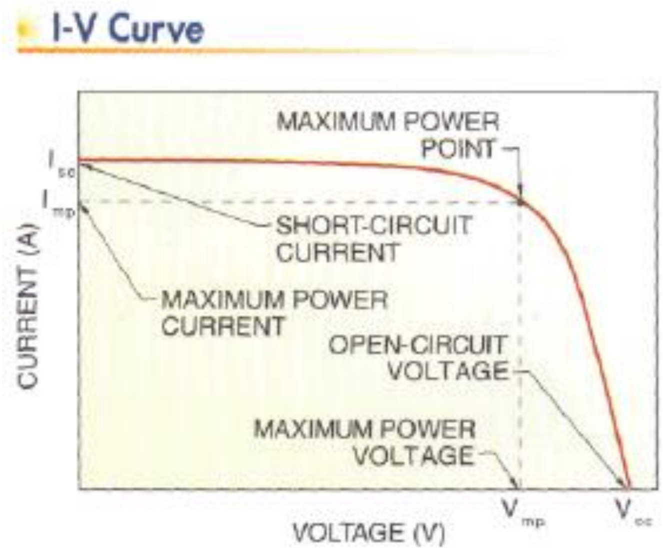
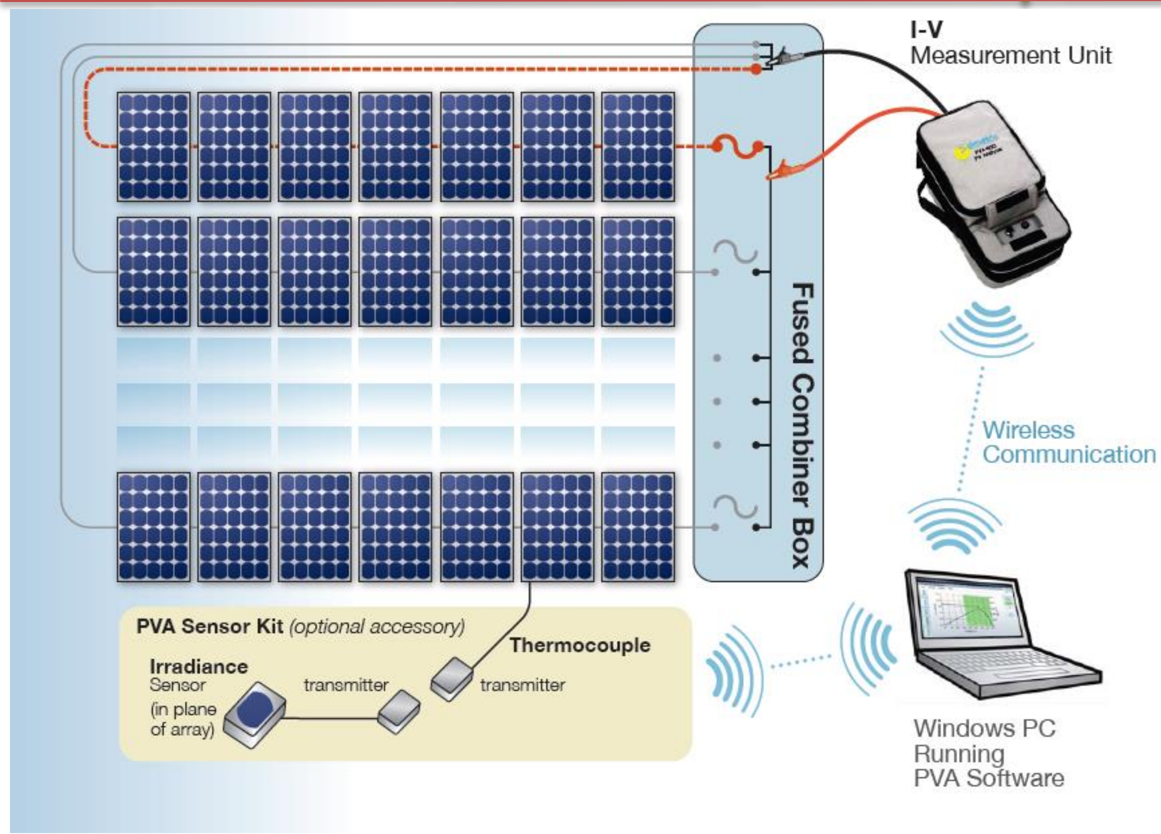
I-V Characteristic

19/4

L12



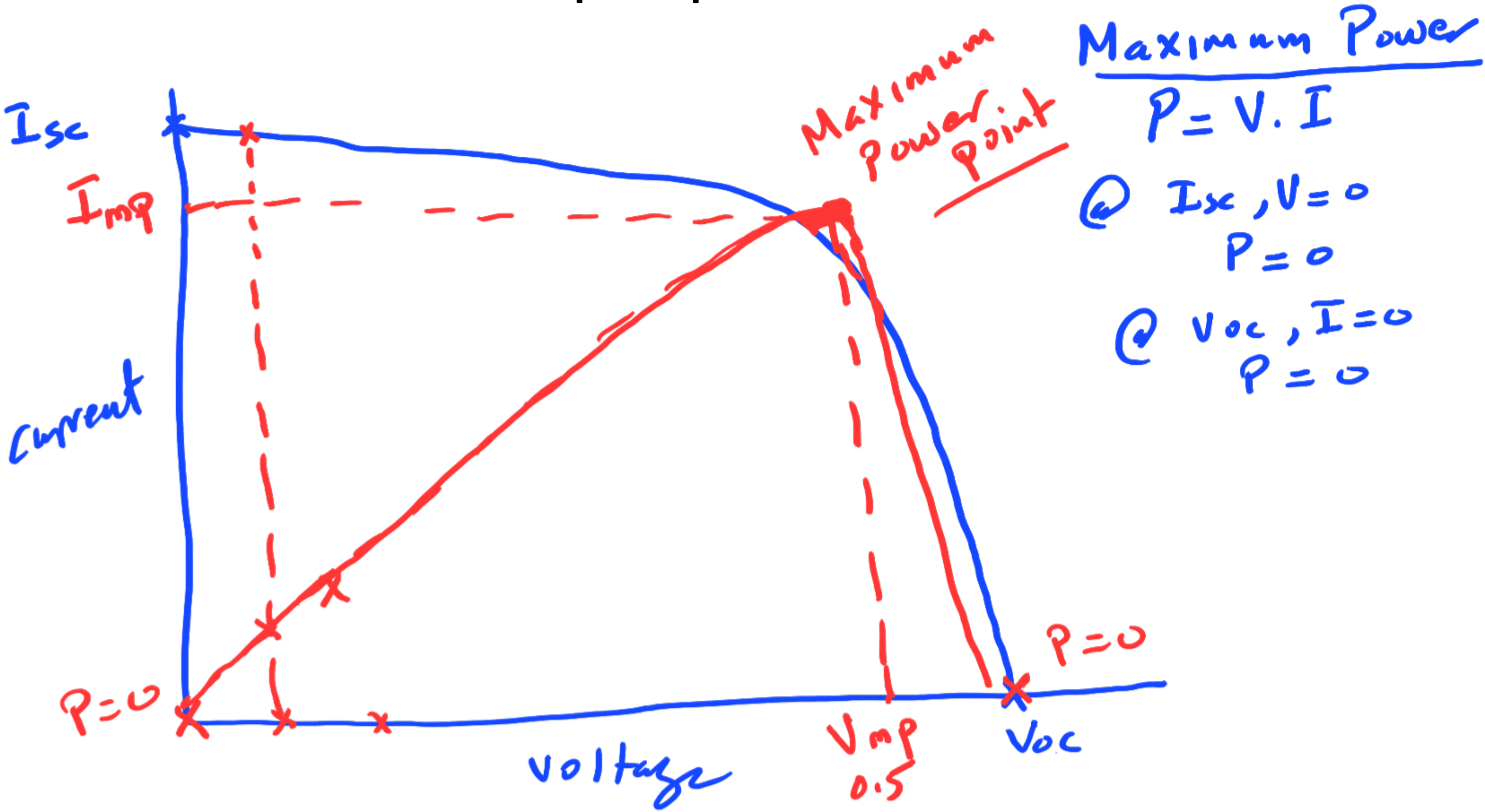


ENEE5307
Renewable Energy
& PV Systems

Nasser Ismail
BZU-2020

The *current-voltage (I-V) characteristic*

- The *current-voltage (I-V) characteristic is the* basic electrical output profile of a PV device.

