CLEAN ENERGY GENERATION, INTEGRATION AND STORAGE (EEE-801)

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Lecture-9

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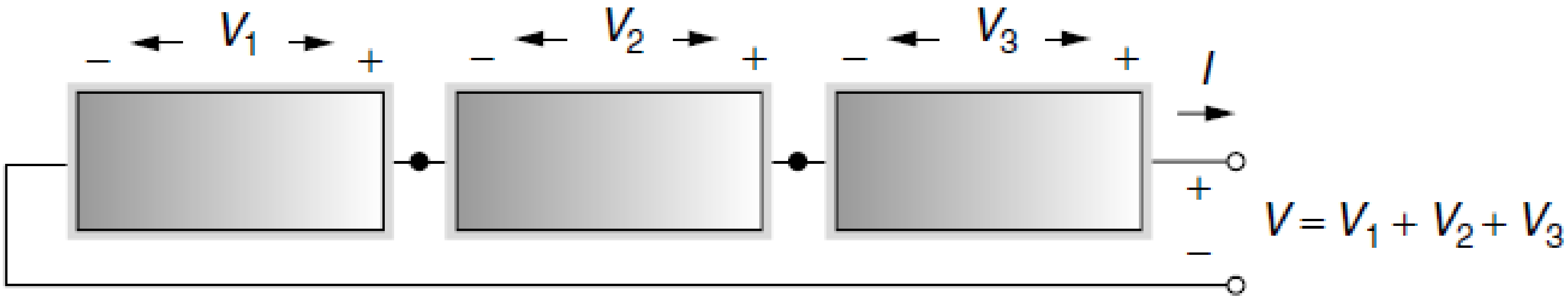
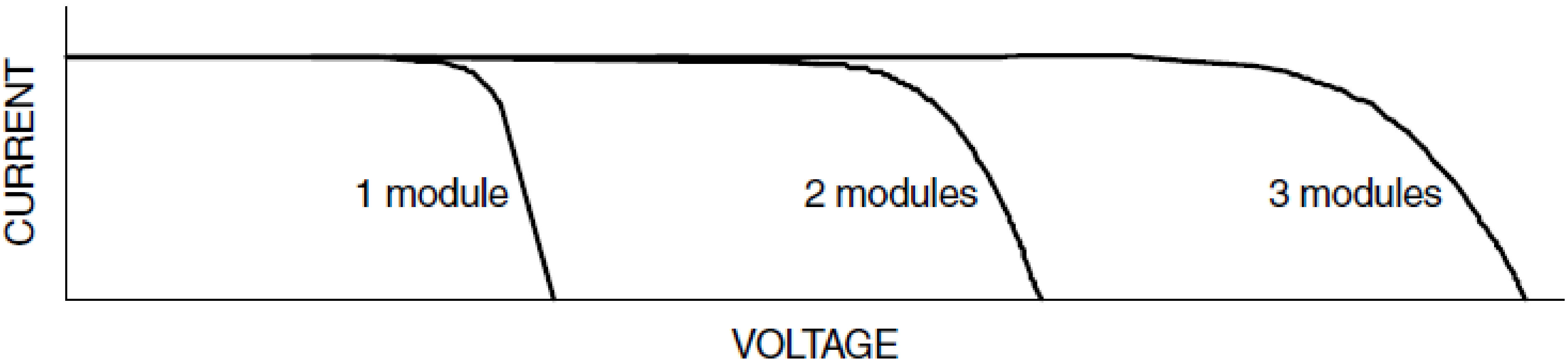
PV: From Modules to Array

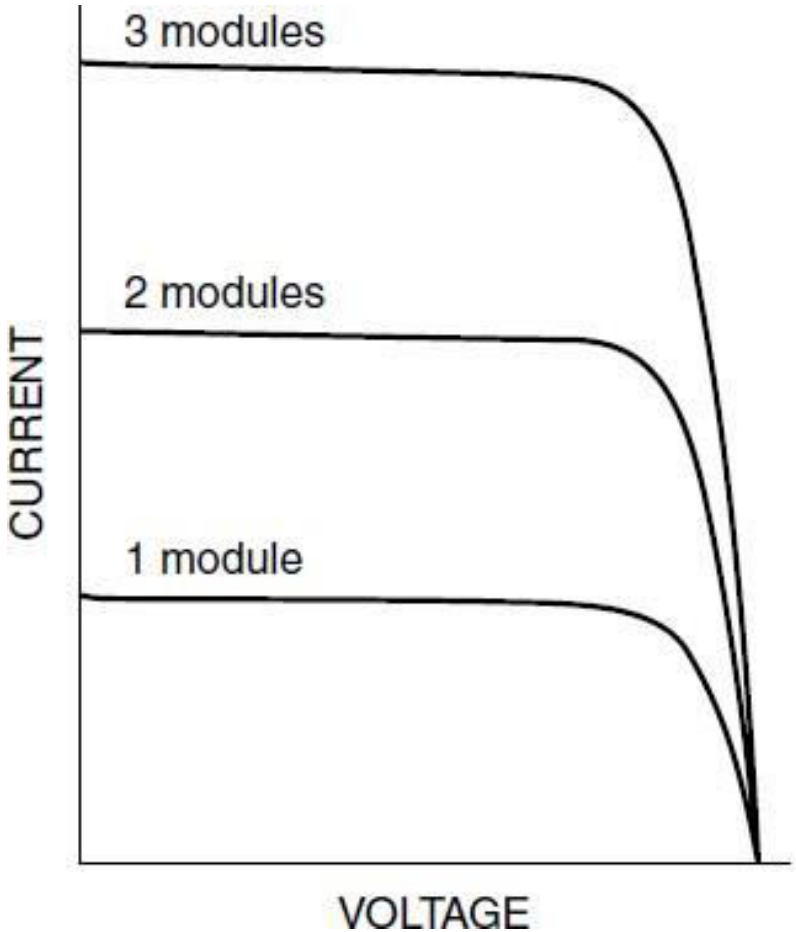
- **Modules can be wired in series to increase voltage, and in parallel to increase current. Arrays are made up of some combination of series and parallel modules to increase power.**
- **For modules in series, the I –V curves are simply added along the voltage axis. That is, at any given current which flows through each of the modules, the total voltage is just the sum of the individual module voltages as given in Figure on next slide.**
- **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. Figure on the next slides shows the I –V curve for three modules in parallel.**

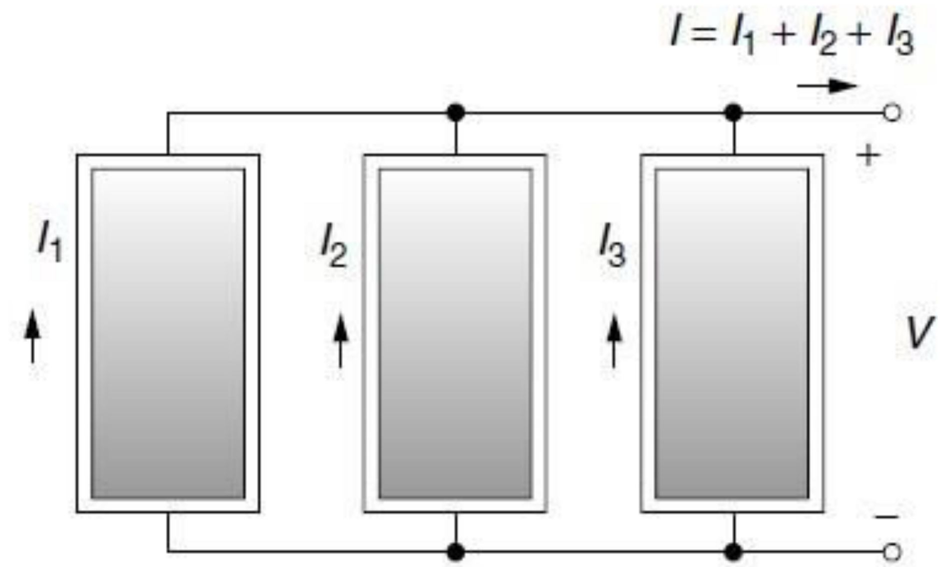
PV: From Modules to Array (Continued)





PV: From Modules to Array (Continued)

