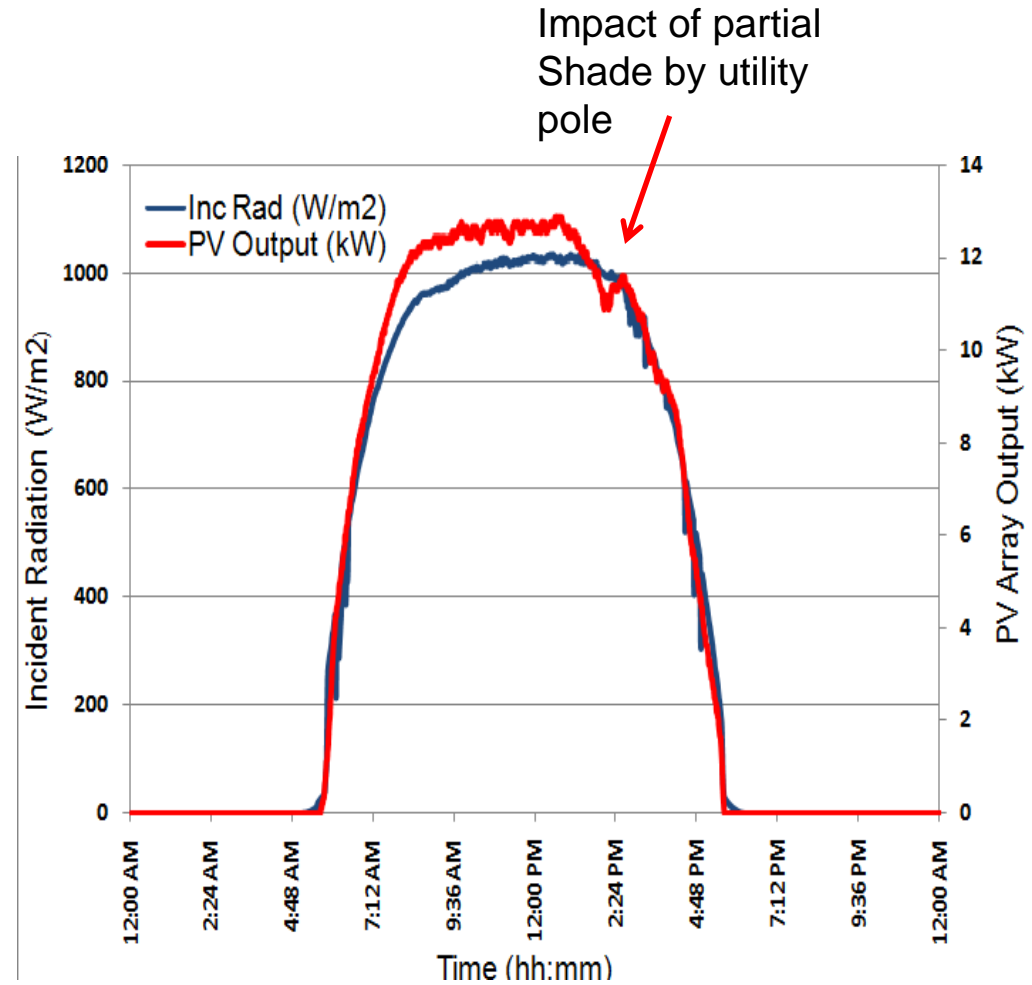
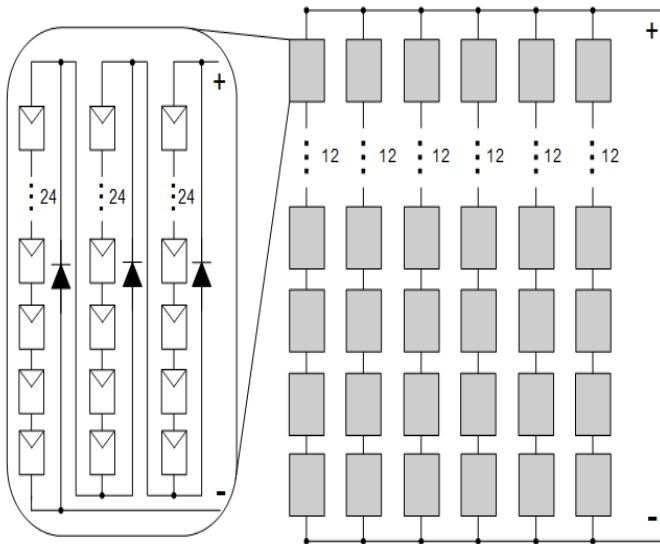
Suppose there is enough shading on the bottom cells to cause the lower diode to start conducting. Draw the new “shaded” I-V curve for the module.



