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

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Lecture-8
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PV: Problem.No.1

- Consider a p–n junction diode at 25◦C with a reverse saturation current of 10^{-9} A. Find the voltage drop across the diode when it is carrying the following:
- a. no current (open-circuit voltage)
- b. 1 A
- c. 10 A

a. In the open-circuit condition, $I_d = 0$, $V_d = 0$.

b. With $I_d = 1$ A, we can find V_d

$$V_d = \frac{1}{38.9} \ln\left(\frac{I_d}{I_0} + 1\right) = \frac{1}{38.9} \ln\left(\frac{1}{10^{-9}} + 1\right) = 0.532 \text{ V}$$

c. with $I_d = 10$ A,

$$V_d = \frac{1}{38.9} \ln\left(\frac{10}{10^{-9}} + 1\right) = 0.592 \text{ V}$$

PV: Ideality factor

- **The Shockley diode equation $I_d = I_o(e^{qV_d/kT} - 1)$ is appropriate for our purposes, it should be noted that in some circumstances it is modified with an "ideality factor" A, which accounts for different mechanisms responsible for moving carriers across the junction.**
- **The resulting equation is then, $I_d = I_o(e^{qV_d/AkT} - 1)$**
- **where the ideality factor A is 1 if the transport process is purely diffusion, and A ≈ 2 if it is primarily recombination in the depletion region.**

PV: Problem.No.2

- **Consider a 100-cm^2 photovoltaic cell with reverse saturation current I_o = 10^{-12} A/cm^2. In full sun, it produces a short-circuit current of 40 mA/cm^2 at 25◦C. Find the open-circuit voltage at full sun and again for 50% sunlight. Plot the results.**

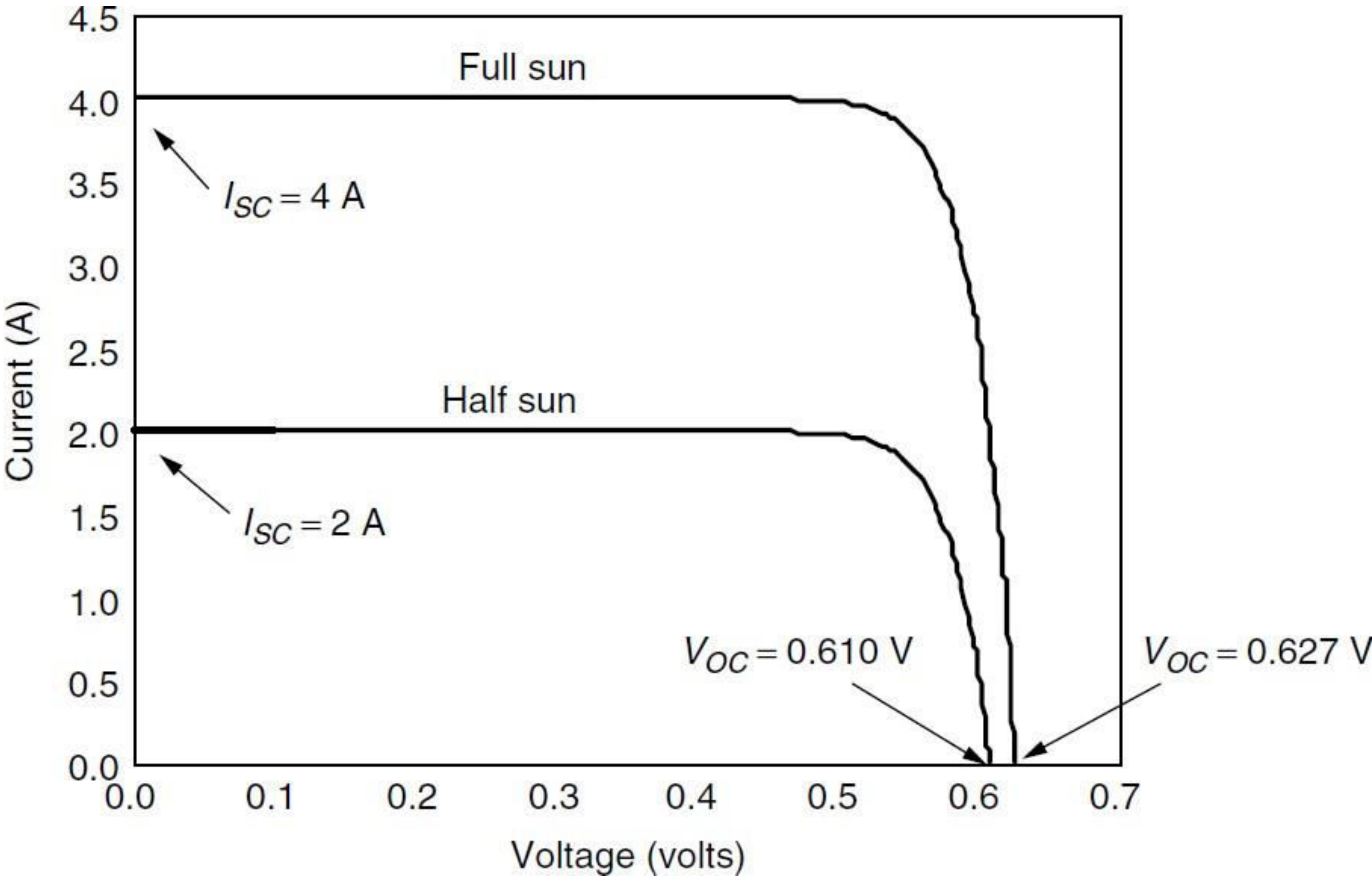
The reverse saturation current I_0 is 10^{-12} A/cm^2 $\times$ 100 cm^2 $=$ 1 $\times$ 10^{-10} A. At full sun I_{SC} is 0.040 A/cm^2 $\times$ 100 cm^2 $=$ 4.0 A.