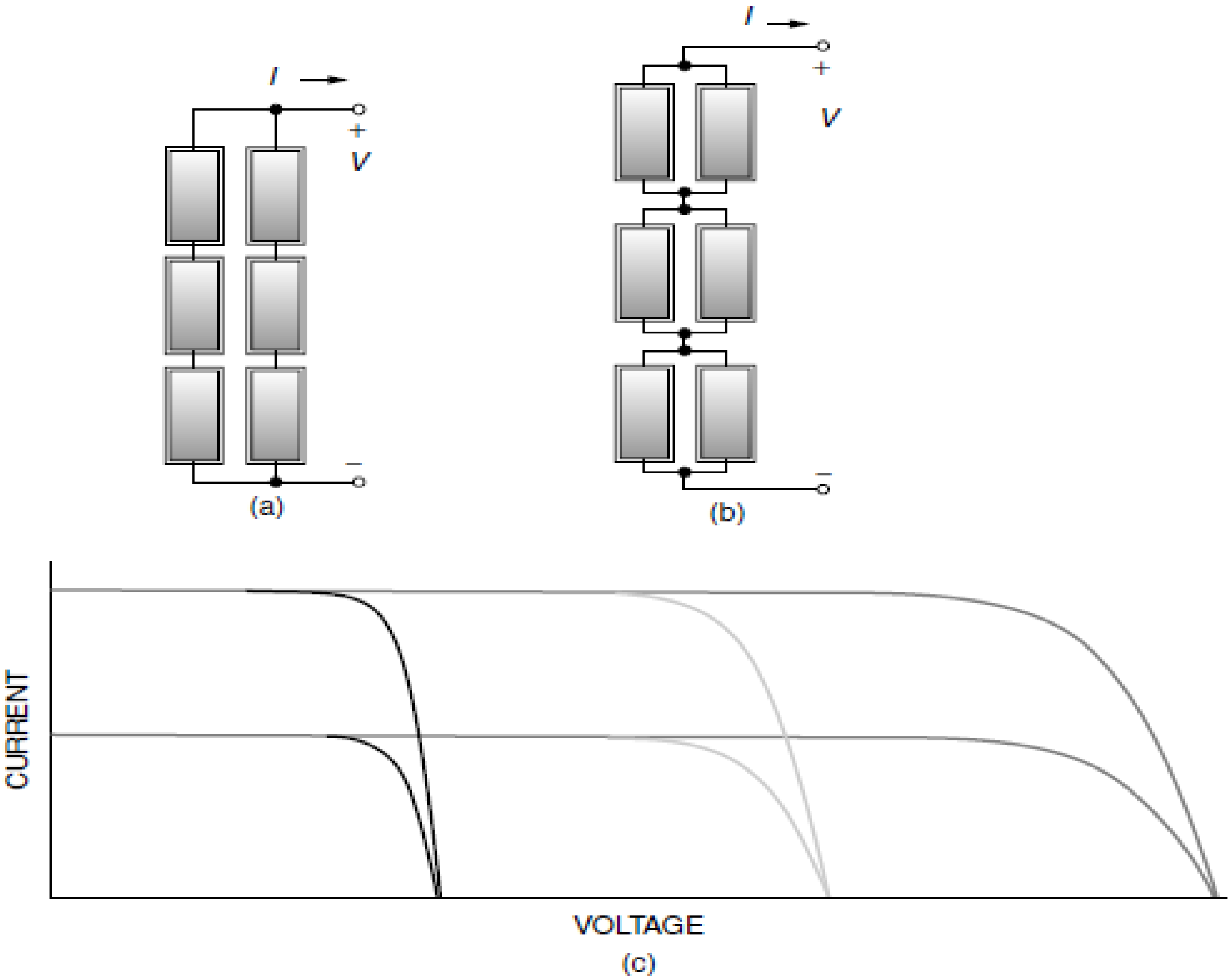




PV: From Modules to Array (Continued)

- When high power is needed, the array will usually consist 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. There are two ways to imagine wiring a series/parallel combination of modules:
- The series modules may be wired as strings, and the strings wired in parallel as shown in Figure on next slide, or the parallel modules may be wired together first and those units combined in series as shown in Figure on next slide.
- The total I –V curve is just the sum of the individual module curves, which is the same in either case when everything is working right. There is a reason, however, to prefer the wiring of strings in parallel as shown in Figure on next slide. If an entire string is removed from service for some reason, the array can still deliver whatever voltage is needed by the load, though the current is diminished, which is not the case when a parallel group of modules is removed.

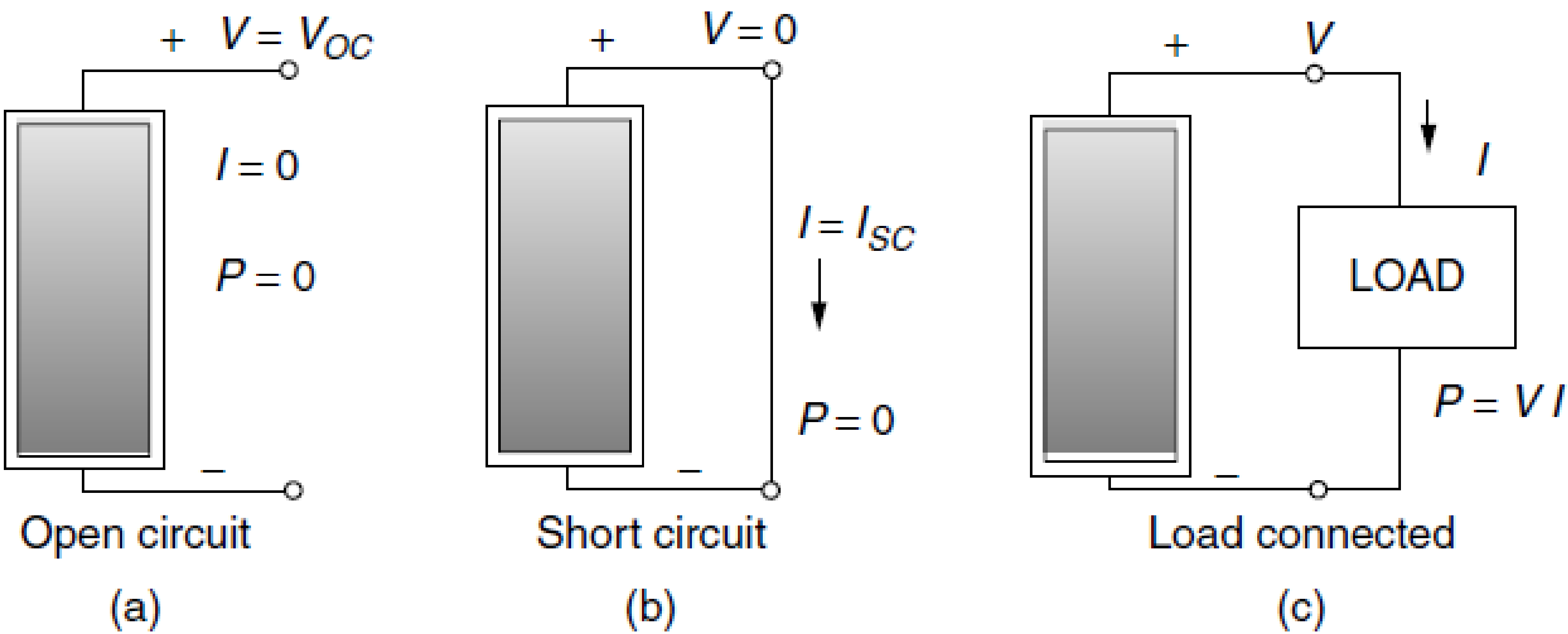
PV: From Modules to Array (Continued)



PV: The PV I-V Curve Under Standard Test Conditions (STC)

- **Consider, for the moment, a single PV module that you want to connect to some sort of a load as shown in Figure on next slide. The load might be a dc motor driving a pump or it might be a battery, for example. Before the load is connected, the module sitting in the sun will produce an open-circuit voltage V_{oc}, but no current will flow.**
- **If the terminals of the module are shorted together (which doesn't hurt the module at all, by the way), the short-circuit current I_{sc} will flow, but the output voltage will be zero. In both cases, since power is the product of current and voltage, no power is delivered by the module and no power is received by the load.**
- **When the load is actually connected, some combination of current and voltage will result and power will be delivered. To figure out how much power, we have to consider the I –V characteristic curve of the module as well as the I –V characteristic curve of the load.**