Impact of Partial Shading on PV system Power



Note shadow of power pole at the bottom left



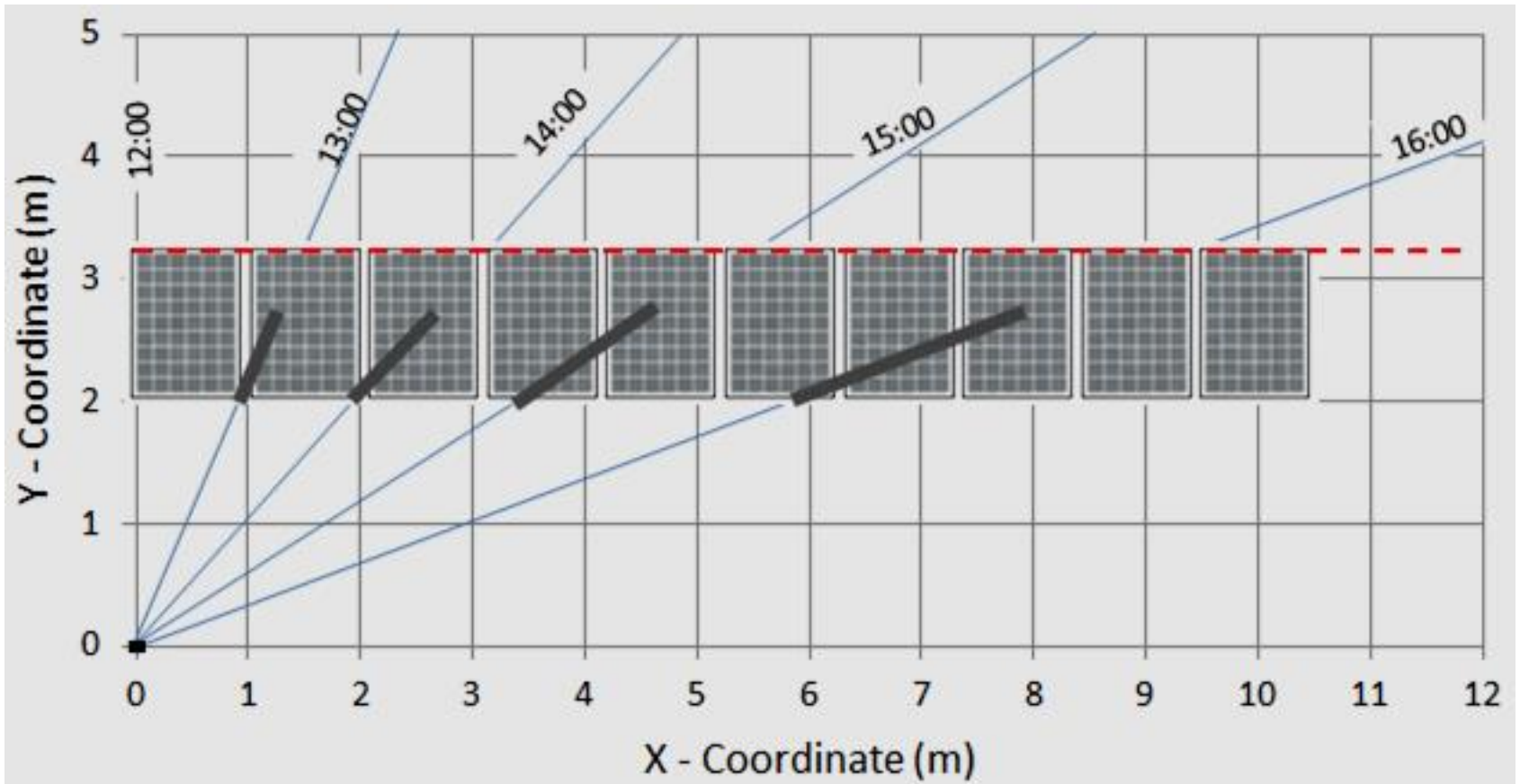
Panel Rating: 150 W, Array Rating: 14.4 kW

Experiment on Impact of Simple Shade

- One can calculate the shadow of the vertical post on the array with relative ease.



Sample of Calculated Shadow Movement (March 21)