$$V_{OC} = 0.0257\ \ln\left(\frac{I_{SC}}{I_0} + 1\right) = 0.0257 \ln\left(\frac{4.0}{10^{-10}} + 1\right) = 0.627\ \text{V}$$

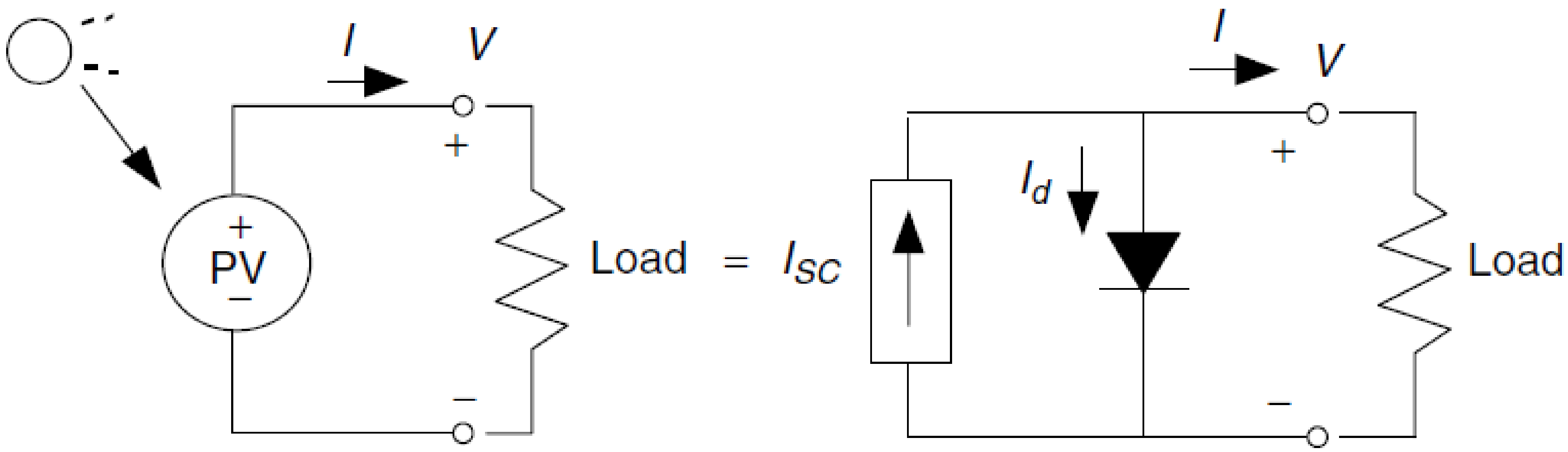
Since short-circuit current is proportional to solar intensity, at half sun $I_{SC} = 2$ A and the open-circuit voltage is

$$V_{OC} = 0.0257 \ln\left(\frac{2}{10^{-10}} + 1\right) = 0.610\ \text{V}$$

PV: Problem.No.2



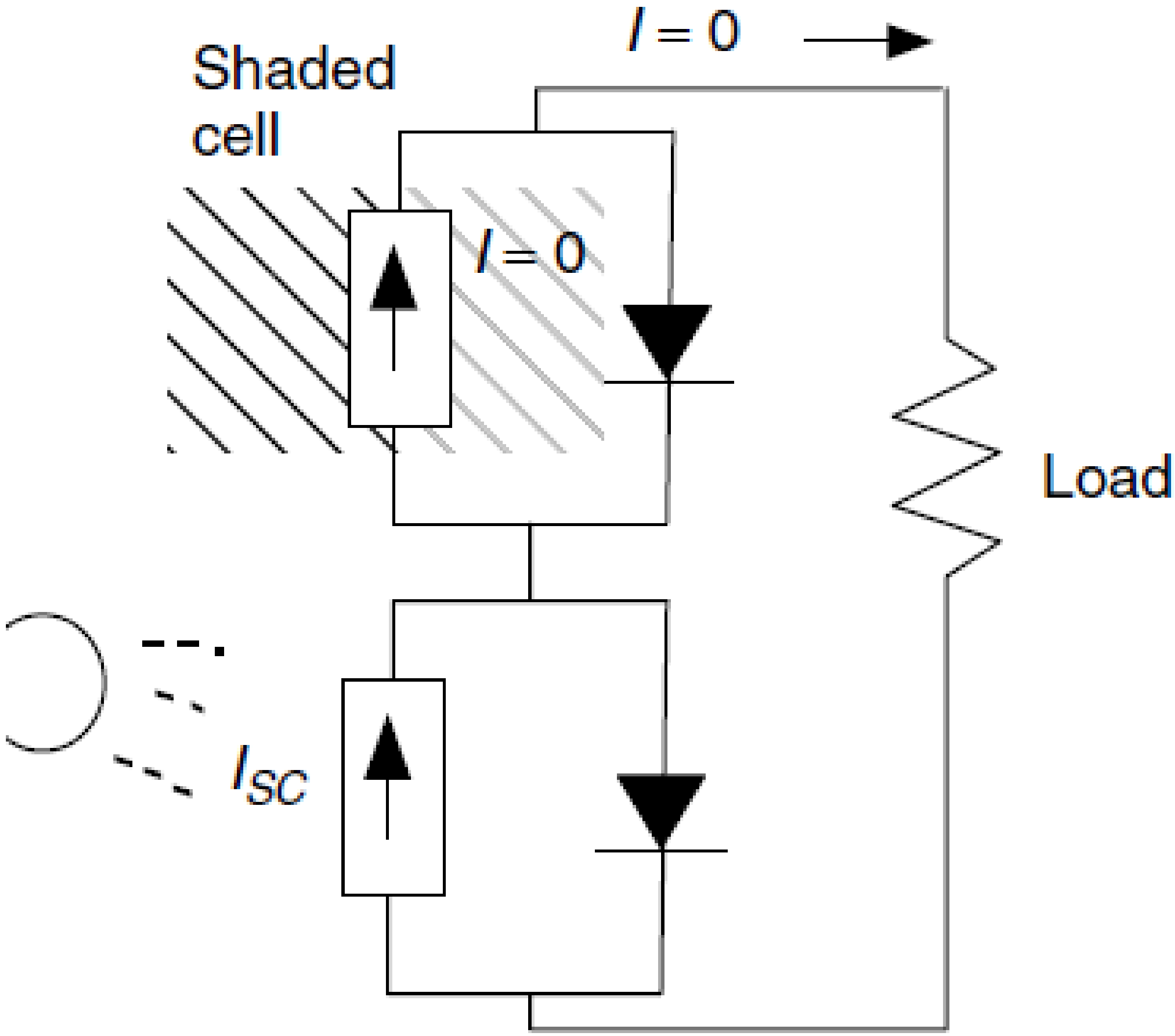
- **A simple equivalent circuit model for a photovoltaic cell consists of a real diode in parallel with an ideal current source as shown in Fig. The ideal current source delivers current in proportion to the solar flux to which it is exposed.**