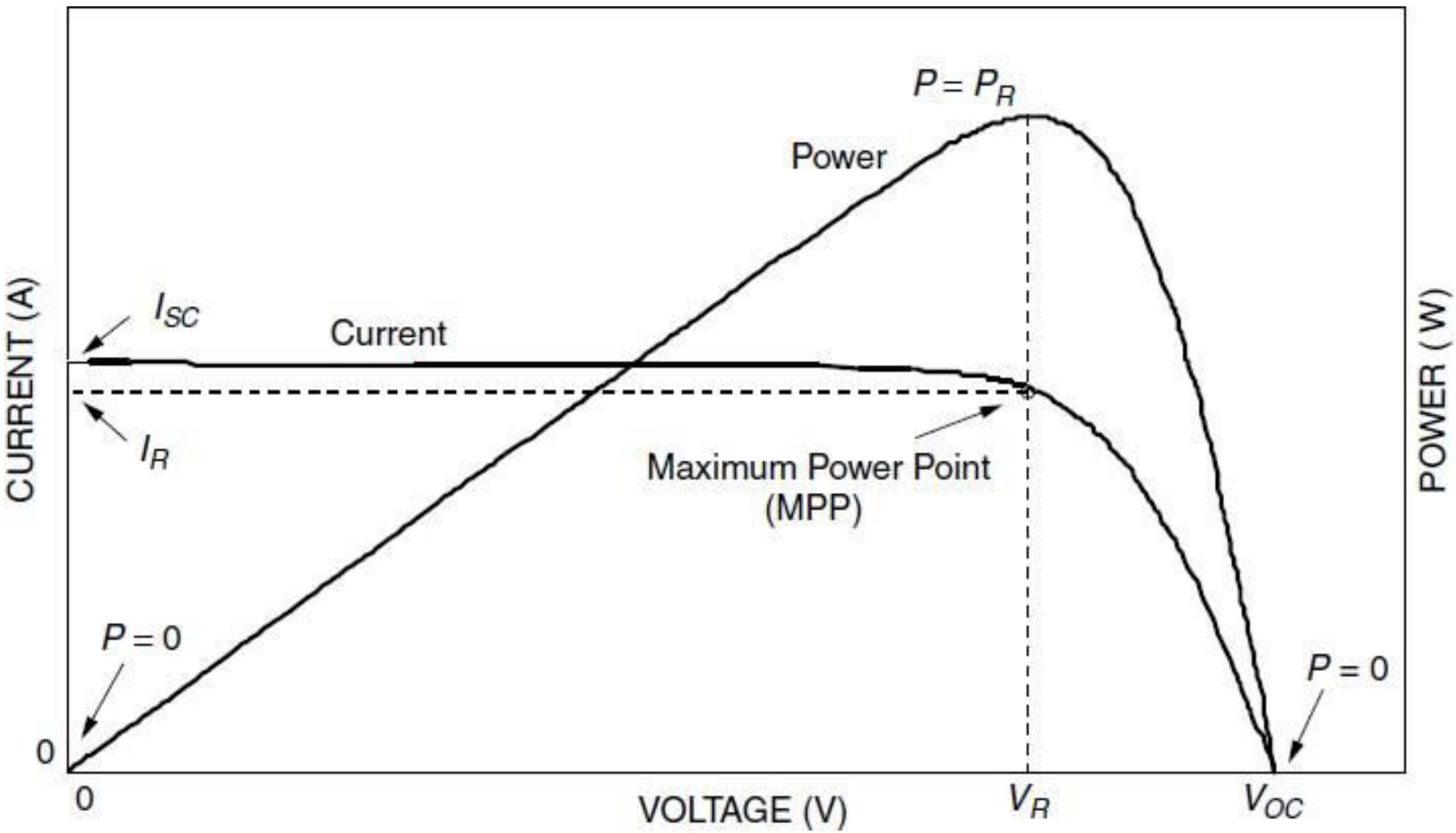
PV: The PV I-V Curve Under Standard Test (Continued)



PV: The PV I-V Curve Under Standard Test (Continued)

- **Figure on next slide shows a generic I –V curve for a PV module, identifying several key parameters including the open-circuit voltage V_{oc} and the short-circuit current I_{sc}. Also shown is the product of voltage and current, that is, power delivered by the module.**
- **At the two ends of the I –V curve, the output power is zero since either current or voltage is zero at those points. The maximum power point (MPP) is that spot near the knee of the I –V curve at which the product of current and voltage reaches its maximum.**
- **The voltage and current at the MPP are sometimes designated as V_m and I_m for the general case and designated V_R and I_R (for rated voltage and rated current) under the special circumstances that correspond to idealized test conditions.**

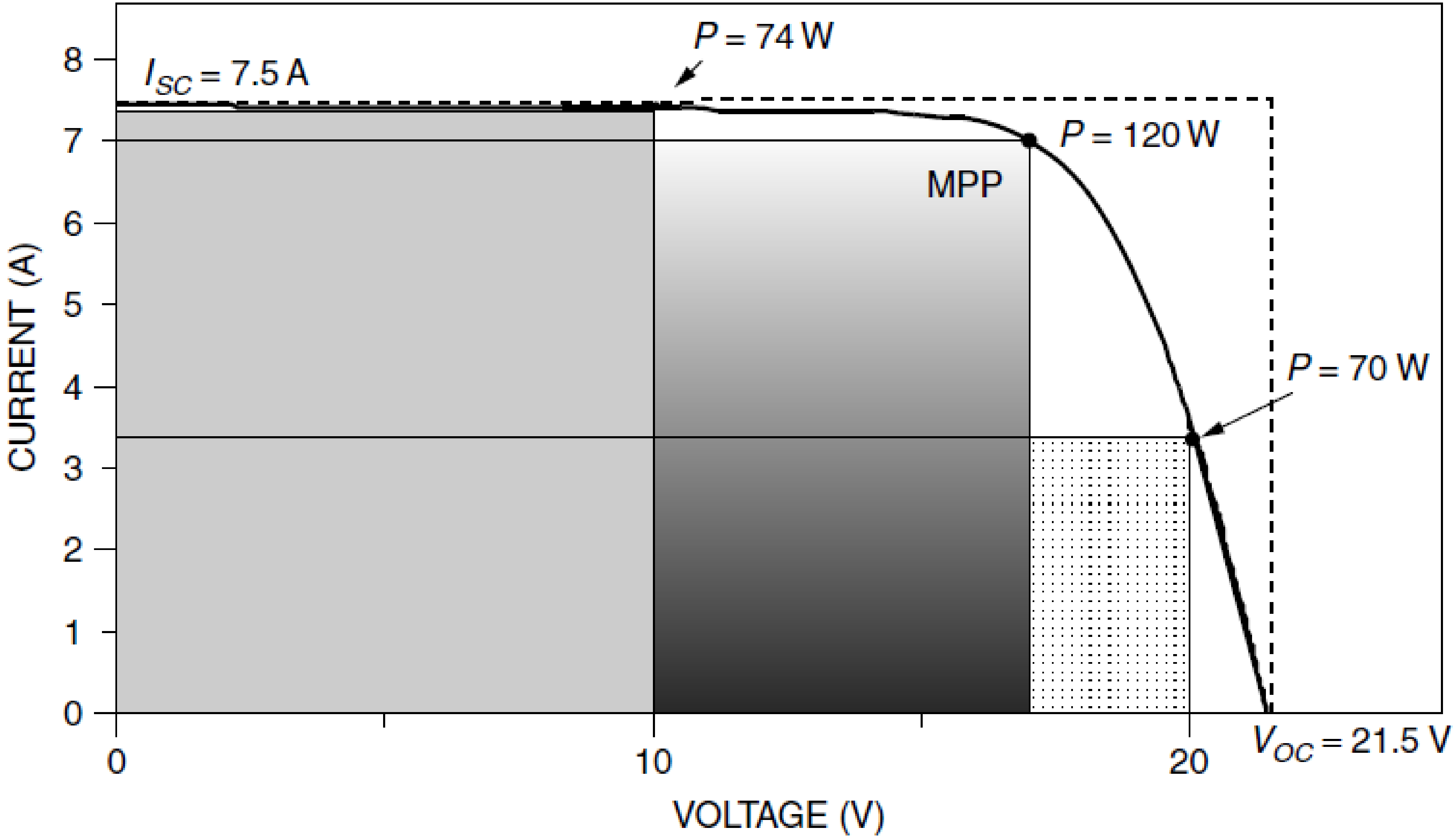
PV: The PV I-V Curve Under Standard Test (Continued)



PV: The PV I-V Curve Under Standard Test (Continued)

- **Another way to visualize the location of the maximum power point is by imagining trying to find the biggest possible rectangle that will fit beneath the I –V curve. As shown in Figure on next slide, the sides of the rectangle correspond to current and voltage, so its area is power.**
- **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 is suggested in Figure. Fill factors around 70–75% for crystalline silicon solar modules are typical, while for multijunction amorphous-Si modules, it is closer to 50–60%.**