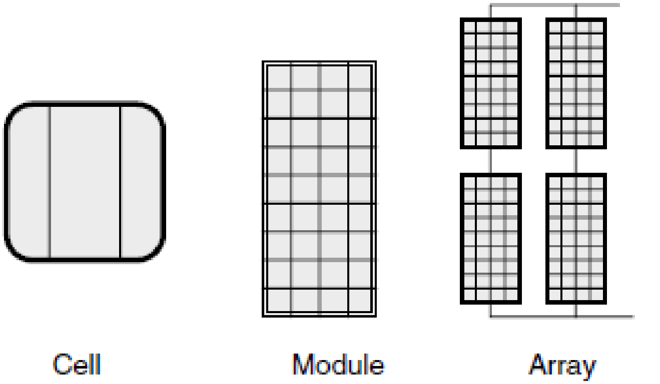


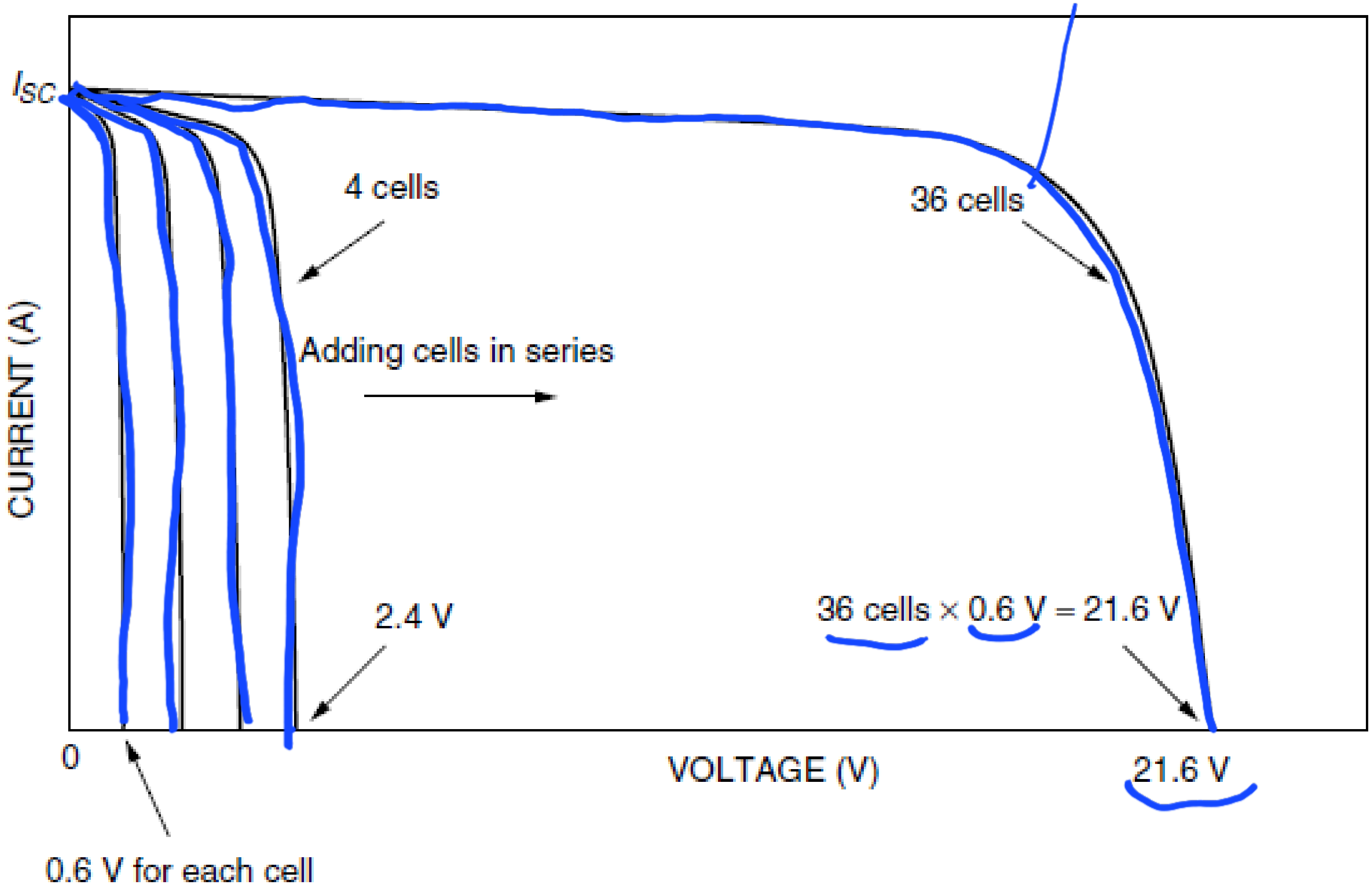
FROM CELLS TO MODULES TO ARRAYS

- Individual cells produce about 0.5 V,
- 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" even though it is capable of delivering much higher voltages than that.
- 12-V modules 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.

FROM CELLS TO MODULES TO ARRAYS

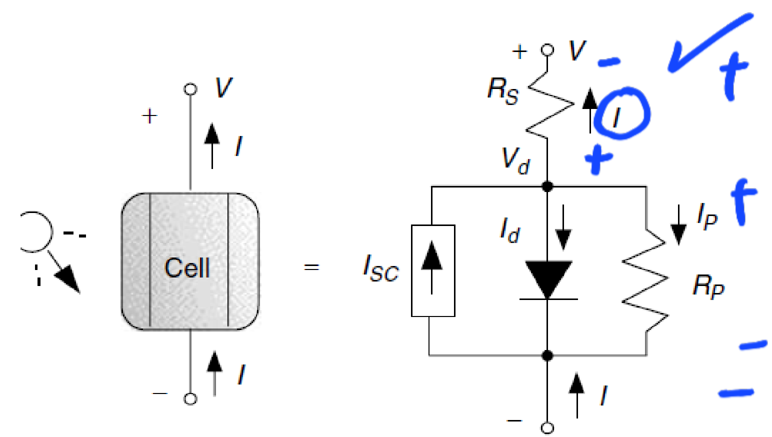
- Some 72-cell modules can be field-wired to act either as 24-V modules with all 72 cells in series or as 12-V modules with two parallel strings having 36 series cells in each.
- **Multiple modules, in turn, can be wired in series to increase voltage and in parallel to increase current, the product of 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*.





For cells wired in series, their voltages at any given current add.
A typical module will have 36 cells.

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

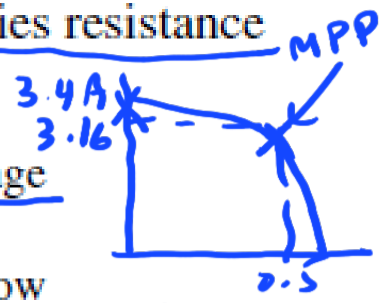


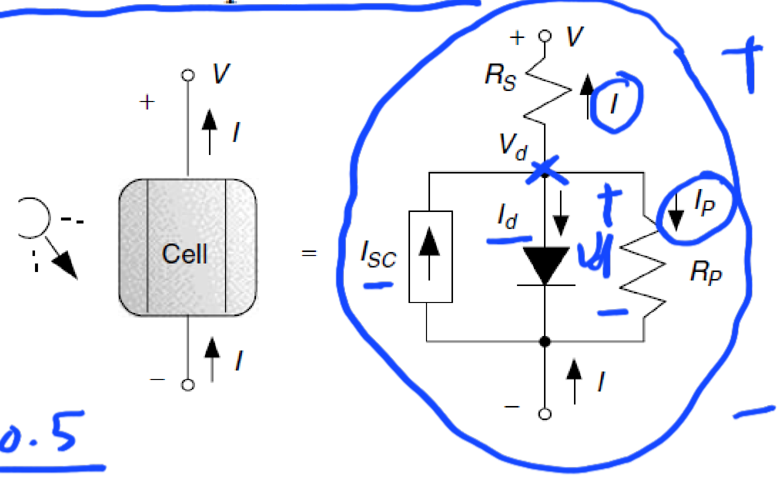
n is number of modules

Example 8.4 Voltage and Current from a PV Module. 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 $I_0 = 6 \times 10^{-10}$ A. Parallel resistance $R_P = 6.6\ \Omega$ and series resistance $R_S = 0.005\ \Omega$.

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.





- Solution:

a. using $V_d = 0.5$ V

$$\rightarrow I = I_{sc} - \underbrace{I_0\left(e^{38.9V_d} - 1\right)}_{I_d} - \frac{V_d}{R_P}$$

$$= 3.4 - 6 \times 10^{-10}\left(e^{38.9 \times 0.5} - 1\right) - \frac{0.5}{6.6}$$

$$= 3.16 \text{ A}$$

$$V_{module} = n(V_d - I R_S) = 36(0.5 - 3.16 \times 0.005) = 17.43 \text{ V}$$

Power delivered is therefore

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

b. A spreadsheet might look something like the following:

Number of cells, $n = 36$

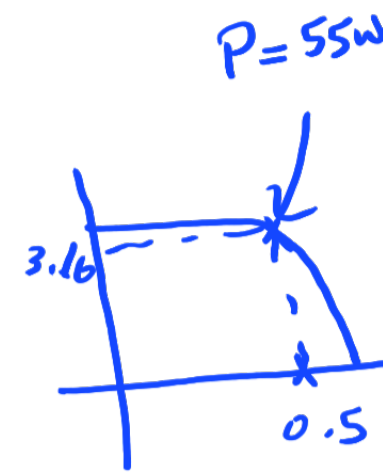
Parallel resistance/cell R_P (ohms) $= 6.6$