PV: A More Accurate Equivalent Circuit for a PV Cell

- **Consider the impact of shading on a string of cells wired in series (Fig. on the next slide two such cells).**
- **If any cell in the string is in the dark (shaded), it produces no current. In our simplified equivalent circuit for the shaded cell, the current through that cell's current source is zero and its diode is back biased so it doesn't pass any current either (other than a tiny amount of reverse saturation current).**
- **This means that the simple equivalent circuit suggests that no power will be delivered to a load if any of its cells are shaded. While it is true that PV modules are very sensitive to shading, the situation is not quite as bad as that.**

PV: A More Accurate Equivalent Circuit (Continued)

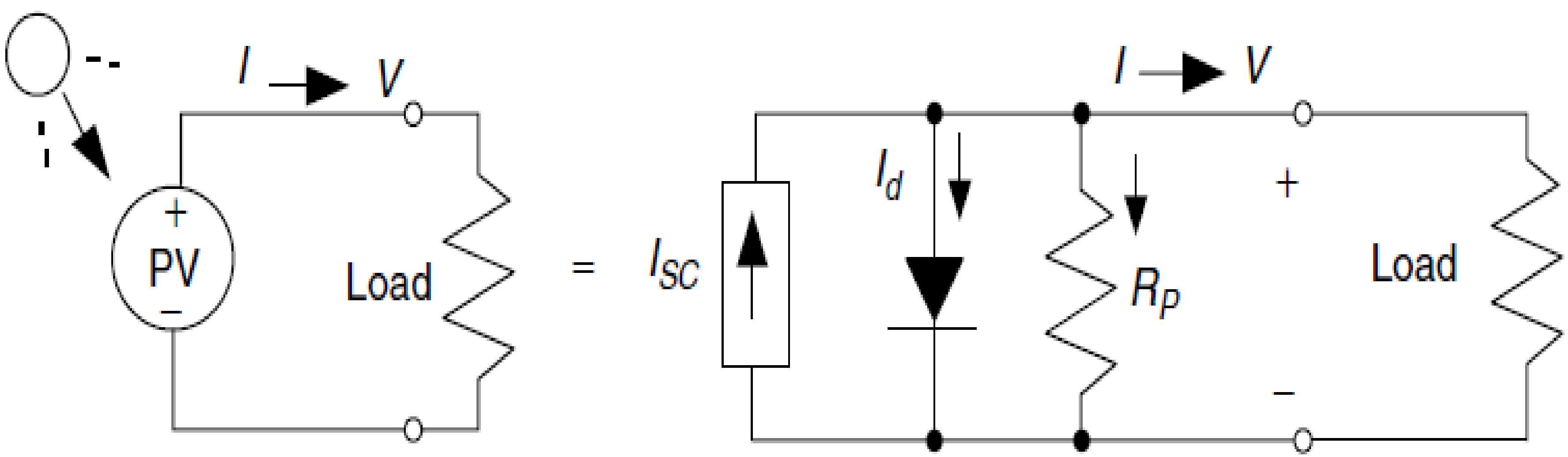


PV: A More Accurate Equivalent Circuit (Continued)