PV: The PV I-V Curve Under Standard Test (Continued)



- **Since PV I –V curves shift all around as the amount of insolation changes and as the temperature of the cells varies, standard test conditions (STC) have been established to enable fair comparisons of one module to another. Those test conditions include a solar irradiance of 1 kW/m^2 (1 sun) with spectral distribution, corresponding to an air mass ratio of 1.5 (AM 1.5). The standard cell temperature for testing purposes is 25◦C.**
- **Manufacturers always provide performance data under these operating conditions, some examples of which are shown in Table on next slide. The key parameter for a module is its rated power; to help us remember that it is dc power measured under standard test conditions, it has been identified in Table as $P_{DC,STC}$.**

Manufacturer	Kyocera	Sharp	BP	Uni-Solar	Shell
Model	KC-120-1	NE-Q5E2U	2150S	US-64	ST40
Material	Multicrystal	Polycrystal	Monocrystal	Triple junction a-Si	CIS-thin film
Number of cells n	36	72	72		42
Rated Power $P_{DC,STC}$ (W)	120	165	150	64	40
Voltage at max power (V)	16.9	34.6	34	16.5	16.6
Current at rated power (A)	7.1	4.77	4.45	3.88	2.41
Open-circuit voltage V_{OC} (V)	21.5	43.1	42.8	23.8	23.3
Short-circuit current I_{SC} (A)	7.45	5.46	4.75	4.80	2.68
Length (mm/in.)	1425/56.1	1575/62.05	1587/62.5	1366/53.78	1293/50.9
Width (mm/in.)	652/25.7	826/32.44	790/31.1	741/29.18	329/12.9
Depth (mm/in.)	52/2.0	46/1.81	50/1.97	31.8/1.25	54/2.1
Weight (kg/lb)	11.9/26.3	17/37.5	15.4/34	9.2/20.2	14.8/32.6
Module efficiency	12.9%	12.7%	12.0%	6.3%	9.4%

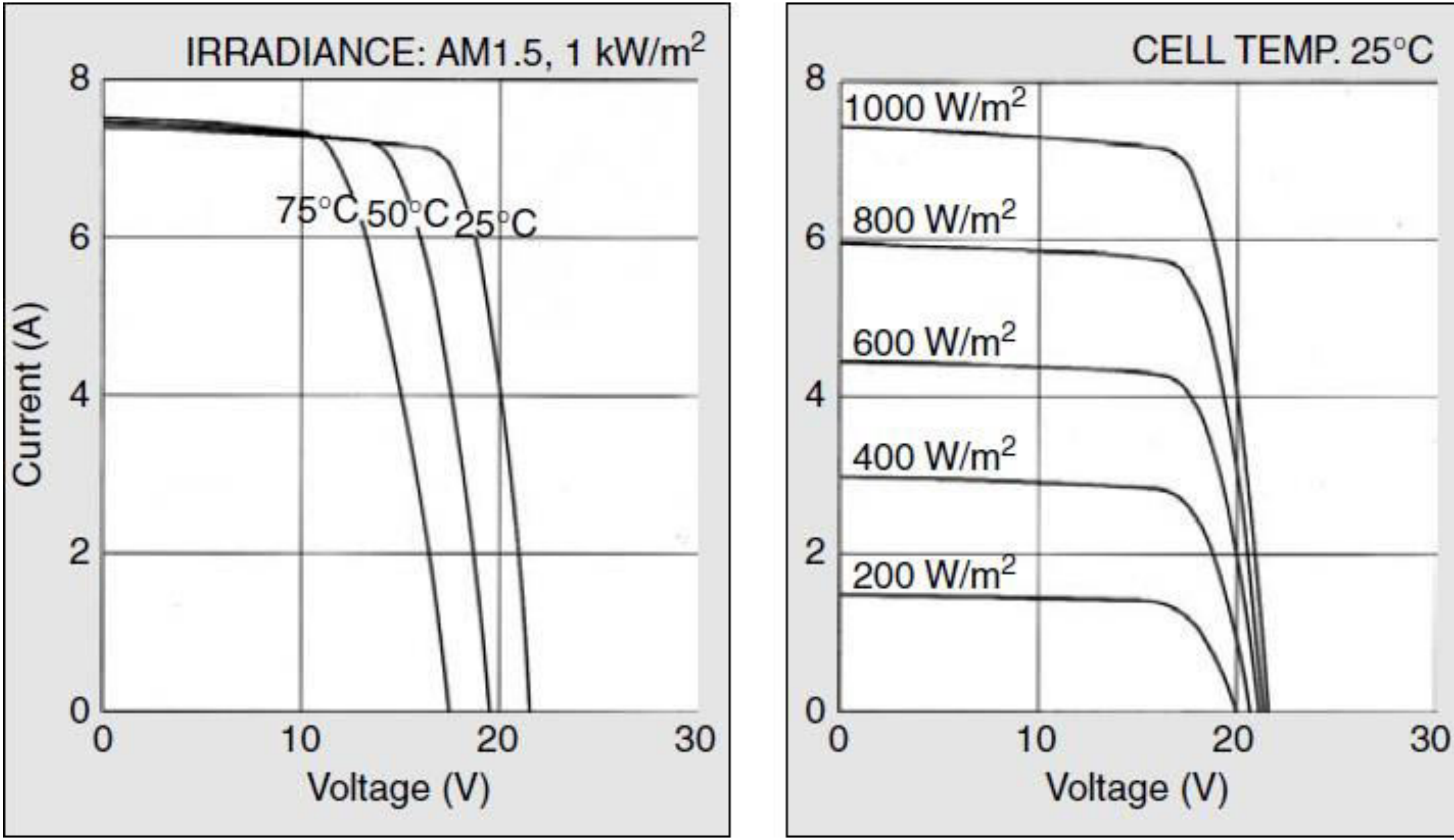
PV: Impacts of Temperature and Insolation on I-V Curves

- Manufacturers will often provide I –V curves that show how the curves shift as insolation and cell temperature changes. Figure on next slide shows examples for the Kyocera 120-W multicrystal-silicon module described in Table which is shown on previous slide. Notice as insolation drops, short-circuit current drops in direct proportion. Cutting insolation in half, for example, drops I_{sc} by half.

insolation: the amount of solar radiation reaching a given area.

- Decreasing insolation also reduces V_{oc}, but it does so following a logarithmic relationship that results in relatively modest changes in V_{oc}.

PV: Impacts of Temperature and Insolation on I-V (Cont)



PV: Impacts of Temperature and Insolation on I-V (Cont)

- **As can be seen in Figure on previous slide, as cell temperature increases, the open-circuit voltage decreases substantially while the short-circuit current increases only slightly. Photovoltaics, perhaps surprisingly, therefore perform better on cold, clear days than hot ones.**
- **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%. The net result when cells heat up is the MPP slides slightly upward and toward the left with a decrease in maximum power available of about 0.5%/◦C.** It depends on each cell.
- **Given this significant shift in performance as cell temperature changes, it should be quite apparent that temperature needs to be included in any estimate of module performance.**

PV: Impacts of Temperature and Insolation on I-V (Cont)

Room temperature

- **Cells vary in temperature not only because ambient temperatures change, but also because insolation on the cells changes. Since only a small fraction of the insolation hitting a module is converted to electricity and carried away, most of that incident energy is absorbed and converted to heat.**

- **To help system designers account for changes in cell performance with temperature, manufacturers often provide an indicator called the NOCT, which stands for nominal operating cell temperature. The NOCT is cell temperature in a module when ambient is 20◦C, solar irradiation is 0.8 kW/m^2, and windspeed is 1 m/s. To account for other ambient conditions, the following expression may be used, where T_{cell} is cell temperature (◦C), T_{amb} is ambient temperature, and S is solar insolation (kW/m^2).**

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

- 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 windspeed 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◦C hotter than their environment.