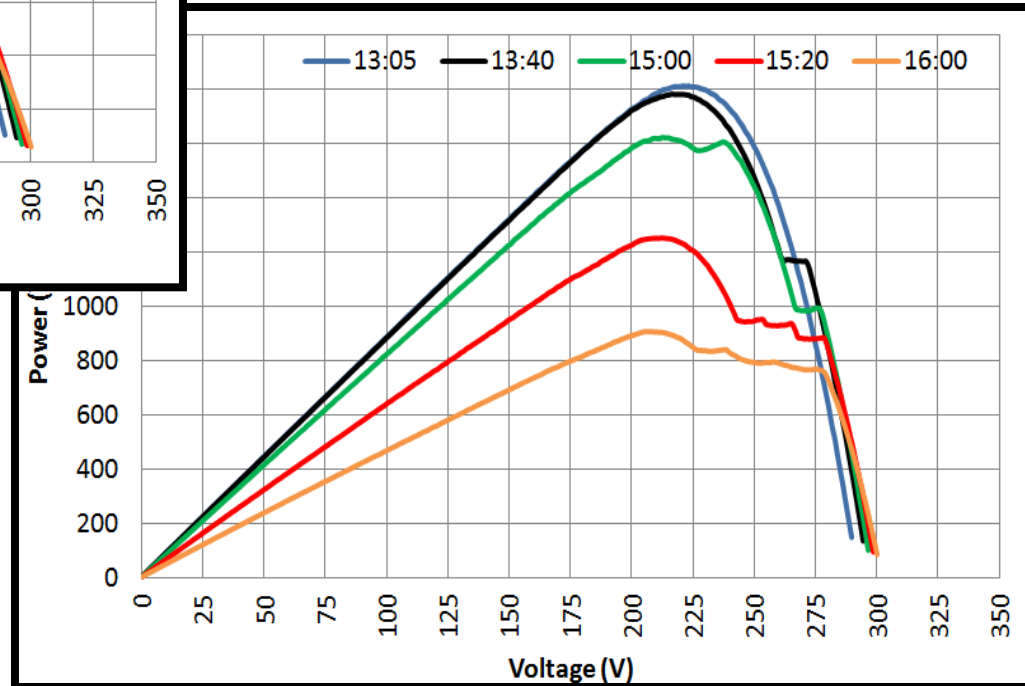
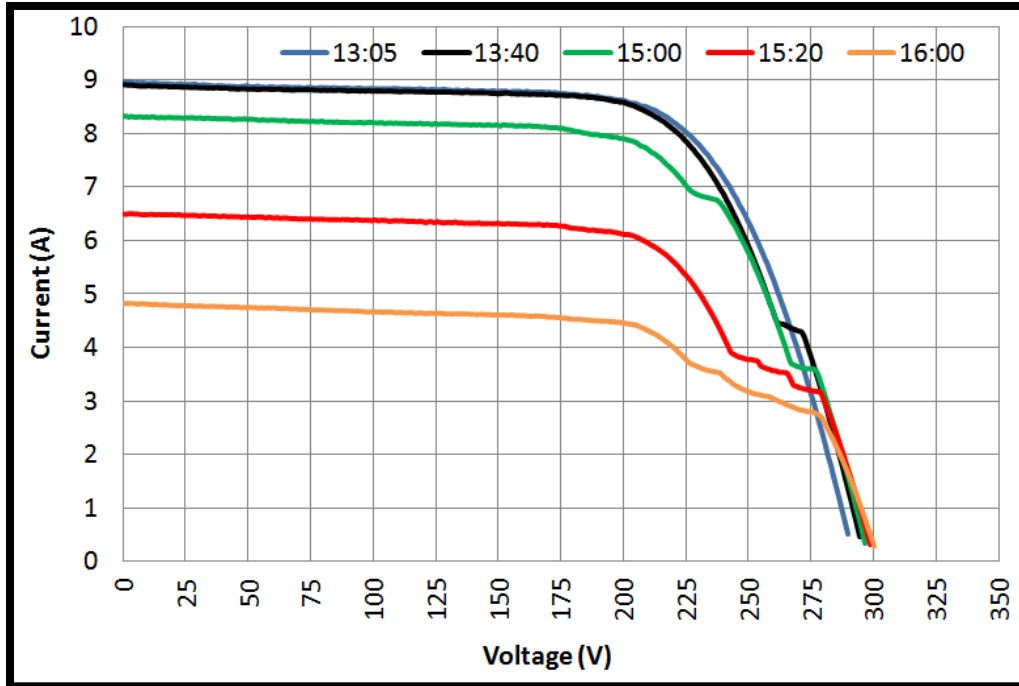


* Time Shown is in Solar Time

Sample of Actual Shadow Movement (March 21)