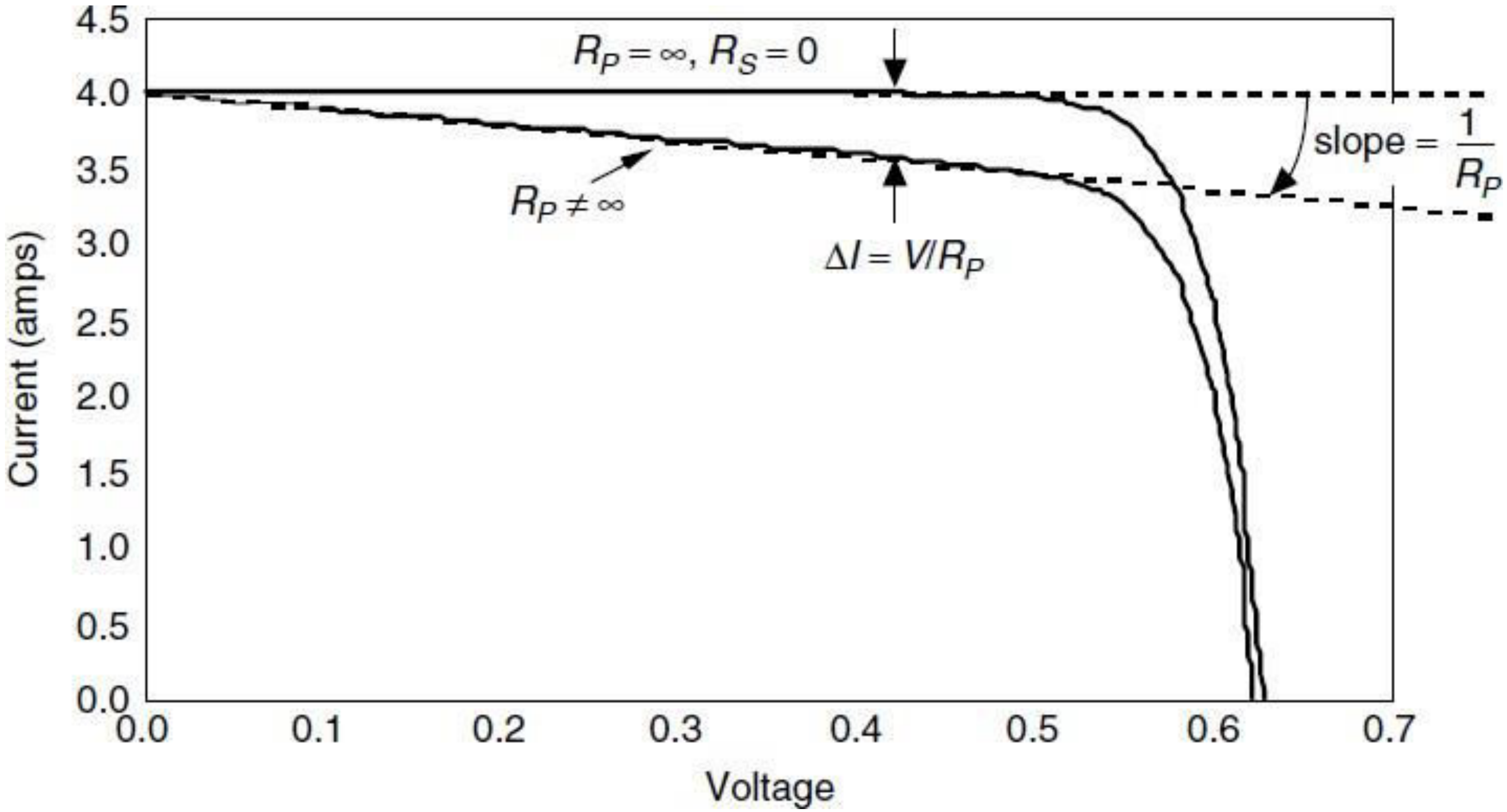
- So, we need a more complex model if we are going to be able to deal with realities such as the shading problem.
- Figure on next slide shows a PV equivalent circuit that includes some parallel leakage resistance R_p. The ideal current source I_{sc} in this case delivers current to the diode, the parallel resistance, and the load.
- The term in the parentheses of equation which is given below, it is the same current that we had for the simple model.

$$I = (I_{SC} - I_d) - \frac{V}{R_p}$$

PV: A More Accurate Equivalent Circuit (Continued)



- **So, what the equation tells us is that at any given voltage, the parallel leakage resistance causes load current for the ideal model to be decreased by V/R_p as is shown in Fig.**



PV: A More Accurate Equivalent Circuit (Continued)

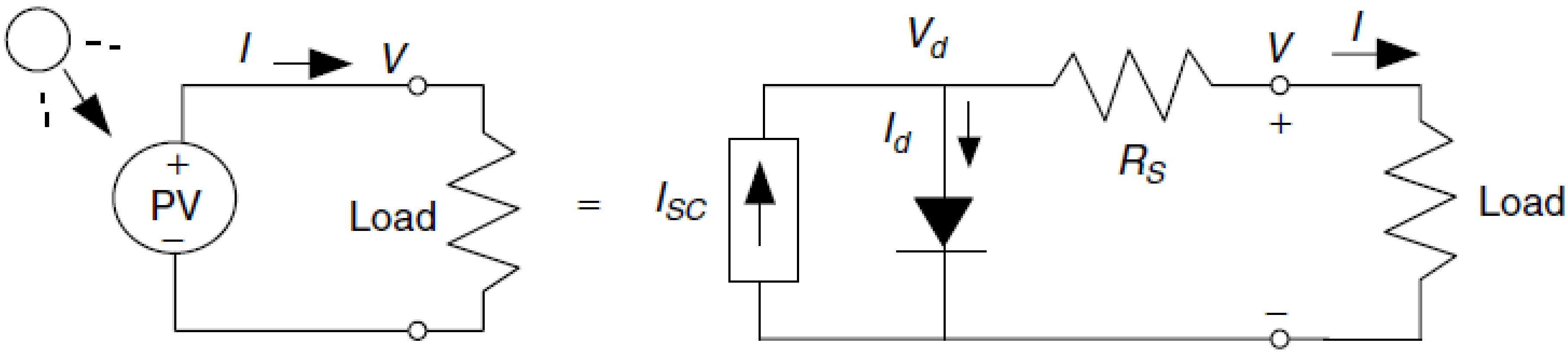
- **For a cell to have losses of less than 1% due to its parallel resistance, R_p should be greater than about**
- $$R_p > \frac{100V_{oc}}{I_{sc}}$$

In book it is 6A and resistance is 10 ohm.

- **For a large cell, I_{sc} might be around 6.5 A and V_{oc} might be about 0.6 V, which says its parallel resistance should be greater than about 9 Ω.**
- **An even better equivalent circuit will include series resistance as well as parallel resistance. Before we can develop that model, consider a figure in which the original PV equivalent circuit has been modified to just include some series resistance, R_s . Some of this might be contact resistance associated with the bond between the cell and its wire leads, and some might be due to the resistance of the semiconductor itself.**

PV: A More Accurate Equivalent Circuit (Continued)