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) $= 3.4$

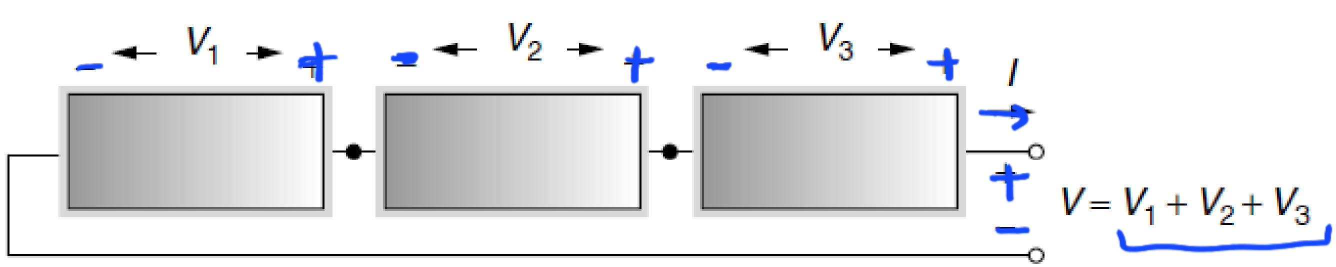
V_d	$I = I_{SC} - I_0\left(e^{38.9V_d} - 1\right) - \frac{V_d}{R_p}$	$V_{\text{module}} = n(V_d - I R_S)$	P (watts) $= V_{\text{module}} I$
0.49	3.21	17.06	54.80
0.50	3.16	17.43	55.02
0.51	3.07	17.81	54.75
0.52	2.96	18.19	53.76
0.53	2.78	18.58	51.65
0.54	2.52	18.99	47.89
0.55	2.14	19.41	41.59

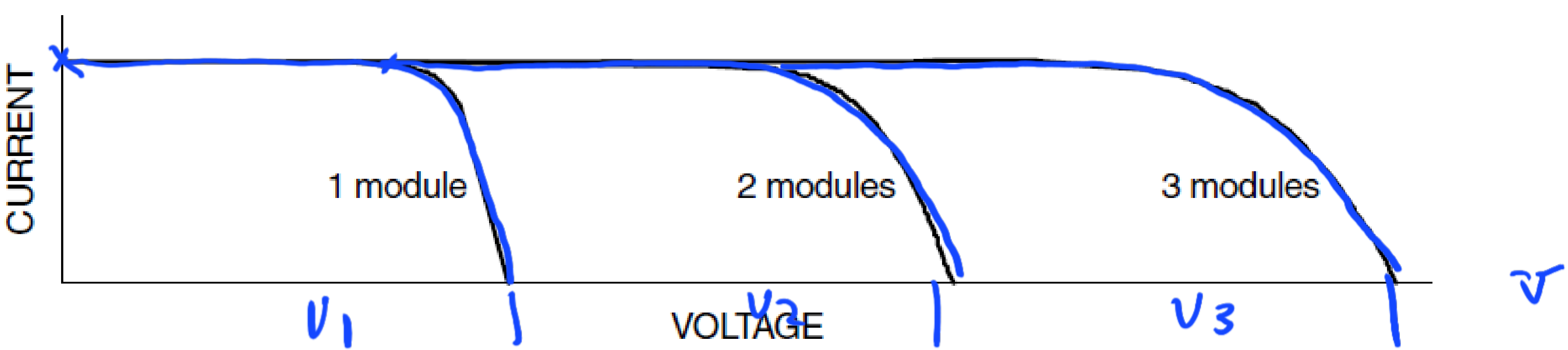


Notice that we have found the maximum power point for this module, which is at $I = 3.16$ A, $V = 17.43$ V, and $P = 55$ W. This would be described as a 55-W module. ← Maximum Power Point ≡ rated Power of the Module

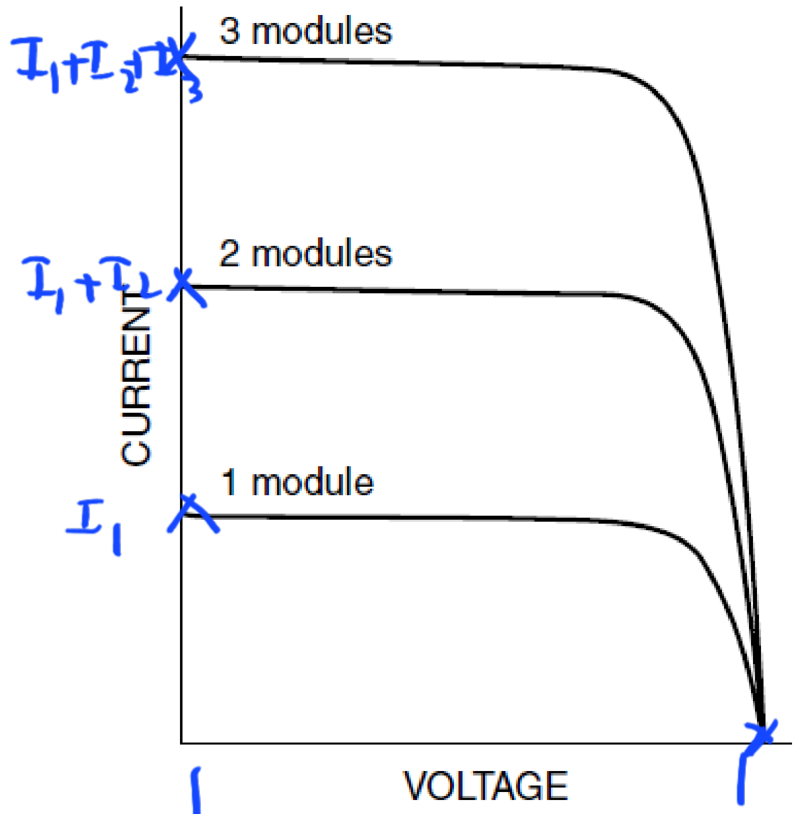
From Modules to Arrays

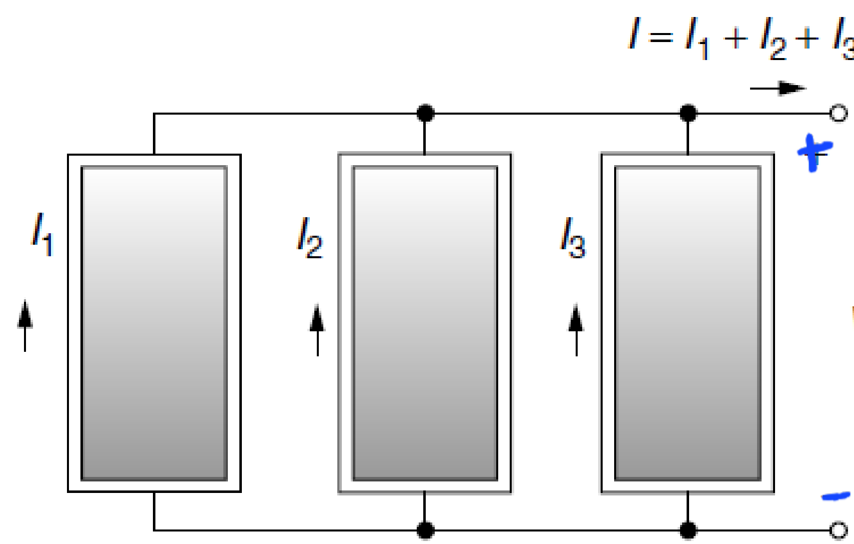
- Modules can be wired in series to increase voltage, and in parallel to increase current.
- Arrays are made up of some combination of series and parallel modules to increase power.
- For modules in series, the $I-V$ curves are simply added along the voltage axis.

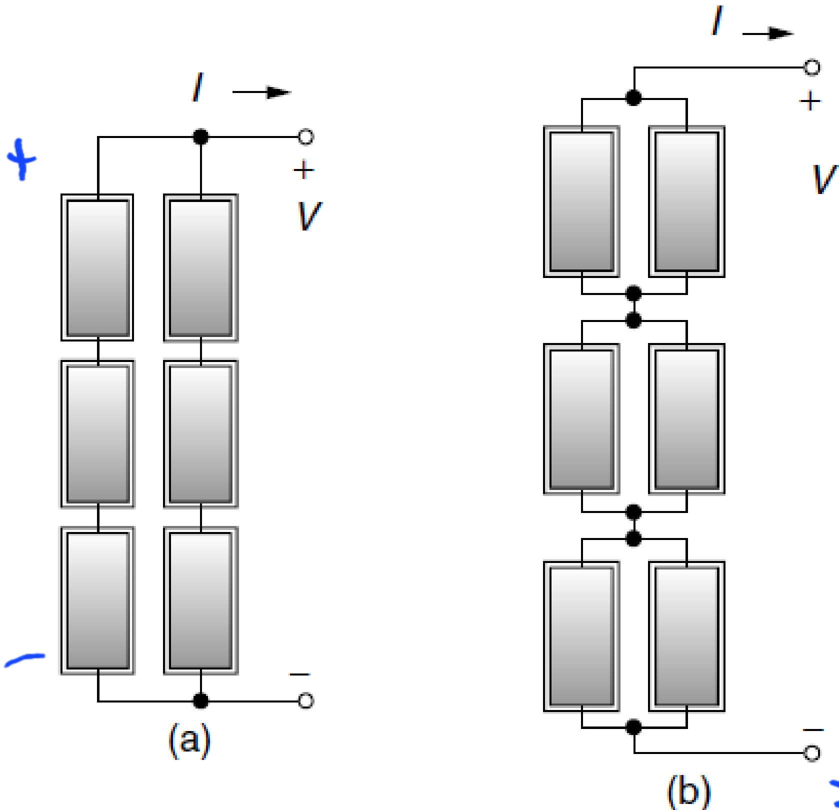




- For modules in parallel, the same voltage is across each module and the total current is the sum of the currents.
- That is, at any given voltage, the $I-V$ curve of the parallel combination is just the sum of the individual module currents at that voltage