Sample of Measure IV and PV Curves



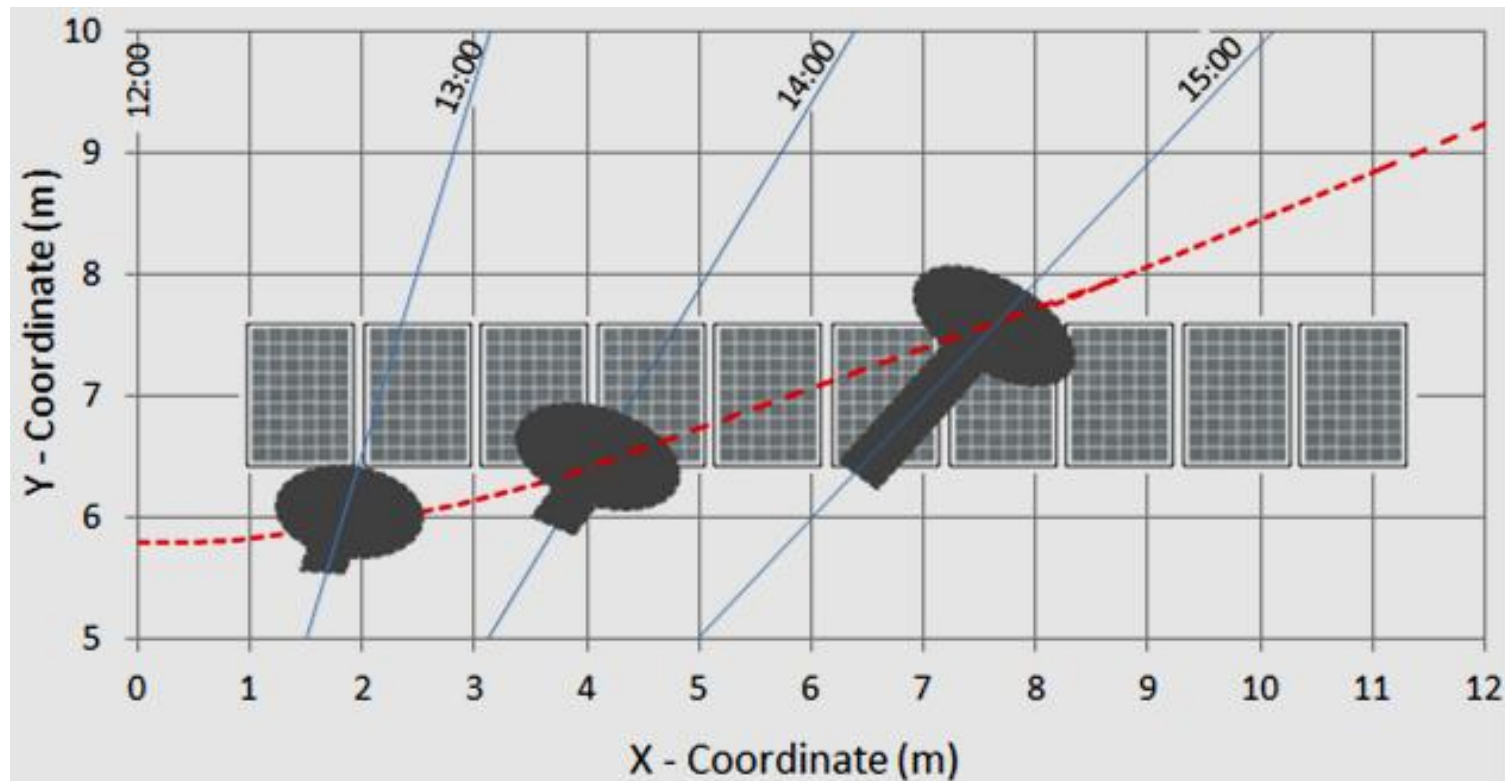
Impact of Relatively Complex Shade

- Herein, the shadow geometry of the solar dish collector is too complicated to calculate due to the uneven shape of the structure.