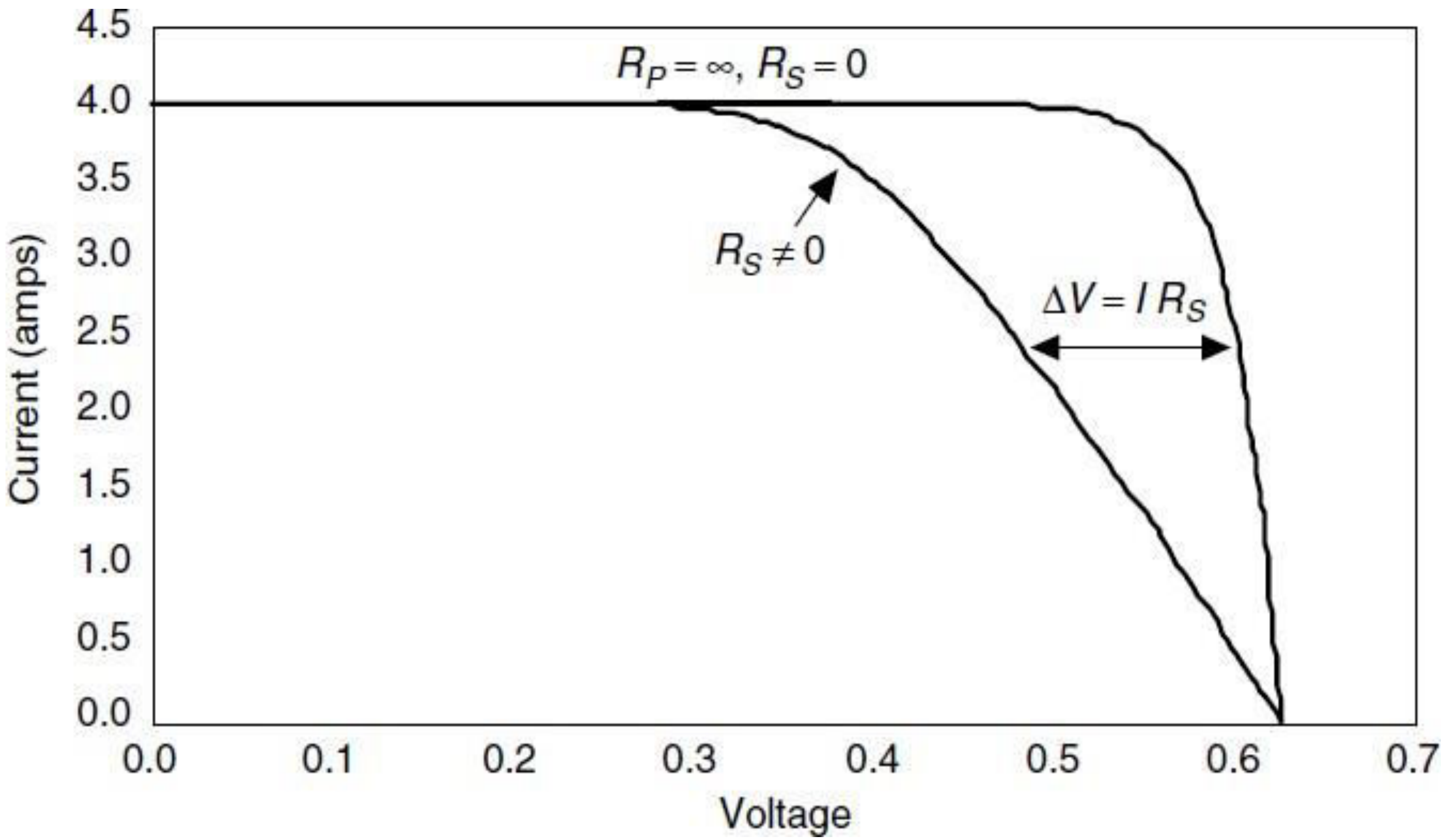
How does series resistance affect the conversion efficiency of a photovoltaic cell?
Increasing the shunt resistance (Rsh) and decreasing the series resistance (Rs) lead to a higher fill factor, thus resulting in greater efficiency, and bringing the cell's output power closer to its theoretical maximum. Typical fill factors range from 50% to 82%. The fill factor for a normal silicon PV cell is 80%.



The main impact of series resistance is to reduce the fill factor, although excessively high values may also reduce the short-circuit current.

$$I = I_{SC} - I_0 \left\{ \exp\left[\frac{q(V + I \cdot R_S)}{kT} \right] - 1 \right\}$$

PV: A More Accurate Equivalent Circuit (Continued)



PV: A More Accurate Equivalent Circuit (Continued)

- **For a cell to have less than 1% losses due to the series resistance, R_s will need to be less than about**