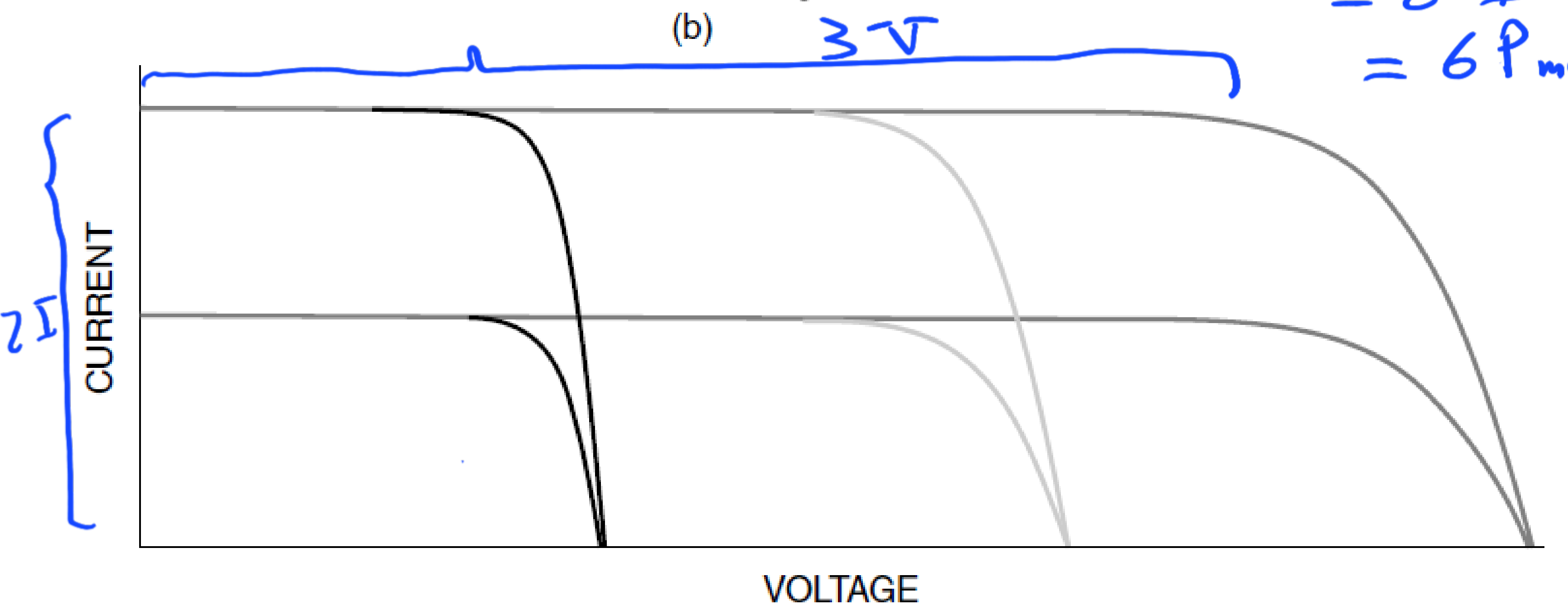






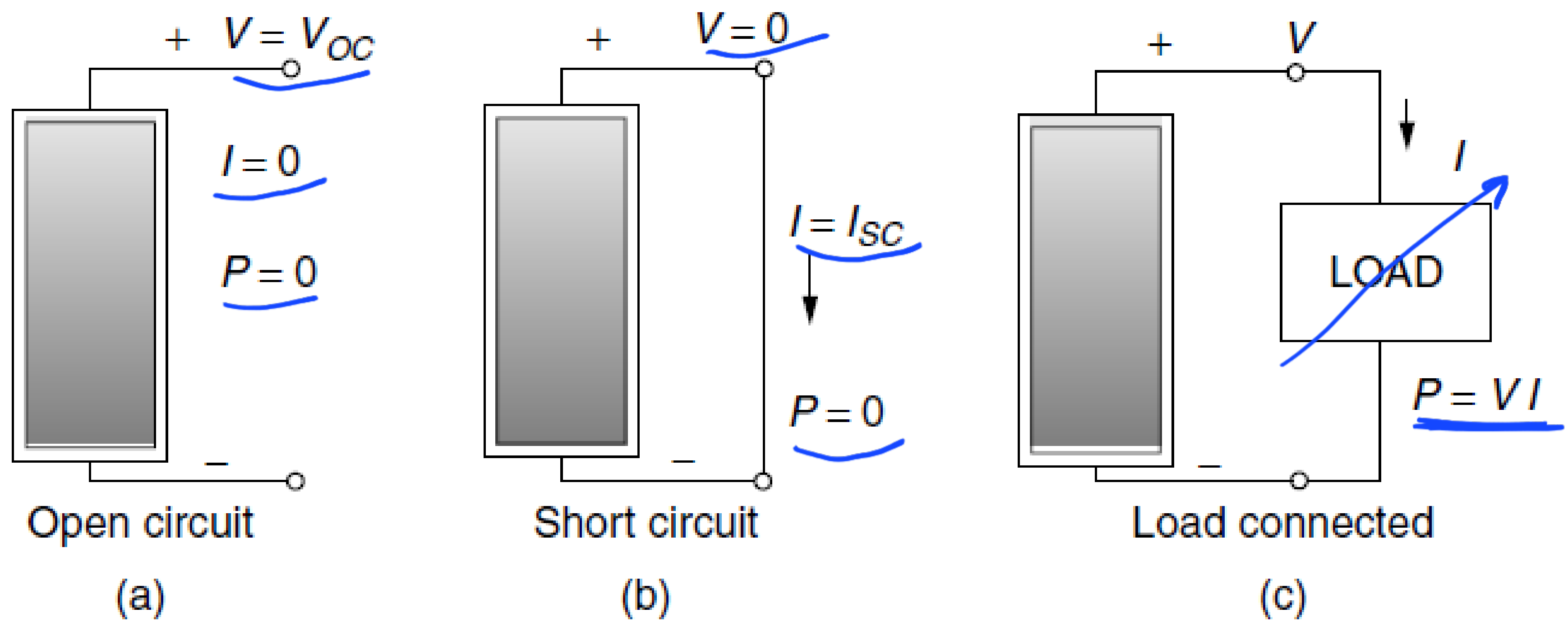
Two ways to wire an array with three modules in series and two modules in parallel.
Both I-V curves are the same