Sample of Calculated Shadow Movement

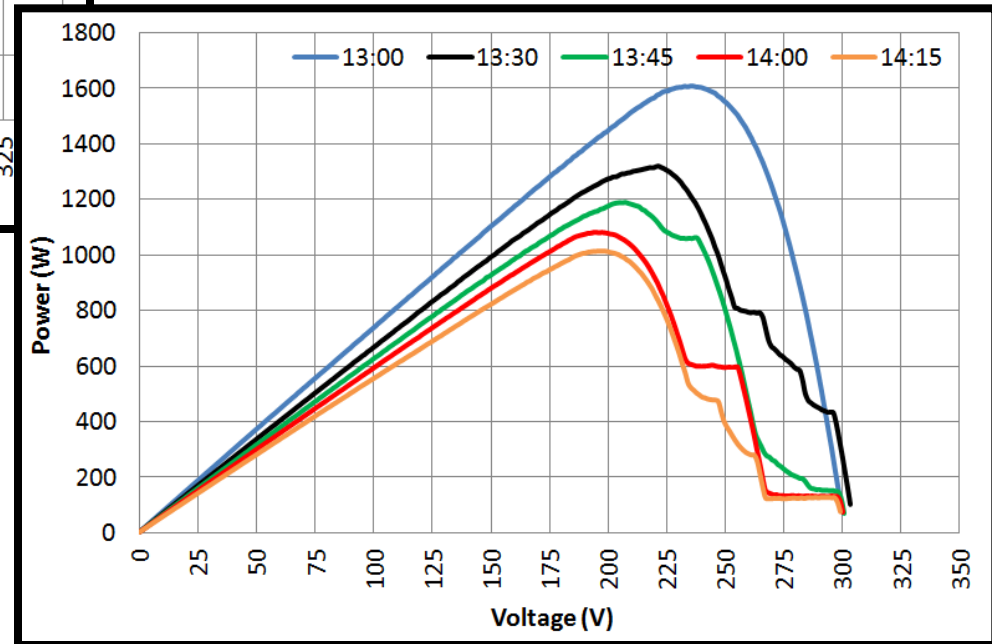
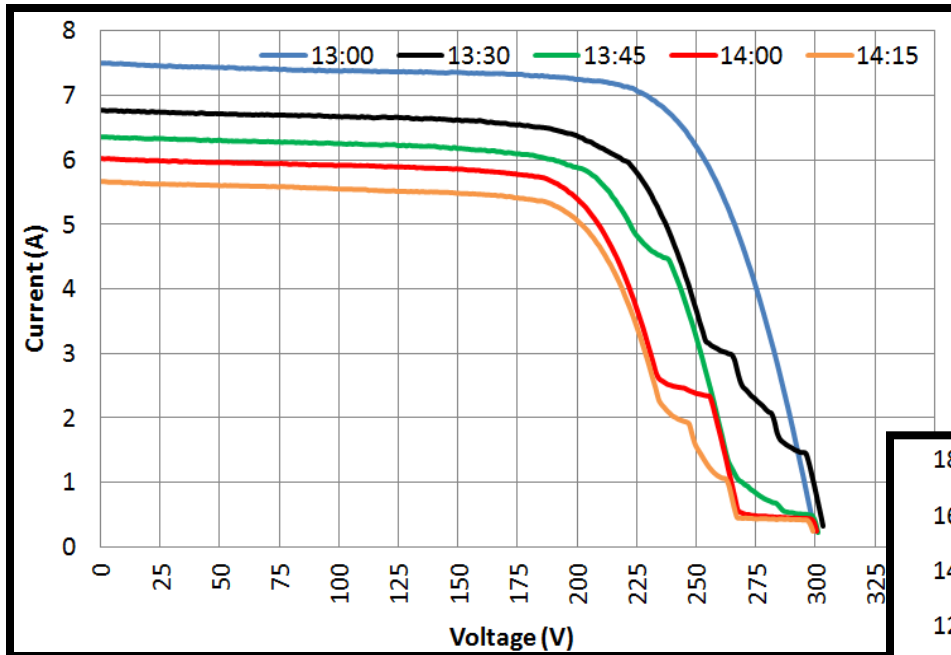
- Attempts can be made to compute the shadow geometry – expect errors.