PV: Shading Impacts on I-V Curves

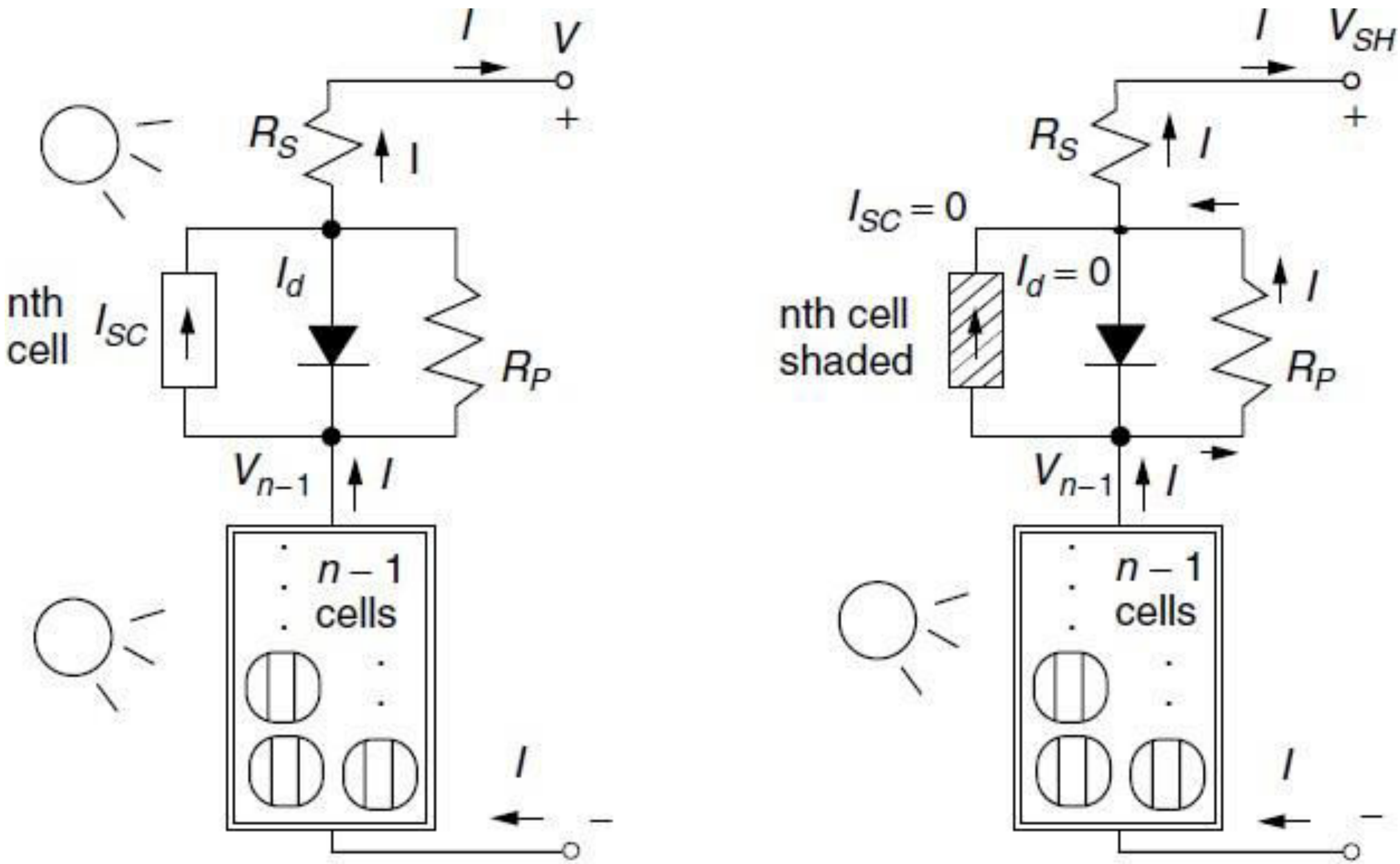
- The output of a PV module can be reduced dramatically when even a small portion of it is shaded. Unless special efforts are made to compensate for shade problems, even a single shaded cell in a long string of cells can easily cut output power by more than half.

- External diodes, purposely added by the PV manufacturer or by the system designer, can help preserve the performance of PV modules. The main purpose for such diodes is to mitigate the impacts of shading on PV I –V curves. Such diodes are usually added in parallel with modules or blocks of cells within a module.

PV: Physics of Shading

- To help understand this important shading phenomenon, consider Figure on next slide in which an n-cell module with current I and output voltage V shows one cell separated from the others (shown as the top cell, though it can be any cell in the string). The equivalent circuit of the top cell has been drawn using complete model of PV cell, while the other (n – 1) cells in the string are shown as just a module with current I and output voltage V_{n-1}.
- In Figure (a), all of the cells are in the sun and since they are in series, the same current I flows through each of them. In Figure (b), however, the top cell is shaded and its current source I_{sc} has been reduced to zero. The voltage drop across R_p as current flows through it causes the diode to be reverse biased, so the diode current is also (essentially) zero. That means the entire current flowing through the module must travel through both R_p and R_s in the shaded cell on its way to the load. That means the top cell, instead of adding to the output voltage, actually reduces it.

PV: Physics of Shading (Continued)



(a) All cells in the sun (b) Top cell shaded

PV: Physics of Shading (Continued)

- Consider the case when the bottom n – 1 cells still have full sun and still some how carry their original current I so they will still produce their original voltage V_{n-1}. This means that the output voltage of the entire module V_{SH} with one cell shaded will drop to

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

- With all n cells in the sun and carrying *I* , the output voltage was V so the voltage of the bottom n – 1 cells will be

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

- Combining both equations gives

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

PV: Physics of Shading (Continued)

- The **drop in voltage ΔV at any given current I , caused by the shaded cell, is given by**

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

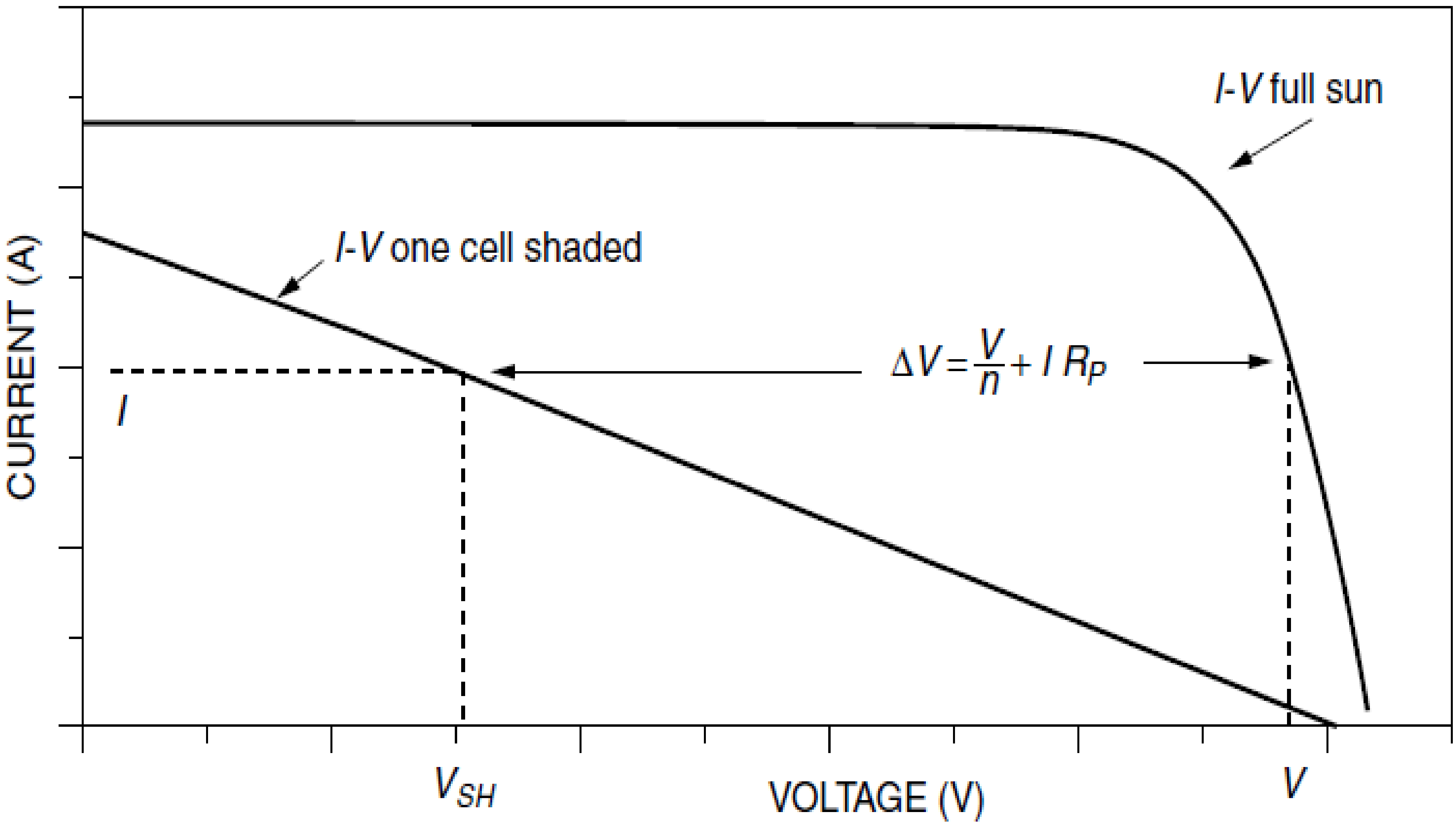
$$\Delta V = \frac{V}{n} + I\,(R_P + R_S)$$