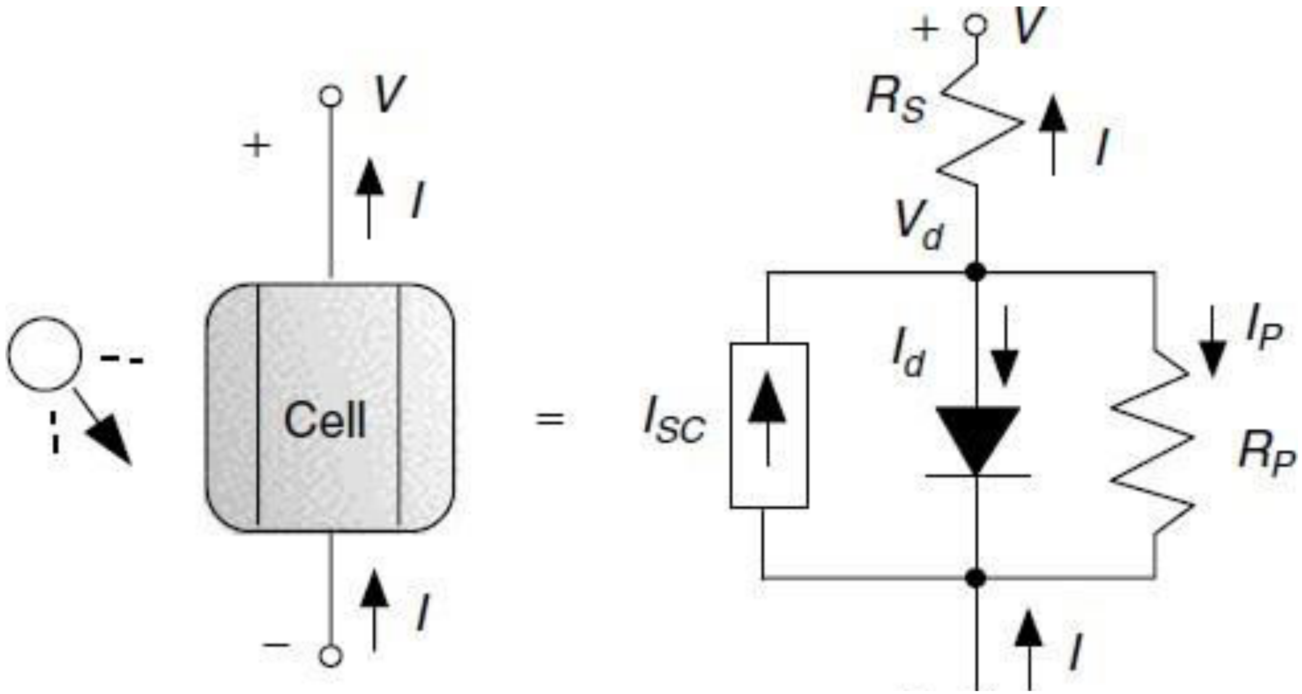
$$R_s < \frac{0.01\, V_{oc}}{I_{sc}}$$

- **which, for a large cell with I_{sc} = 6.5 A and V_{oc} = 0.6 V, would be less than 0.0010 Ω.**

- **Finally, let us generalize the PV equivalent circuit by including both series and parallel resistances as shown in Figure on next slide. We can write the following equation for current and voltage:**

$$I = I_{SC} - I_0 \left\{ \exp\left[\frac{q(V + I \cdot R_S)}{kT} \right] - 1 \right\} - \left(\frac{V + I \cdot R_S}{R_P} \right)$$

PV: A More Accurate Equivalent Circuit (Continued)



$$I = I_{SC} - I_0 \left\{ \exp\left[\frac{q(V + I \cdot R_S)}{kT} \right] - 1 \right\} - \left(\frac{V + I \cdot R_S}{R_P} \right)$$

$$I = I_{SC} - I_0 \left[e^{38.9(V + I R_S)} - 1 \right] - \frac{1}{R_P}(V + I R_S)$$

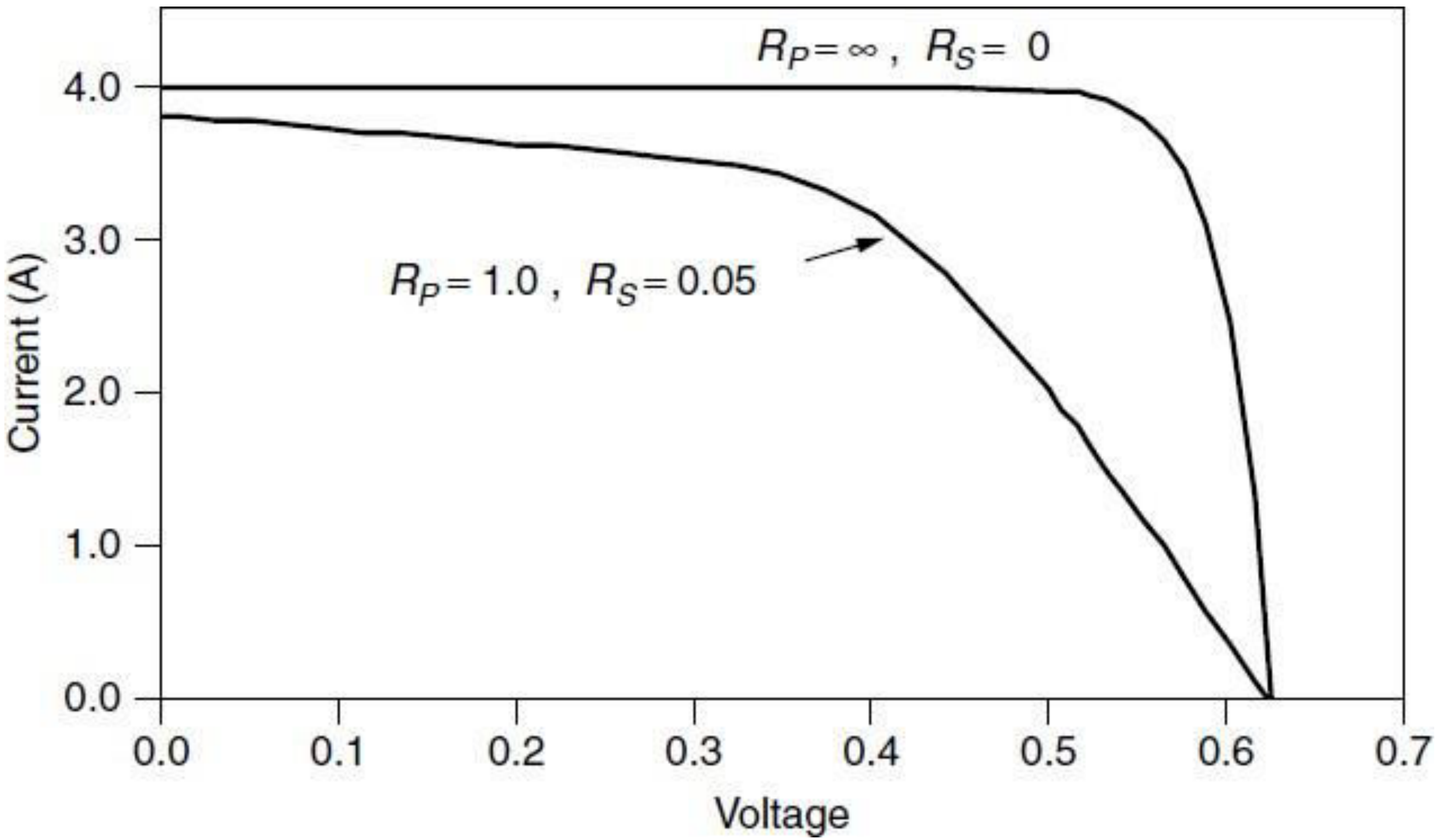
- **Unfortunately, the last equation is a complex equation for which there is no explicit solution for either voltage V or current I .**

$$I_{SC} = I + I_d + I_P$$

$$I = I_{SC} - \mathrm{I}_0(e^{38.9V_d} - 1) - \frac{V_d}{R_P}$$

$$V = V_d - I R_S$$

PV: A More Accurate Equivalent Circuit (Continued)