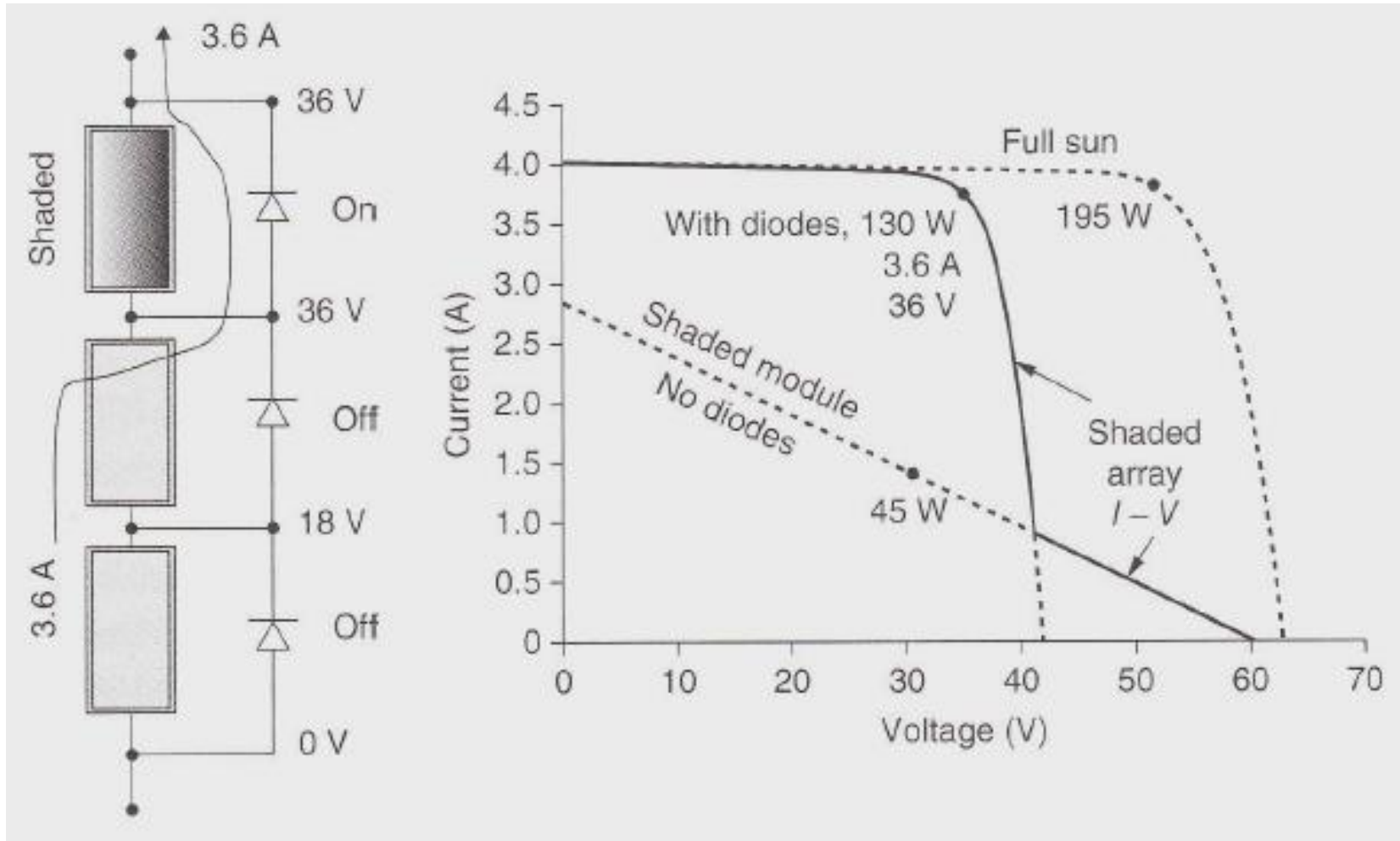
Sample of Actual Shadow Movement



Sample of Measure IV and PV Curves

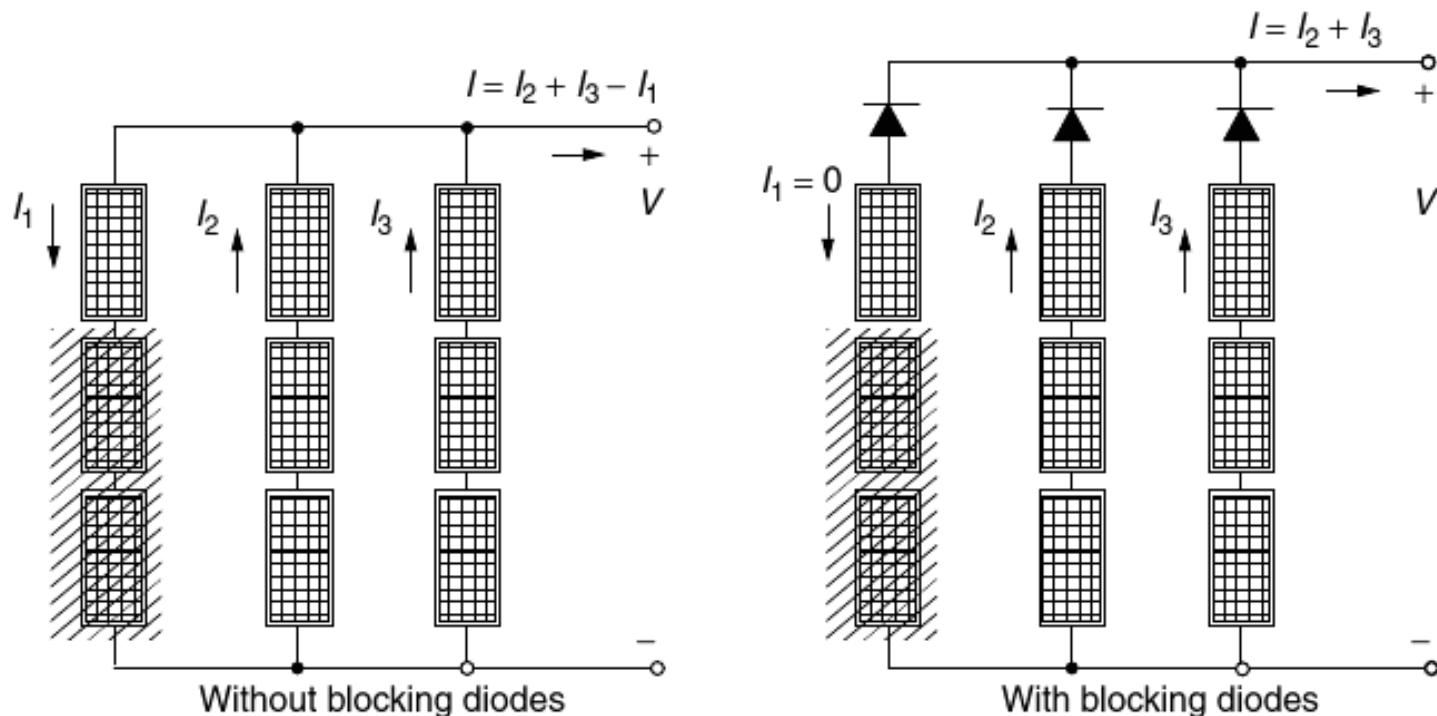


Externally installed bypass diodes



Blocking diodes

- When strings of modules are connected in parallel, one of the strings can draw current from the rest of the array if not performing well (due to malfunctioning defects or shading).
- By placing blocking diodes (also called isolation diodes) at the top of each string as shown below, the reverse current drawn by a shaded string can be prevented.



Problems

- 5.8 A 4-module array has two south-facing modules in series exposed to 1000 W/m^2 of insolation, and two west-facing modules exposed to 500 W/m^2 . The 1-sun I - V curve for a single module with its maximum power point at 4A , 40V is shown below.