$$P_{array} = 2I \times 3V = 6IV = 6P_{module}$$

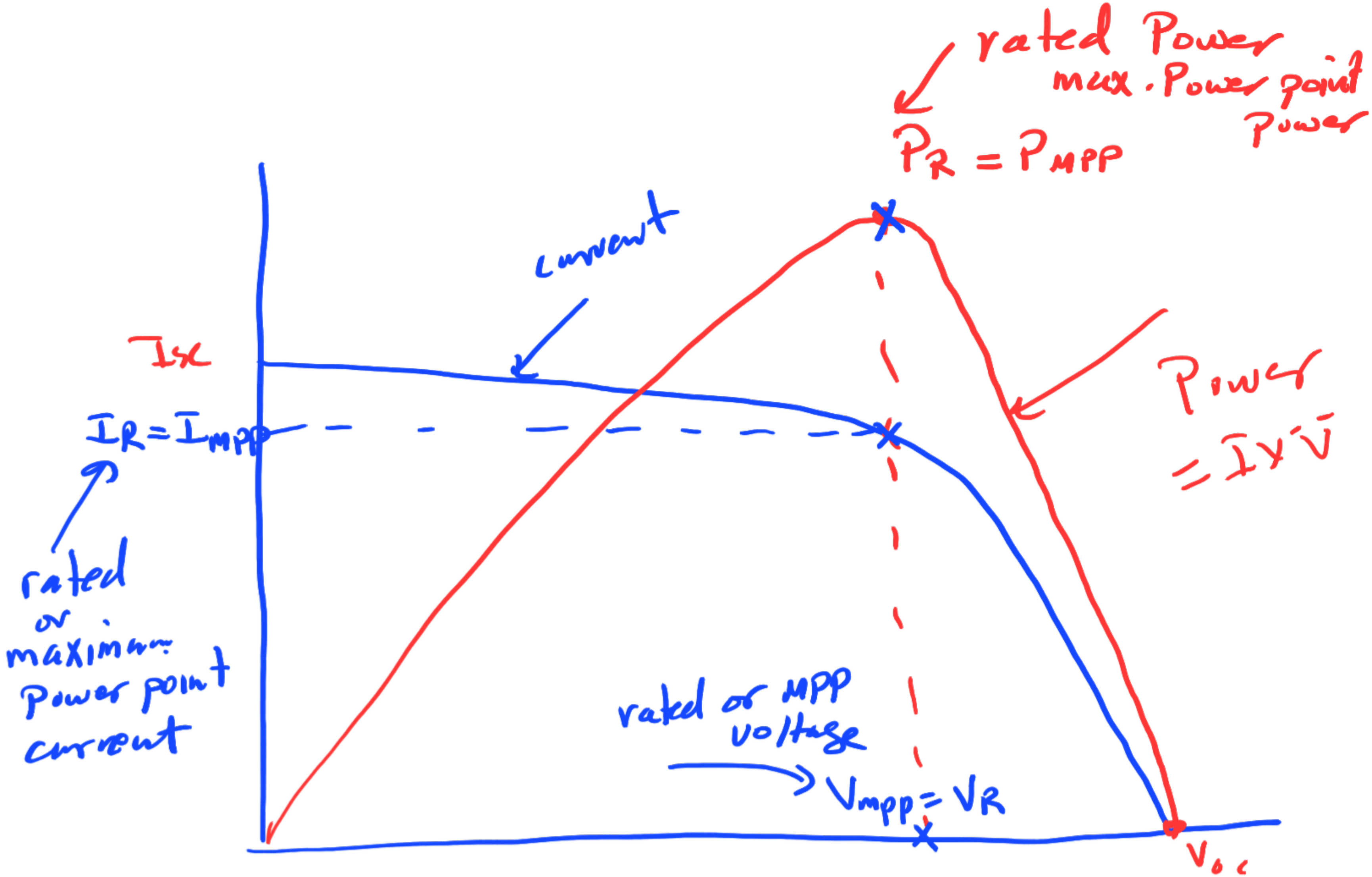


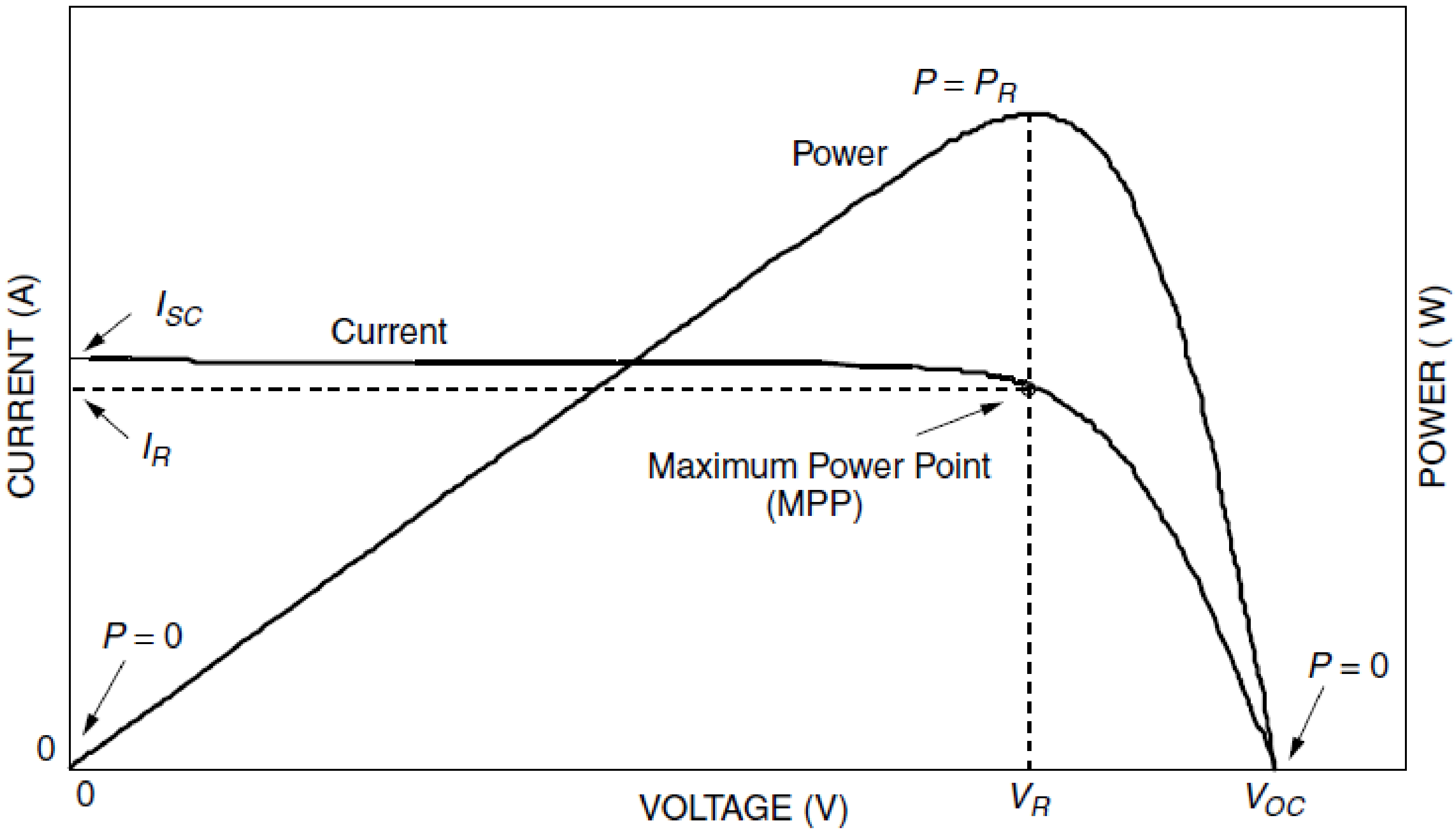
THE PV *I–V* CURVE UNDER STANDARD TEST CONDITIONS (STC)

- Before the load is connected, the module sitting in the sun will produce an **open-circuit voltage Voc**, 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 Isc** 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.

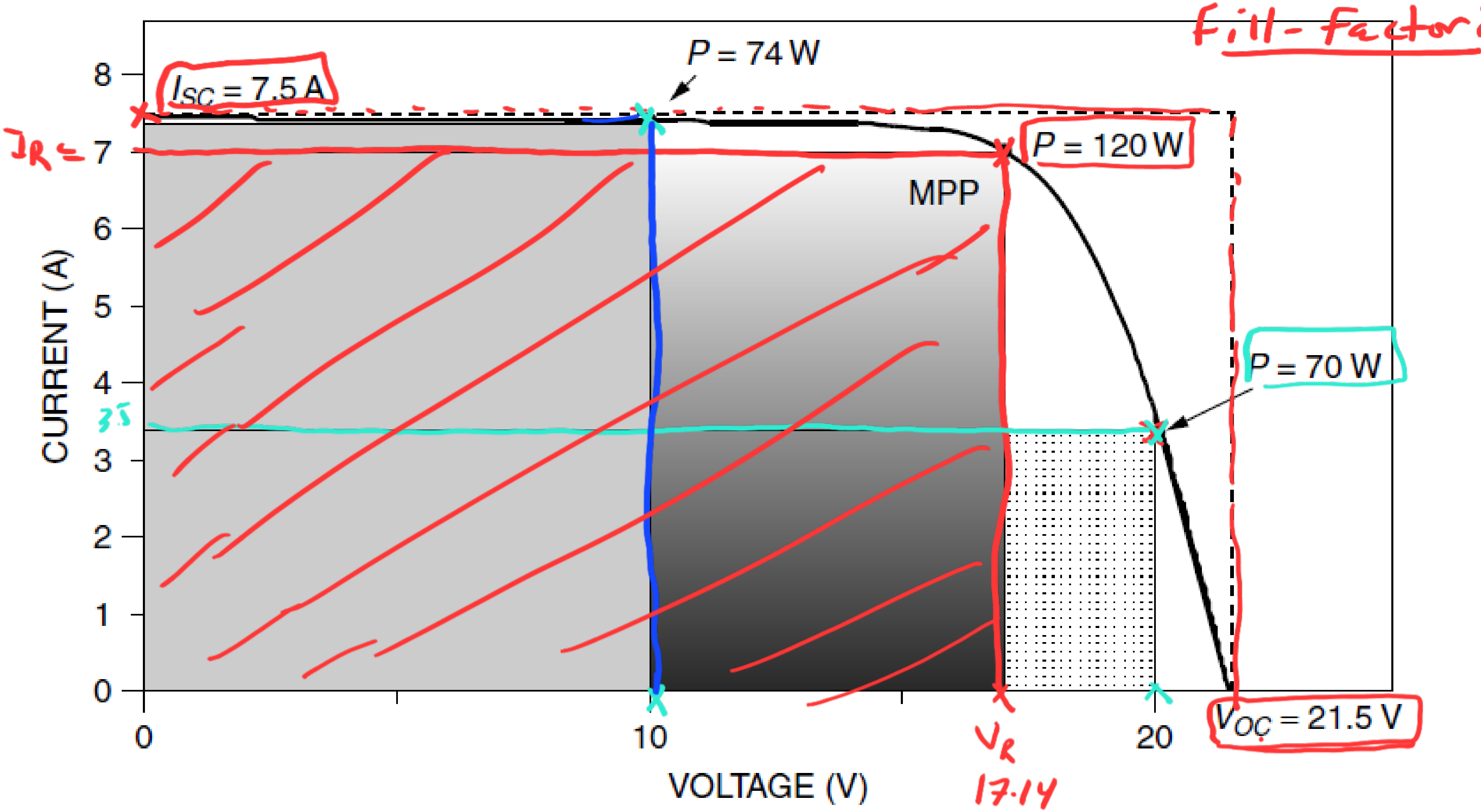


- No power is delivered when the circuit is open (a) or shorted (b).
- When the load is connected (c), the same current flows through the load and module and the same voltage appears across them.


rated Power
max. Power point Power
$P_R = P_{MPP}$
current
Isc
$I_R = I_{MPP}$
rated or maximum Power point current
Power $= I \times V$
rated or MPP voltage
$V_{mpp} = V_R$
Voc



The $I-V$ curve and power output for a PV module.
At the maximum power point (MPP) the module delivers the most power that it can under the conditions of sunlight and temperature for which the $I-V$ curve has been drawn.



- The maximum power point (MPP) corresponds to the biggest rectangle that can fit beneath the $I-V$ curve.
- The fill factor (FF) is the ratio of the area (power) at MPP to the area formed by a rectangle with sides ***Voc*** and ***ISC***.