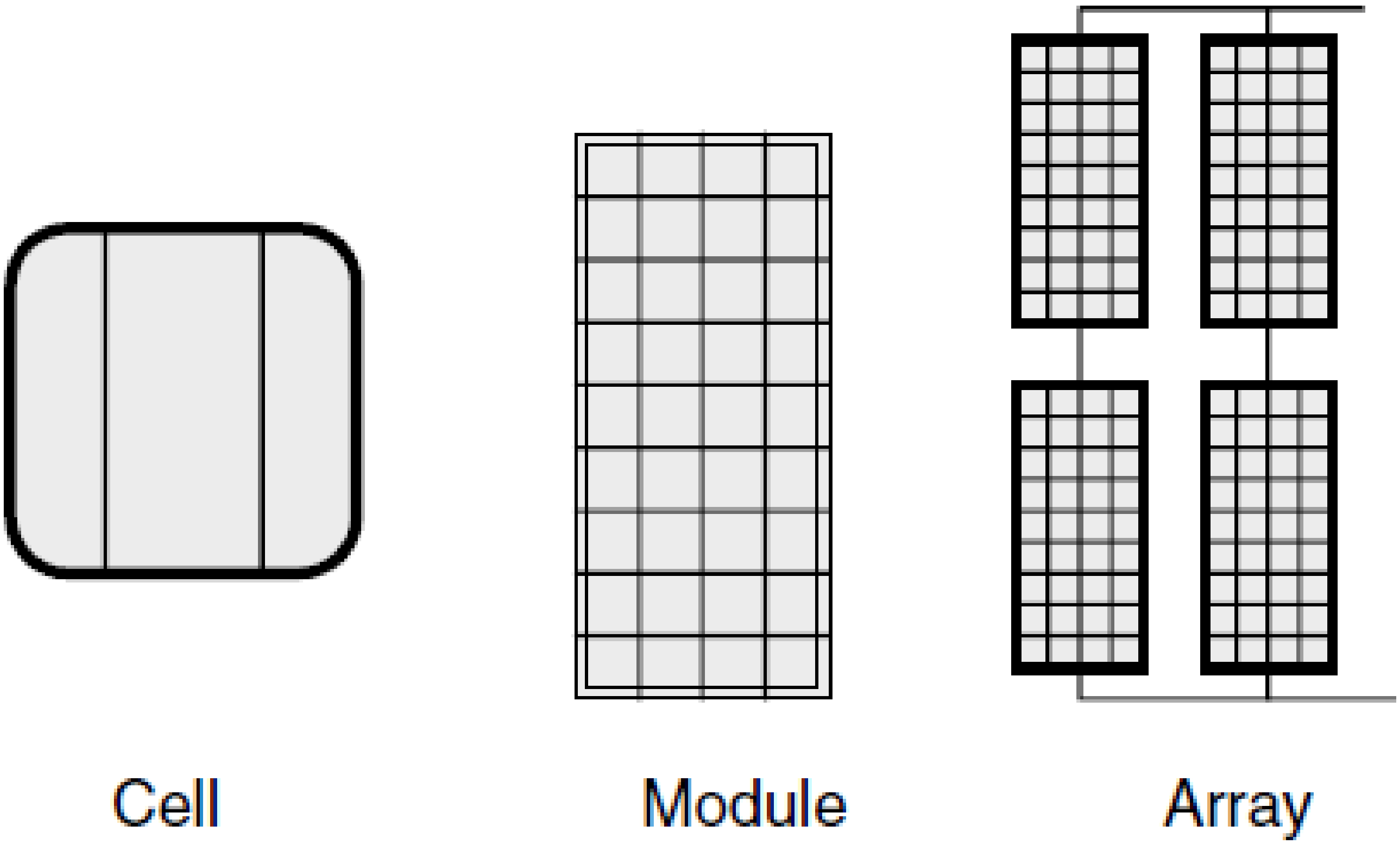
➢ PV: From Cells To Modules To Arrays

- Since an individual cell produces only about 0.5 V, it is a rare application for which just a single cell is of any use. Instead, the basic building block for PV applications is a module consisting of a number of pre-wired cells in series, all encased in tough, weather-resistant packages.
- A typical module has 36 cells in series and is often designated as a "12-V module".
- Some 12-V modules have only 33 cells, which, as will be seen later may, be desirable in certain very simple battery charging systems.
- Large 72-cell modules are now quite common, some of which have all of the cells wired in series, in which case they are referred to as 24-V modules.