- **Since the parallel resistance R_p is so much greater than the series resistance R_s , the equation simplifies to**

$$\Delta V \cong \frac{V}{n} + I\,R_P$$

- **At any given current, the I –V curve for the module with one shaded cell drops by ΔV. The huge impact this can have is illustrated in Figure on next slide.**

PV: Physics of Shading (Continued)



PV: Problem.No.1

- **The 36-cell PV module had a parallel resistance per cell of R_p = 6.6 Ω and series resistance of $R_s = 0.005\ \Omega$. In full sun and at current I = 2.14 A the output voltage was found there to be V = 19.41 V. If one cell is shaded and this current somehow stays the same, then:**

a. What would be the new module output voltage and power?

b. What would be the voltage drop across the shaded cell?

c. How much power would be dissipated in the shaded cell?

Problem in Example 5.6 in book

PV: Solution of Problem.No.1

$$\Delta V = \frac{V}{n} + IR_P = \frac{19.41}{36} + 2.14 \times 6.6 = 14.66 \text{ V}$$

$19.41 - 14.66 = 4.75$ V.

41.5 W.

$$P_{\text{module}} = VI = 4.75 \text{ V} \times 2.14 \text{ A} = 10.1 \text{ W}$$

All of that 2.14 A of current goes through the parallel plus series resistance (0.005 Ω) of the shaded cell, so the drop across the shaded cell will be

$$V_c = I(R_P + R_S) = 2.14(6.6 + 0.005) = 14.14 \ V$$

(normally a cell in the sun will add about 0.5 V to the module; this shaded cell subtracts over 14 V from the module).

The power dissipated in the shaded cell is voltage drop times current, which is

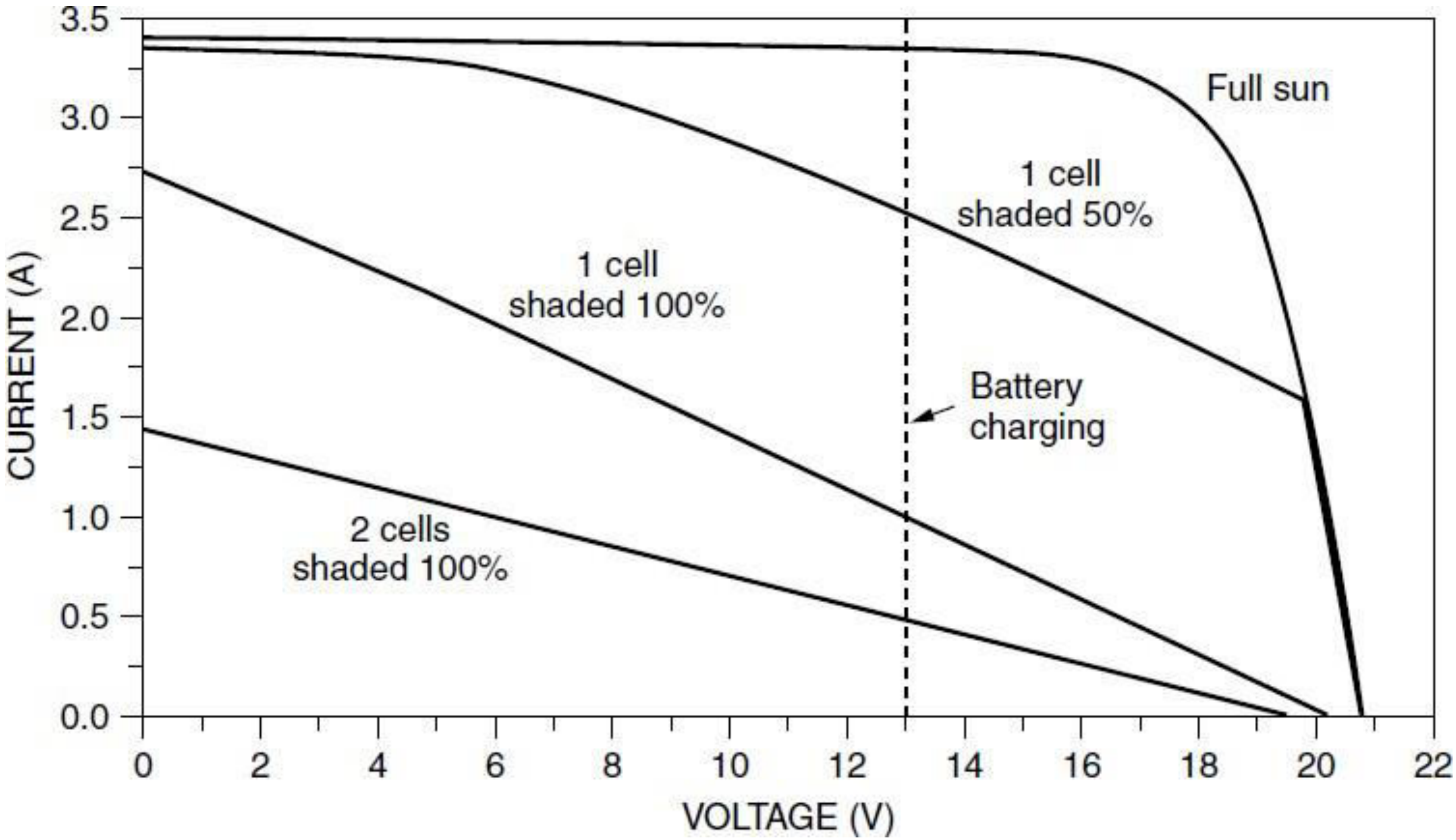
$$P = V_c I = 14.14 \text{ V} \times 2.14 \text{ A} = 30.2 \text{ W}$$

All of that power dissipated in the shaded cell is converted to heat, which can cause a local hot spot that may permanently damage the plastic laminates enclosing the cell.

PV: Physics of Shading (Continued)

- **To develop I –V curves under various conditions of shading. Figure on the next slide shows such curves for the example module under full-sun conditions and with one cell 50% shaded, one cell completely shaded, and two cells completely shaded.**
- **Also shown on the graph is a dashed vertical line at 13 V, which is a typical operating voltage for a module charging a 12-V battery. The reduction in charging current for even modest amounts of shading is severe. With just one cell shaded out of 36 in the module, the power delivered to the battery is decreased by about two-thirds.**

PV: Physics of Shading (Continued)