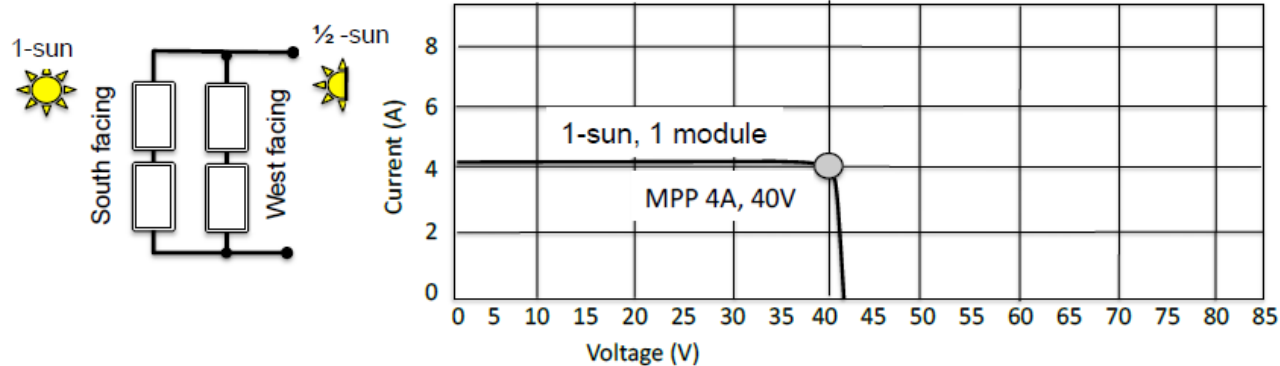
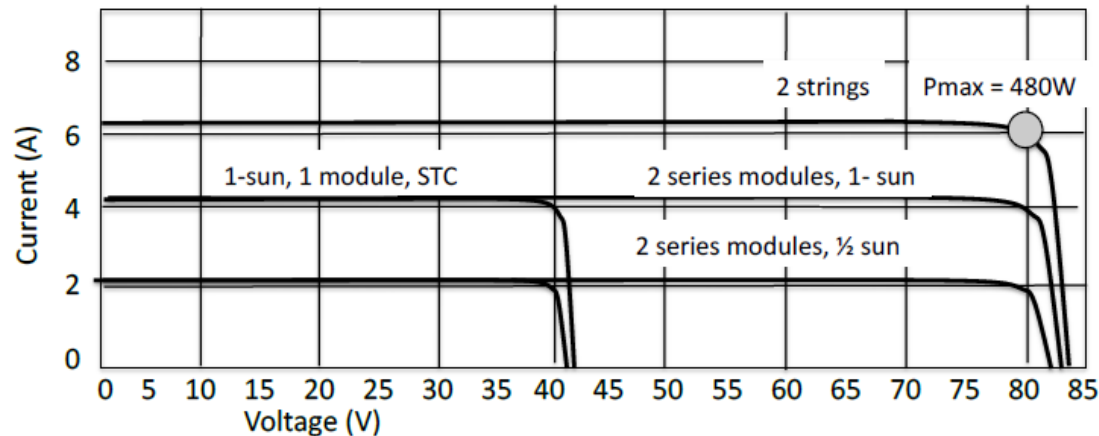


Figure P5.8

Draw the I - V curve for the 4-module array under these conditions. What is the output power (W) at the array's MPP?

SOLN: 480 W



Problems

5.9 A 200-W c-Si PV module has $NOCT = 45^\circ\text{C}$ and a temperature coefficient for rated power of $-0.5\%/^\circ\text{C}$.

a. At 1-sun of irradiation while the ambient is 25°C , estimate the cell temperature and output power.

SOLN: Using (5.23),

$$T_{\text{cell}} = T_{\text{amb}} + \left(\frac{NOCT - 20^\circ}{0.8} \right) \cdot S = 25 + \left(\frac{45 - 20}{0.8} \right) \cdot 1 = 56.25^\circ\text{C}$$

$$P_{\text{max}} = 200\text{W} \left[1 - 0.5\%/^\circ\text{C} (56.25 - 25)^\circ\text{C} \right] = 168.8\text{ W} \quad \dots \text{ a drop of } 15.6\%$$

b. Suppose the module is rigged with a heat exchanger that can cool the module while simultaneously providing solar water heating. How much power would be delivered if the module temperature is now 35°C ? What % improvement is

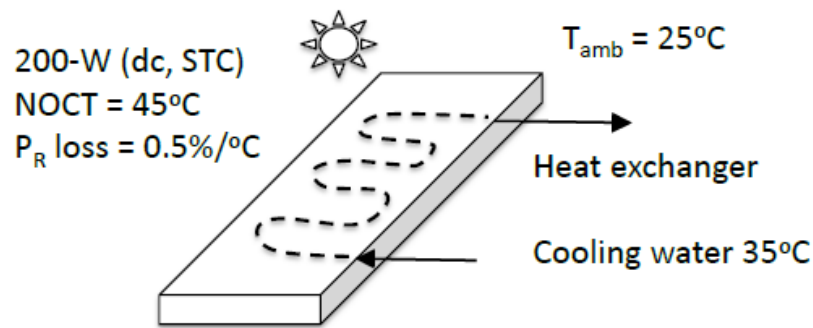


Figure P 5.9

SOLN:

$$P_{\text{max}} = 200\text{W} \left[1 - 0.5\%/^\circ\text{C} (35 - 25)^\circ\text{C} \right] = 190\text{ W}$$

$$\text{Improvement} = \frac{190 - 168.8}{168.8} = 12.56\%$$

Problems

- 5.10** Consider this very simple model for cells wired in series within a PV module. Those cells that are exposed to full sun deliver 0.5 V; those that are completely shaded act like 5- Ω resistors. For a module containing 40 such cells, an idealized I - V curve with all cells in full sun is as follows.