PV: From Cells To Modules To Arrays (Continued)

- **Some 72-cell modules can be field-wired to act either as 24-V modules with all 72 cells in series or as 12-V modules with two parallel strings having 36 series cells in each.**
- **Multiple modules, in turn, can be wired in series to increase voltage and in parallel to increase current, the product of which is power.**
- **An important element in PV system design is deciding how many modules should be connected in series and how many in parallel to deliver whatever energy is needed.**
- **Such combinations of modules are referred to as an array.**

PV: From Cells To Modules To Arrays (Continued)

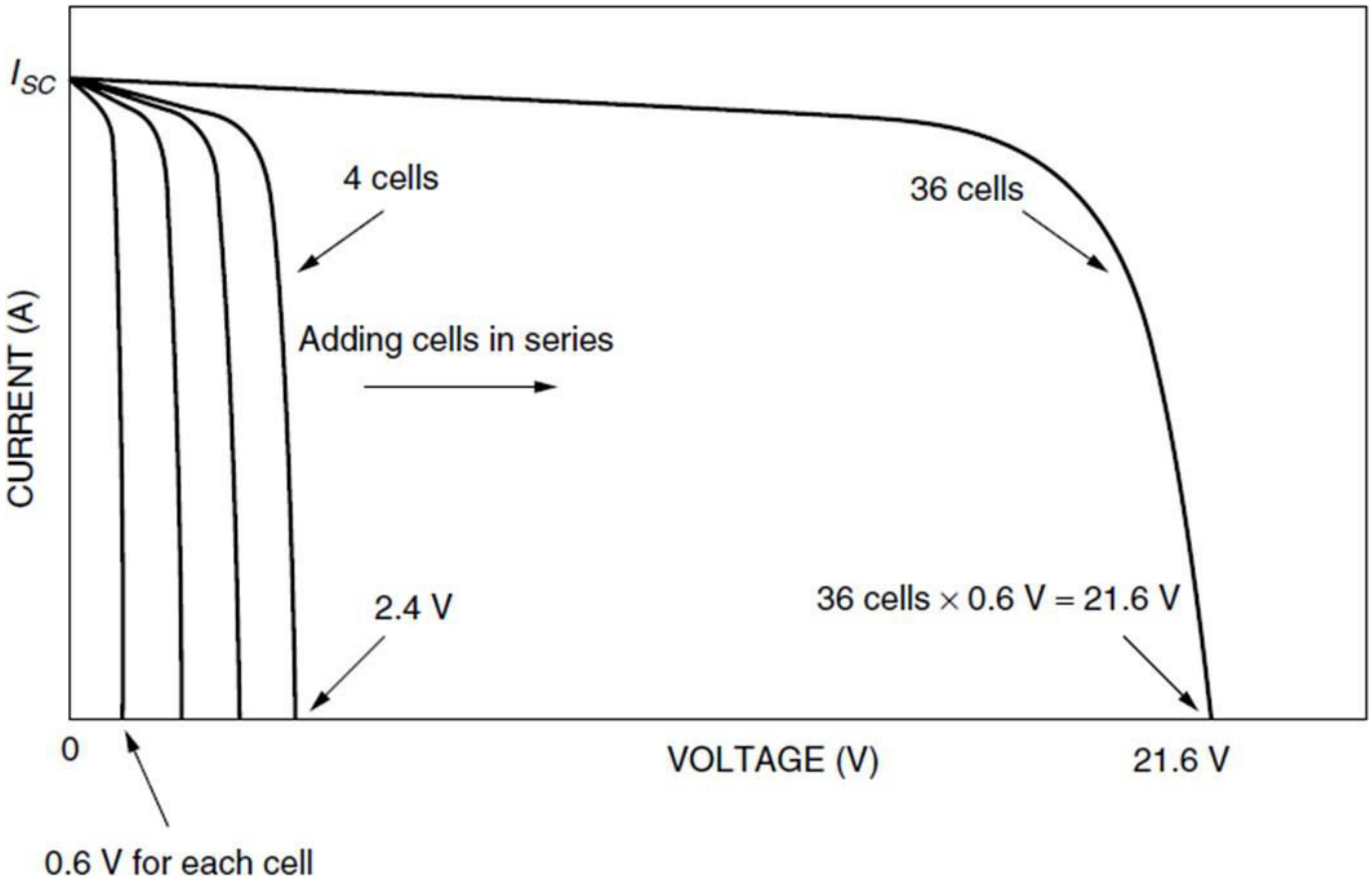


- When photovoltaics are wired in series, they all carry the same current, and at any given current their voltages add as shown in Figure.
- That means we can continue with the current equation to find an overall module voltage V_{module} by multiplying the voltage equation with number of cells in the module n.

$$I = I_{SC} - I_0\left[e^{38.9(V+IR_S)} - 1\right] - \frac{1}{R_P}(V + IR_S)$$

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

PV: From Cells To a Module (Continued)



➢ PV: Problem. No.3

- **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 A and at 25◦C its reverse saturation current is I_o= 6×10^{-10} A. Parallel resistance R_p = 6.6 Ω and series resistance R_s = 0.005 Ω.**
- **a. Find the voltage, current, and power delivered when the junction voltage of each cell is 0.50 V.**
- **b. Set up a spreadsheet for I and V and present a few lines of output to show how it works.**

PV: Problem. No.3 (Continued)

a. Using $V_d = 0.50$ V

$$I = I_{SC} - I_0(e^{38.9V_d} - 1) - \frac{V_d}{R_P}$$

$$= 3.4 - 6 \times 10^{-10}(e^{38.9 \times 0.50} - 1) - \frac{0.50}{6.6} = 3.16 \text{ A}$$

$$V_{\text{module}} = n(V_d - IR_S) = 36(0.50 - 3.16 \times 0.005) = 17.43 \text{ V}$$

Power delivered is therefore

$$P(\text{watts}) = V_{\text{module}}\, I = 17.43 \times 3.16 = 55.0 \text{ W}$$

PV: Problem. No.3 (Continued)

Number of cells, $n = 36$

Parallel resistance/cell R_P (ohms) $= 6.6$

Series resistance/cell R_S (ohms) $= 0.005$

Reverse saturation current I_0 (A) $= 6.00\text{E-}10$

Short-circuit current at 1-sun (A) $= 3.4$

V_d	$I = I_{SC} - I_0\left(e^{38.9V_d} - 1\right) - \dfrac{V_d}{R_p}$	$V_{module} = n(V_d - IR_S)$	P (watts) $= V_{module} I$
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