Fill Factor

- Fill factors around 70–75% for crystalline silicon solar modules are typical, while for multijunction amorphous-Si modules, it is closer to 50–60%.

$$Fill\ Factor\ (FF) = \frac{Power\ at\ MPP\ (i.e.\ Rated\ Power)}{V_{OC}I_{SC}} = \frac{V_R I_R}{V_{OC}I_{SC}}$$

$$= \frac{V_{mpp} \times I_{mpp}}{V_{oc} \cdot I_{sc}}$$

- 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.

Standard Test Conditions :STC

- **STC: include a solar irradiance of 1 kW/m^2 (1 sun) , spectral distribution, corresponding to an air mass ratio of 1.5 (AM 1.5).**
- The standard cell temperature for testing purposes is 25◦C (it is important to note that 25◦ is cell temperature, not ambient temperature).
- Manufacturers always provide performance data under these operating conditions,
- The key parameter for a module is its rated power; $P_{DC,STC}$.
- Power adjustments to take into account temperature effects will be done later
- Also the actual ac power that the module and inverter combination will deliver will be estimated.

TABLE 8.3 Examples of PV Module Performance Data Under Standard Test Conditions (1 kW/m², AM 1.5, 25°C Cell Temperature)

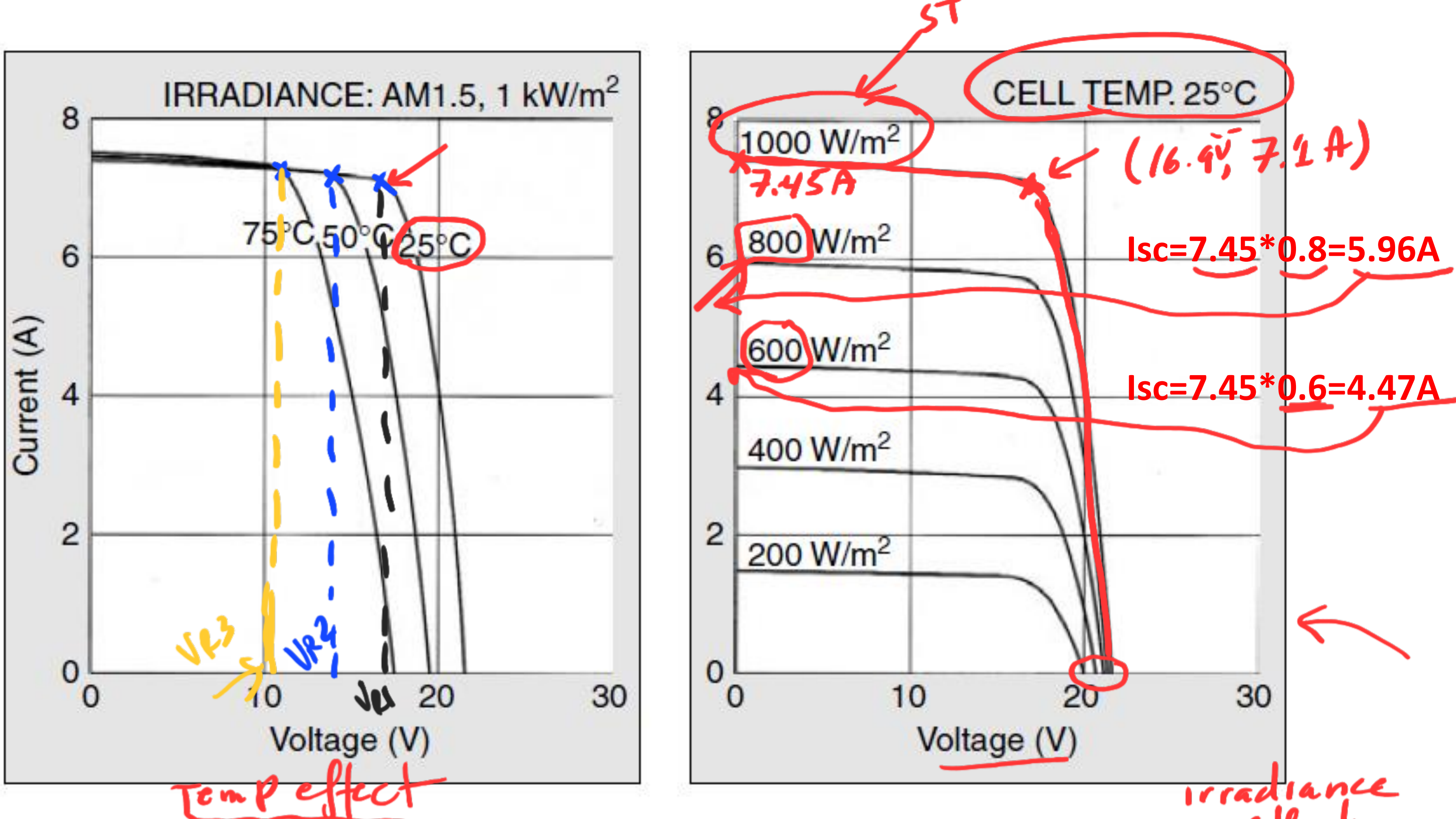
Manufacturer	Kyocera	Sharp	BP	Uni-Solar	Shell
Model	KC-120-1	NE-Q5E2U	2150S	US-64	ST40
Material	Multicrystal	Polycrystal	Monocrystal	Triple junction a-Si	CIS-thin film
Number of cells n	36	72	72		42
Rated Power $P_{DC,STC}$ (W)	120	165	150	64	40
Voltage at max power (V)	16.9	34.6	34	16.5	16.6
Current 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%

$FF = \frac{120}{7.45 \times 21.5} = 0.749$

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.
- An example for the Kyocera 120-W multicrystal-silicon module described in Table 8.3. is given
- Notice as insolation drops, short-circuit current drops in direct proportion.
- **Cutting insolation in half, for example, drops Isc by half.**
- **Decreasing insolation also reduces Voc, but it does so following a logarithmic relationship that results in relatively modest changes in Voc.**

as seen before



Current-voltage characteristic curves under various cell temperatures and irradiance levels for the Kyocera KC120-1 PV module.

Temp Effect

- 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 Isc 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.**
- 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.

NOCT

- 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. given in data sheet
- 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:

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

irradiance

sun?

- where *Tcell* is cell temperature (◦C), *Tamb* is ambient temperature, and *S* is solar insolation (kW/m^2).

Impact of Cell Temperature on Power for a PV Module.

- Estimate cell temperature, open-circuit voltage, and maximum power output for the 150-W BP2150S module under conditions of 1-sun insolation and ambient temperature 30◦C. The module has a NOCT of 47◦C.
- Solution: cell temperature is estimated to be

$$T_{\text{cell}} = T_{\text{amb}} + \left(\frac{\text{NOCT} - 20^\circ}{0.8}\right) \cdot S = 30 + \left(\frac{47 - 20}{0.8}\right) \cdot 1 = 64^\circ\text{C}$$

- From Table 8.3, for this module at the standard temperature of 25◦C, V_{OC} = 42.8 V. Since V_{OC} drops by 0.37%/◦C, the new V_{OC} will be about:

Temp. Coeffecient for Voc

Voc = 42.8[1 − 0.0037(64 − 25)] = 36.7 V

= 42.8(1 − 0.1443) = 36.7 V

0.37% = 0.0037

ΔT = 39

= 39 X 0.0037

= 0.1443

$0.5\% = \frac{0.5}{100} = 0.005$

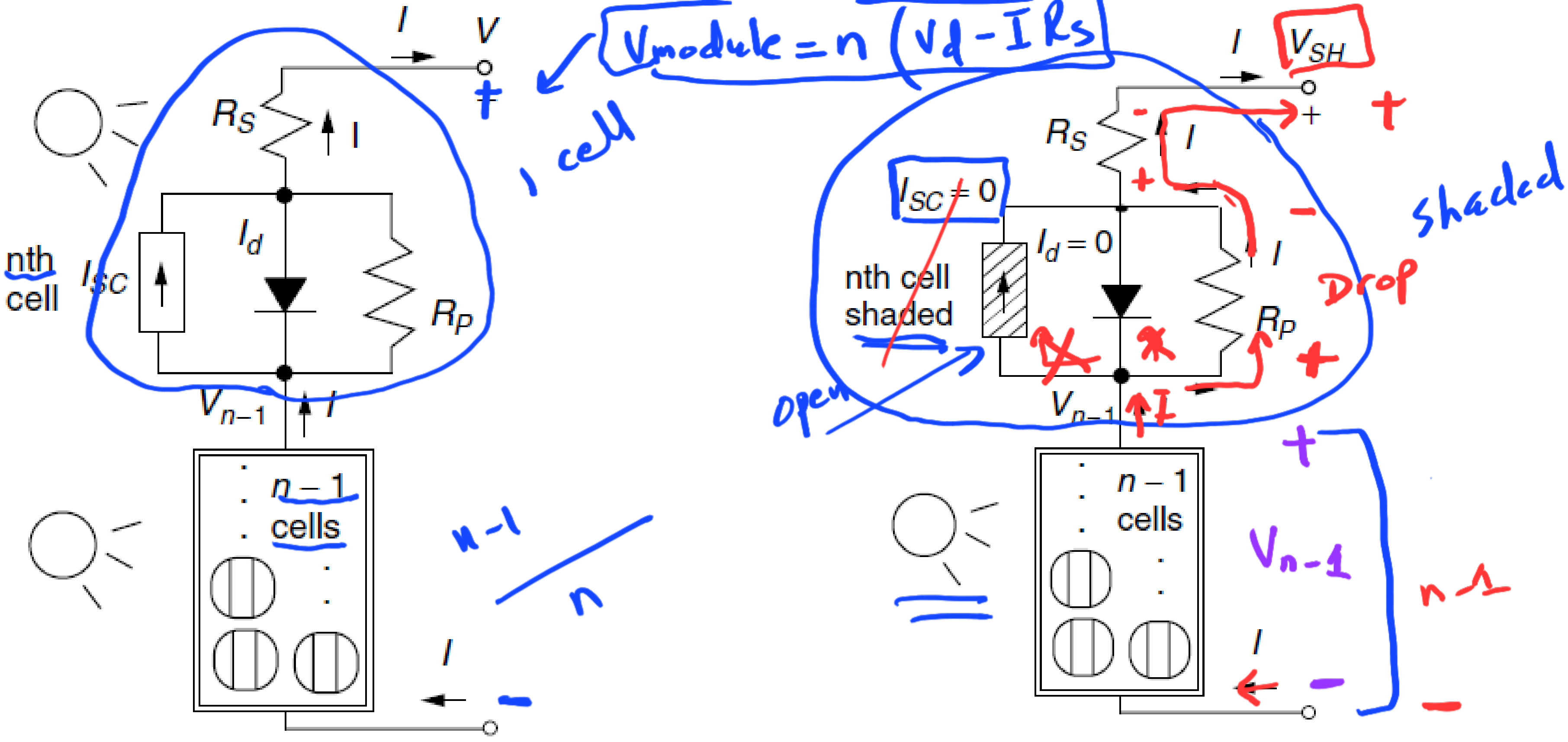
- With maximum power expected to drop about - 0.5%/◦C, this 150-W module at its maximum power point will deliver