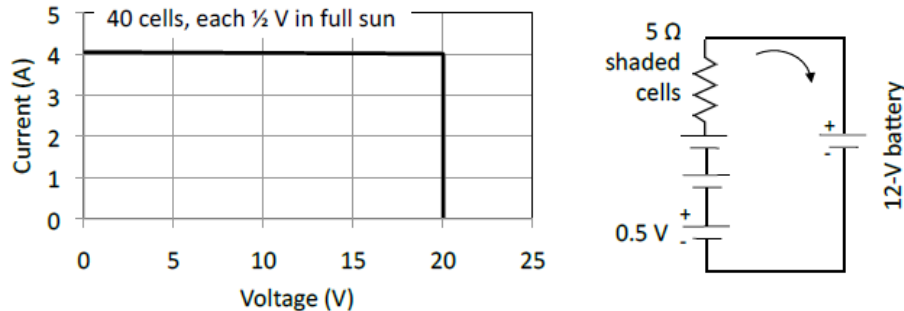
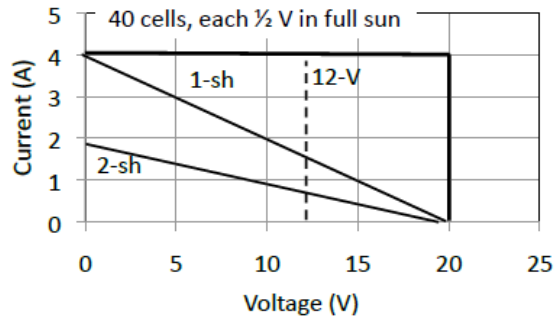


Figure P 5.10

- Draw the PV I - V curves that will result when one cell is shaded and when two cells are shaded (no battery load).
- If you are charging an idealized 12-V battery (vertical I - V curve), compare the current delivered under these three circumstances (full sun and both shaded circumstances).

SOLN: a.



- b. Battery charging:**

Full sun: $I = 4 \text{ A}$

1-cell shaded: $I = (19.5 - 12)/5 = 1.5 \text{ A}$

2-cells shaded $I = (19 - 12)/10 = 0.7 \text{ A}$

Problems

5.12 The 1-sun I - V curve for a 40-cell PV module in full sun is shown below along with an equivalent circuit for a single cell (including its 10Ω parallel resistance).

An array with two such modules in series has one fully shaded cell in one of the modules. Consider the potential impact of bypass diodes around each of the modules.

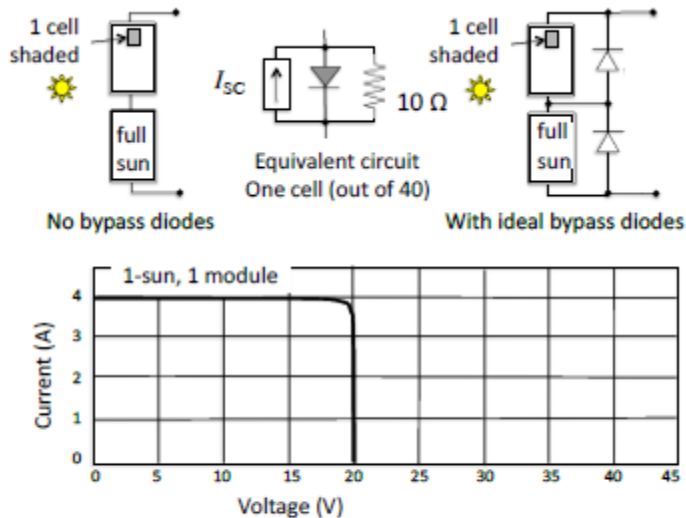
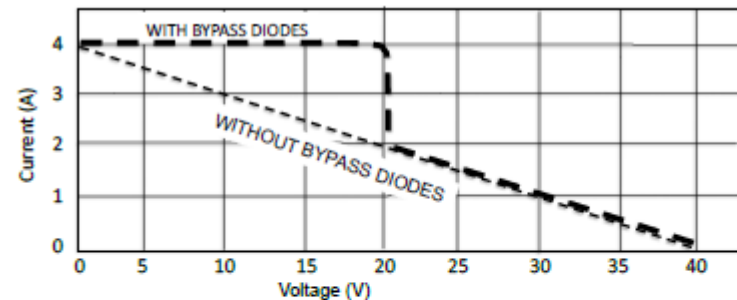


Figure P 5.12

- a. Sketch the 1-sun I - V curve for the series combination of modules with one cell shaded but no bypass diodes. Find the power output at the maximum power point. Compare it to the output when there is no shading.

SOLN:



- a. MPP without diodes is at $2A \times 20V = 40W$ could guess, which is fine or prove it by

$$I = 4 - 0.1V \quad \text{so } P = VI = 4V - 0.1V^2$$

$$dP/dV = 4 - 0.1 \times 2V = 0$$

$$\text{So } V = 4/0.2 = 20V, \quad I = 2A, \quad P_{\text{max}} = 2 \times 20 = 40W$$

Without diodes, the output went from 160 W down to 40 W when 1 cell is shaded !