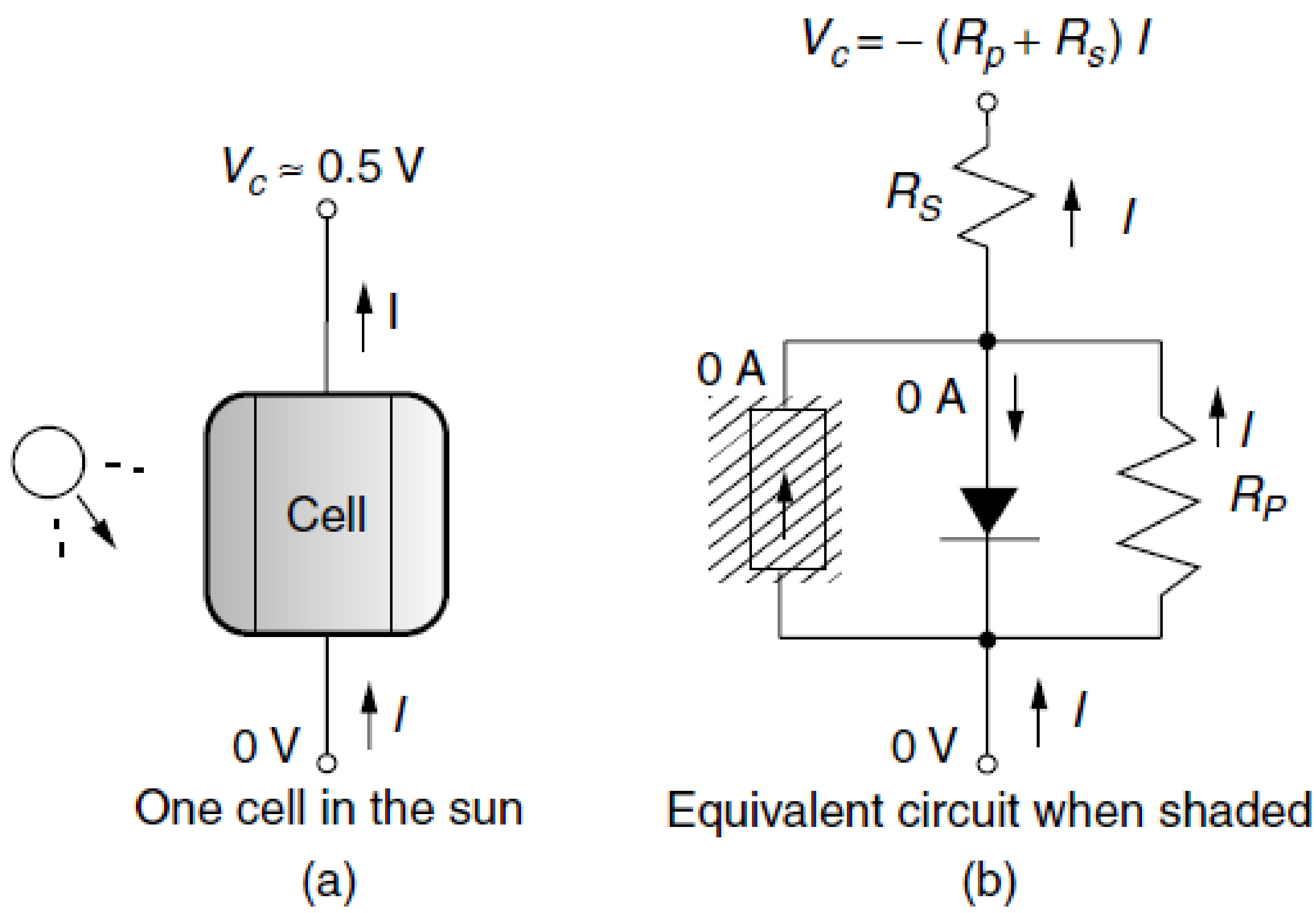


PV: Bypass Diodes for Shade Mitigation

- **So far, we know how drastically shading can shift the I –V curve, but also how local, potentially damaging hot spots can be created in shaded cells. Figure on next slide shows a typical situation.**

- **In Figure (a), a solar cell in full sun operating in its normal range contributes about 0.5 V to the voltage output of the module, but in the equivalent circuit shown in Figure (b), a shaded cell experiences a drop as current is diverted through the parallel and series resistances.**

PV: Bypass Diodes for Shade Mitigation (Continued)

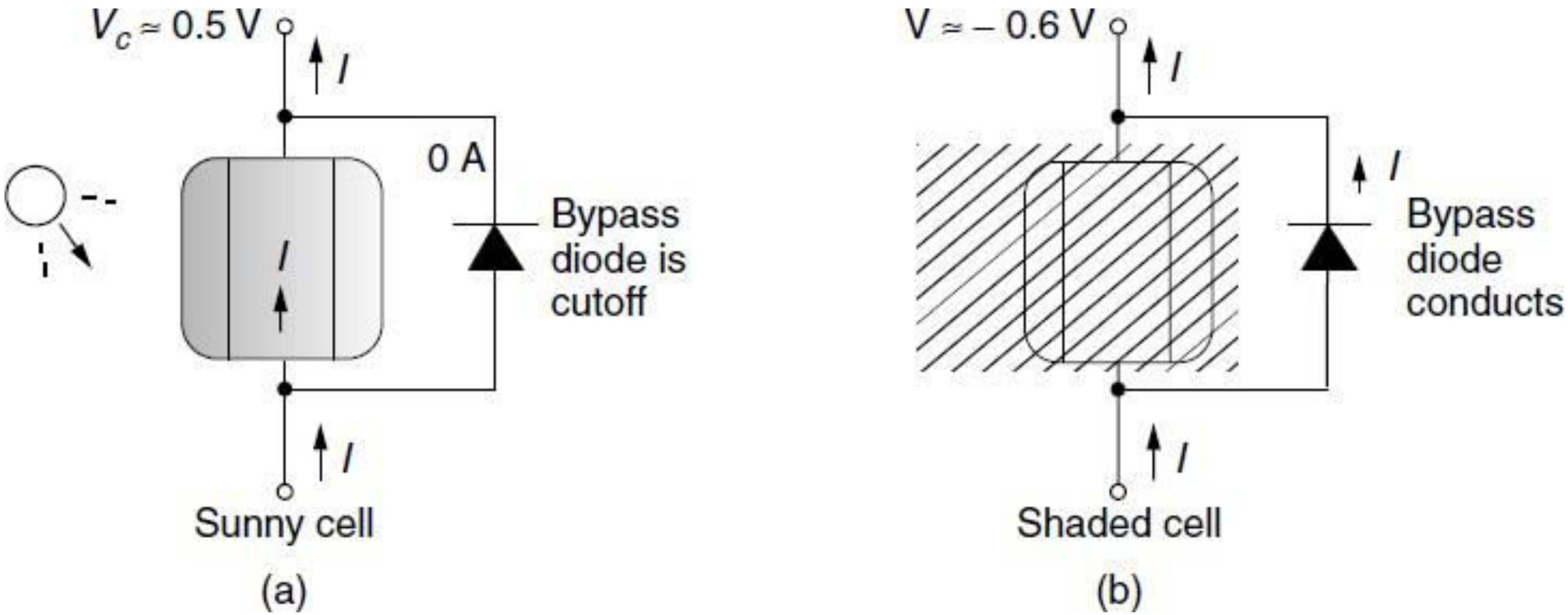


PV: Bypass Diodes for Shade Mitigation (Continued)

- **The voltage drop problem in shaded cells could be corrected by adding a bypass diode across each cell, as shown in Figure on next slide. When a solar cell is in the sun, there is a voltage rise across the cell so the bypass diode is cut off and no current flows through it—it is as if the diode is not even there.**

- **When the solar cell is shaded, however, the drop that would occur if the cell conducted any current would turn on the bypass diode, diverting the current flow through that diode. The bypass diode, when it conducts, drops about 0.6 V. So, the bypass diode controls the voltage drop across the shaded cell, limiting it to a relatively modest 0.6 V instead of the rather large drop that may occur without it.**

PV: Bypass Diodes for Shade Mitigation (Continued)



PV: Bypass Diodes for Shade Mitigation (Continued)

- **In real modules, it would be impractical to add bypass diodes across every solar cell, but manufacturers often do provide at least one bypass diode around a module to help protect arrays, and sometimes several such diodes around groups of cells within a module.**