$$P_{max} = 150\ W \cdot [1 - 0.005(64 - 25)] = 121\ W$$

- which is a rather significant drop of 19% from its rated power.

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.



(a) All cells in the sun

(b) Top cell shaded

A module with n cells in which the top cell is in the sun (a) or in the shade (b)

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

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.

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

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

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

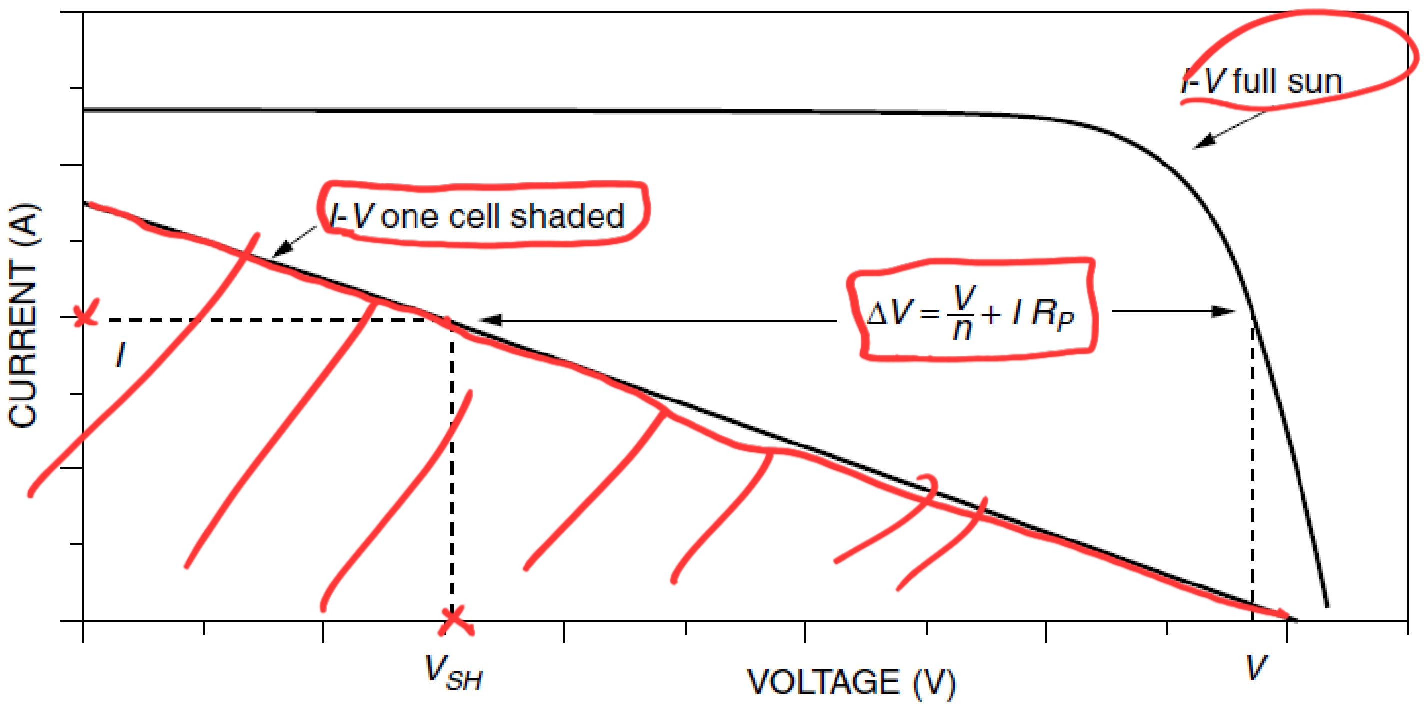
$$\Delta V = V - V_{SH} = V - \left(1 - \frac{1}{n}\right) V + I(R_P + R_S)$$

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

- If *R_P >> R_S , previous equation becomes*

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

- 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



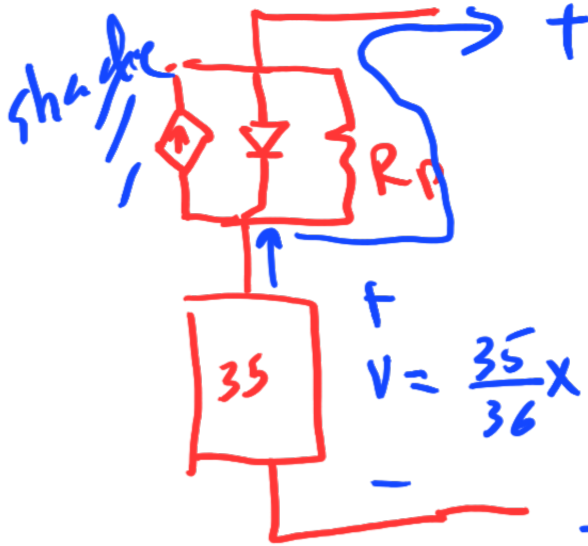
Example :
Impacts of Shading on a PV Module.

- The 36-cell PV module described in previous Example had a parallel resistance per cell of $R_P = 6.6$.
- 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?



V_{sh}

$V = \frac{35}{36} \times 19.41 = 18.87\ V$

$V_{module} = 19.41\ V$

$I = 2.14\ A$

$P = 41.516\ W$

normal

$\Delta V = \frac{V}{n} + 2.14 \times 6.6$

$= \frac{19.41}{36} + 2.14 \times 6.6 = 14.66\ V$

$V_{sh} = 19.41 - 14.66 = 4.75\ V$

$P_{shaded} = 4.75 \times 2.14 = 10.1\ W$

$\frac{19.41}{36}$

B) $V_c = I(R_p + R_s) = 2.14(6.6 + 0.005) = 14.14\ V$

Drop on shaded cell

C) $P_{dissipated} = V_c \times I = 14.14 \times 2.14 = 30.2\ W$

in shaded cell

Ended

21/4/2020

Example solution

Same Previous Example

A) The drop in module voltage will be:

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

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

- The new output voltage will be 19.41 − 14.66 = 4.75 V.
- Power delivered by the module with one cell shaded would be :

  $P_{module} = VI = 4.75 \text{ V} \times 2.14 \text{ A} = 10.1 \text{ W}$
- For comparison, in full sun the module was producing 41.5 W

Solution continued

b) All of that 2.14 A of current goes through the parallel plus series resistance (0.005) 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).