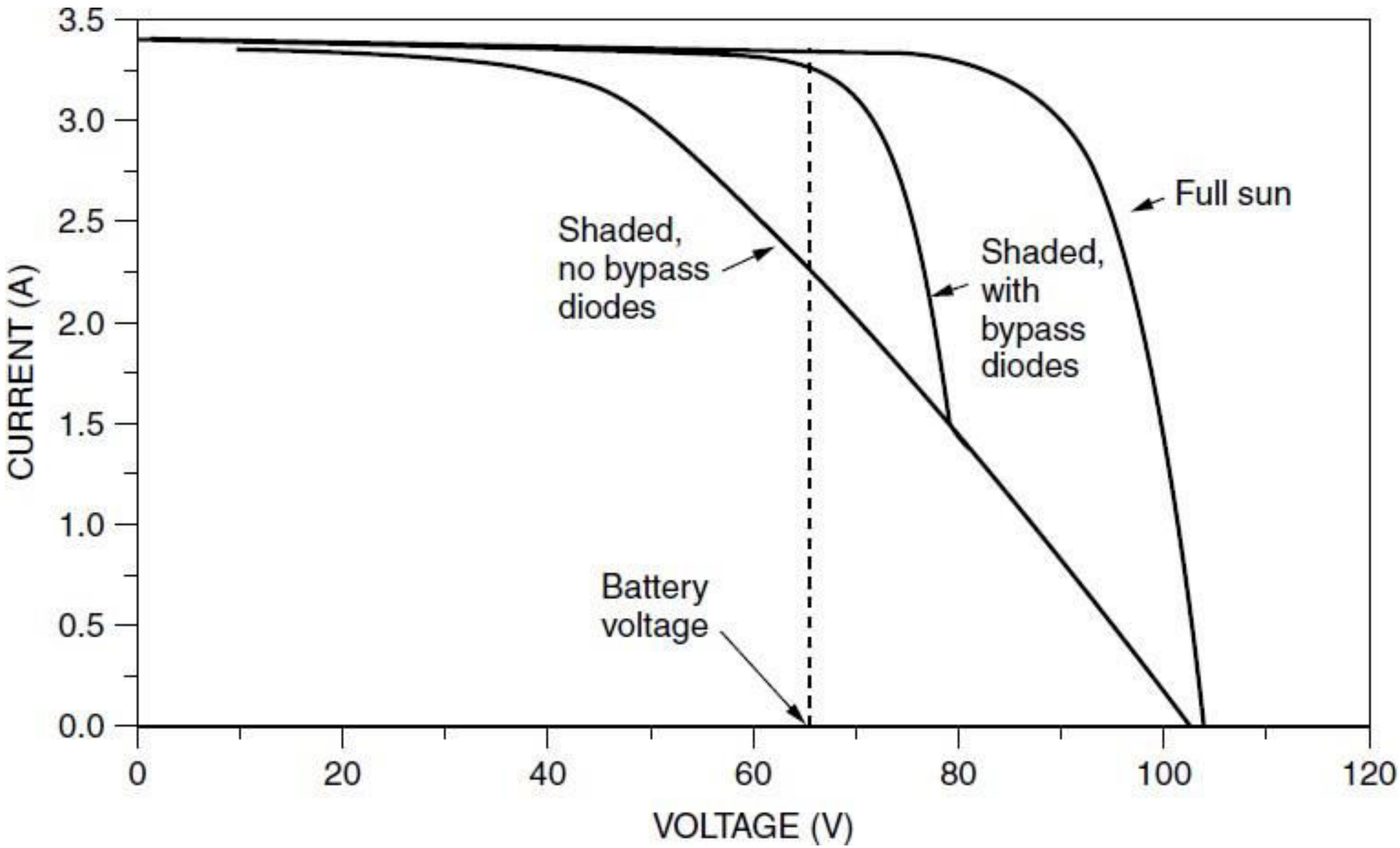
- **These diodes don't have much impact on shading problems of a single module, but they can be very important when a number of modules are connected in series. Just as cells are wired in series to increase module voltage, modules can be wired in series to increase array voltage.**

- **Also, just as a single cell can drag down the current within a module, a few shaded cells in a single module can drag down the current delivered by the entire string in an array. The benefit already demonstrated for a bypass diode on a single cell also applies to a diode applied across a complete module.**

PV: Bypass Diodes for Shade Mitigation (Continued)

- **To see how bypass diodes wired in parallel with modules can help mitigate shading problems, consider Figure on next slide, which shows I –V curves for a string of five modules.**
- **The graph shows the modules in full sun as well as the I –V curve that results when one module has two cells completely shaded. Imagine the PVs delivering charging current at about 65 V to a 60-V battery bank.**
- **As can be seen, in full sun about 3.3 A are delivered to the batteries. However, when just two cells in one module are shaded, the current drops by one-third to about 2.2 A. With a bypass diode across the shaded module, however, the I –V curve is improved considerably as shown in the figure.**

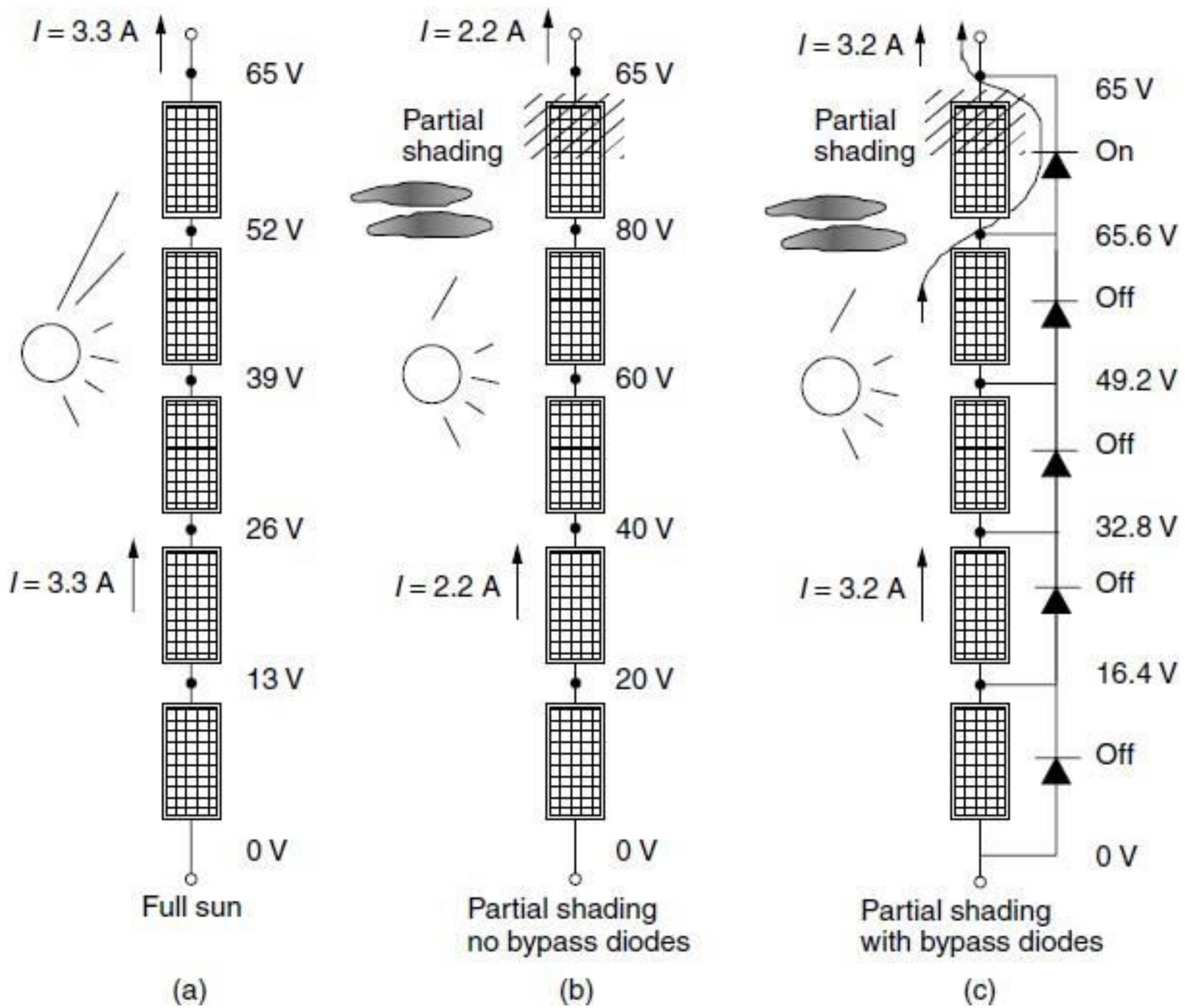
PV: Bypass Diodes for Shade Mitigation (Continued)



PV: Bypass Diodes for Shade Mitigation (Continued)

- Figure on next slide helps explain how the bypass diodes do their job. Imagine five modules, wired in series, connected to a battery that forces the modules to operate at 65 V.
- In full sun the modules deliver 3.3 A at 65 V. When any of the cells are shaded, they cease to produce voltage and instead begin to act like resistors (6.6 Ω per cell in this example) that cause voltage to drop as the other modules continue to try to push current through the string.
- Without a bypass diode to divert the current, the shaded module loses voltage and the other modules try to compensate by increasing voltage, but the net effect is that current in the whole string drops.
- If, however, bypass diodes are provided, as shown in Figure (c), then current will go around the shaded module and the charging current bounces back to nearly the same level that it was before shading occurred.

PV: Bypass Diodes for Shade Mitigation (Continued)



PV: Blocking Diode

- **Bypass diodes help current go around a shaded or malfunctioning module within a string. This not only improves the string performance, but also prevents hot spots from developing in individual shaded cells.**
- **When strings of modules are wired in parallel, a similar problem may arise when one of the strings is not performing well. Instead of supplying current to the array, a malfunctioning or shaded string can withdraw current from the rest of the array.**
- **By placing blocking diodes (also called isolation diodes) at the top of each string as shown in Figure on next slide, the reverse current drawn by a shaded string can be prevented.**

PV: Blocking Diode (Continued)