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

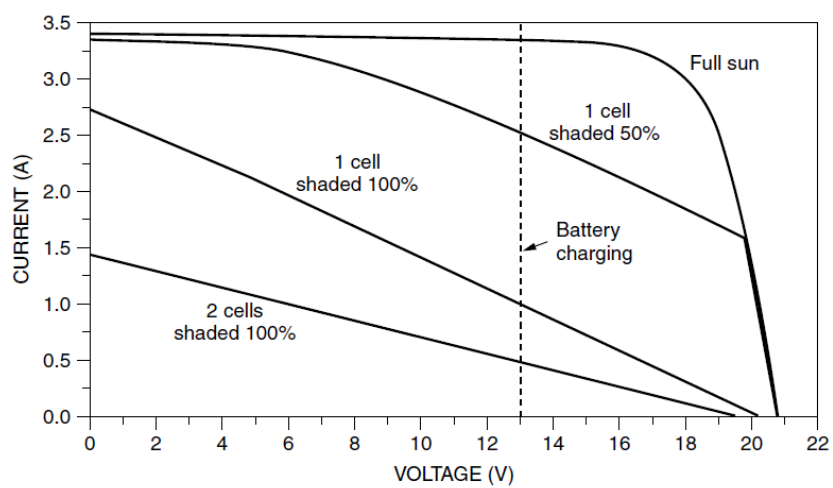
$$P = V_c\, I = 14.14\ \text{V} \times 2.14\ \text{A} = 30.2\ \text{W}$$

- 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

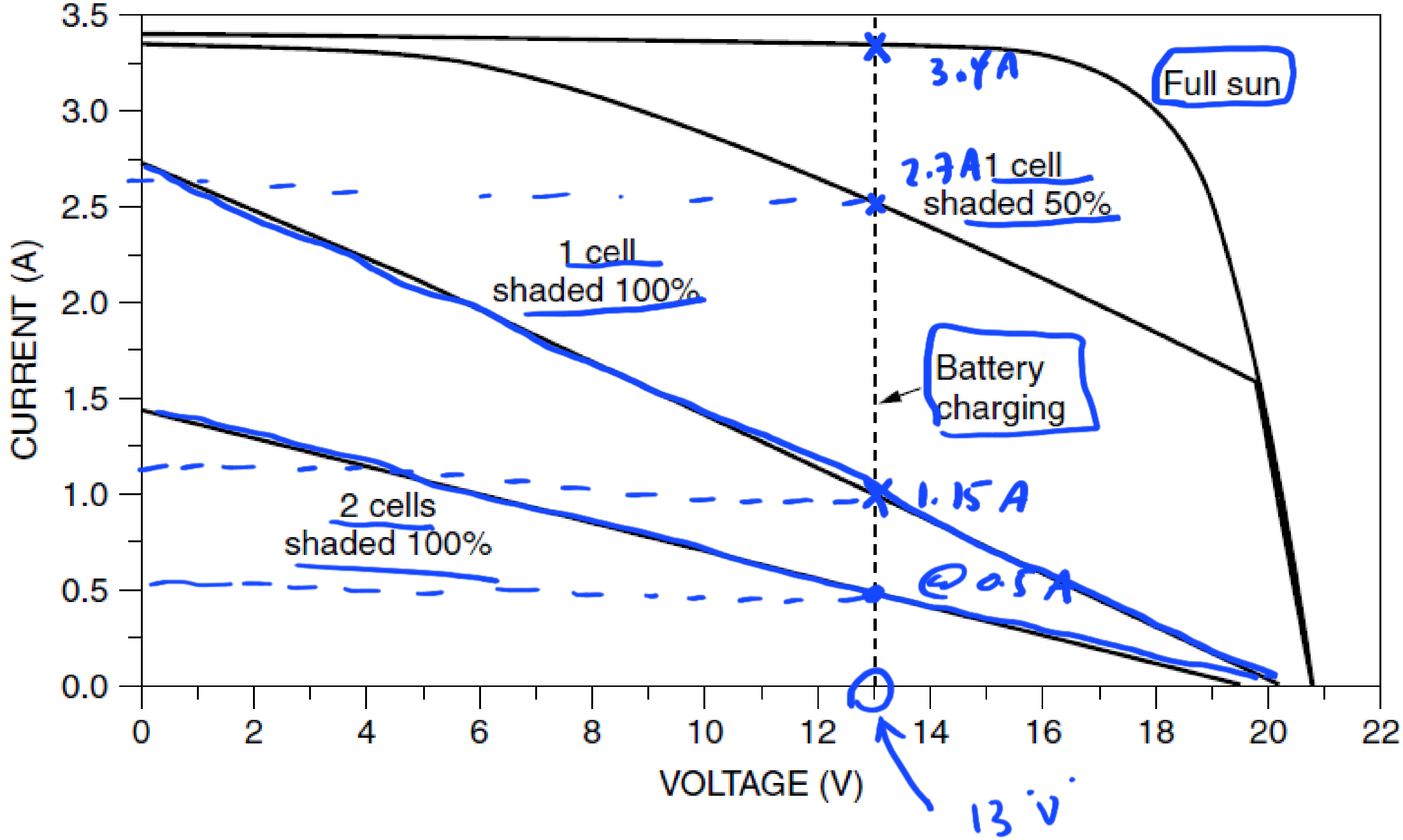
Impact of Shading

L13 24/4/2024

- The procedures demonstrated in previous Examples can be extended to develop $I-V$ curves under various conditions of shading.
- Figure below 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!



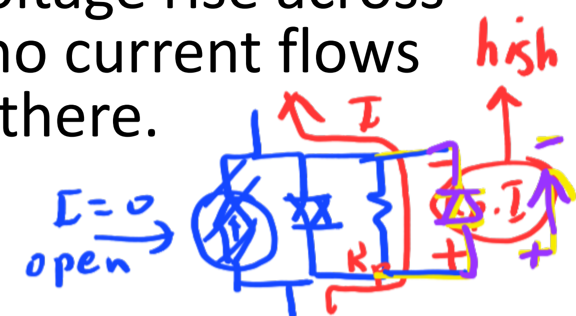
Impact of Shading



Effects of shading on the *I*–*V* curves for a PV module. The dashed line shows a typical voltage that the module would operate at when charging a 12-V battery; the impact on charging current is obviously severe.

Bypass Diodes for Shade Mitigation

- Previous Example shows not only how drastically shading can shift the *I–V* curve, but also how local, potentially damaging hot spots can be created in shaded cells.
- Figure 8.40 shows a typical situation. In Fig. 8.40a 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 8.40b a shaded cell experiences a *drop* as current is diverted through the parallel and series resistances.
- This drop can be considerable (in previous Example it was over 14 V).
- The voltage drop problem in shaded cells could be to corrected by adding a *bypass diode* across each cell, as shown in Fig. 8.41.
- 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.



- The voltage drop problem in shaded cells could be to corrected by adding a *bypass diode* across each cell, as shown in Fig. 8.41. 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.

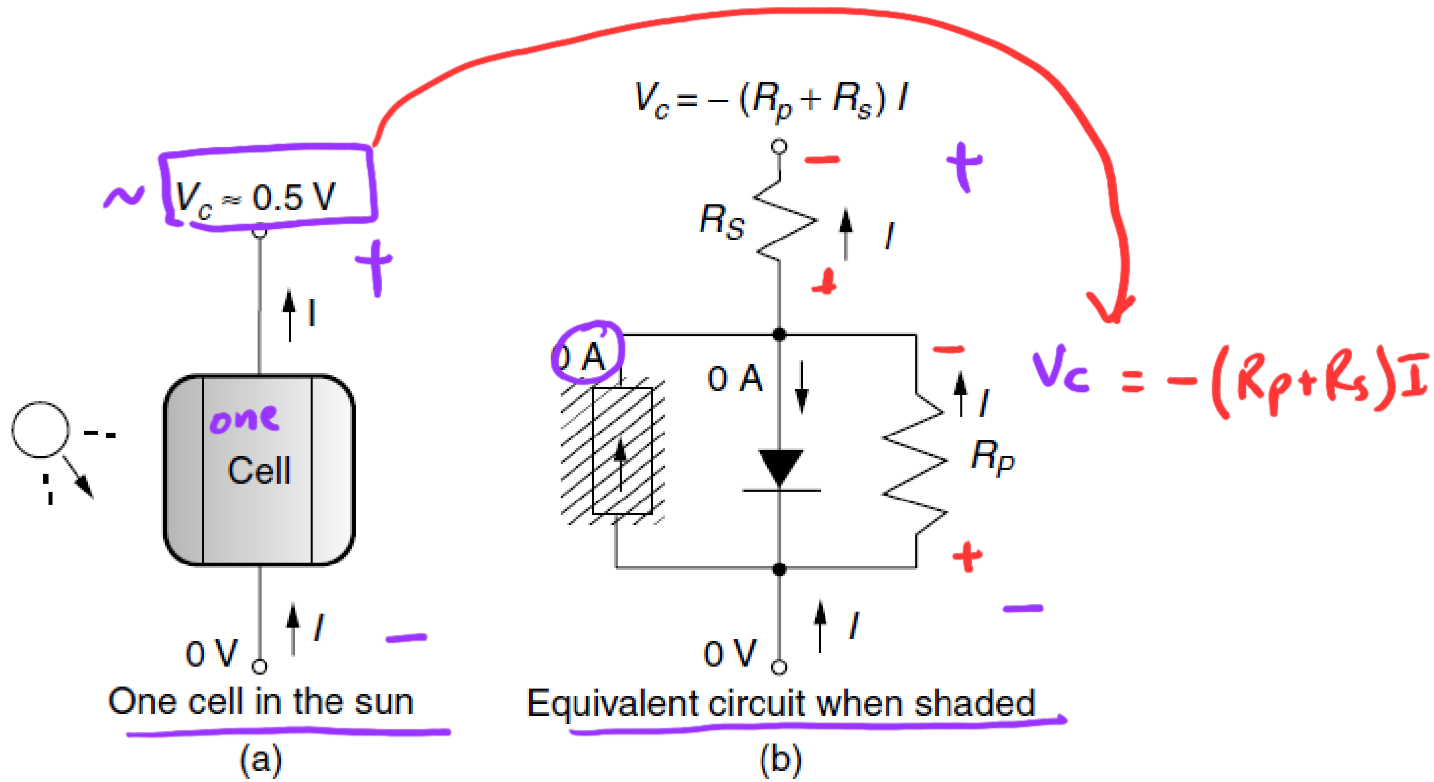


Figure 8.40

- In full sun a cell may contribute around 0.5 V to the module output;
- but when a cell is shaded, it can have a large voltage drop across it.

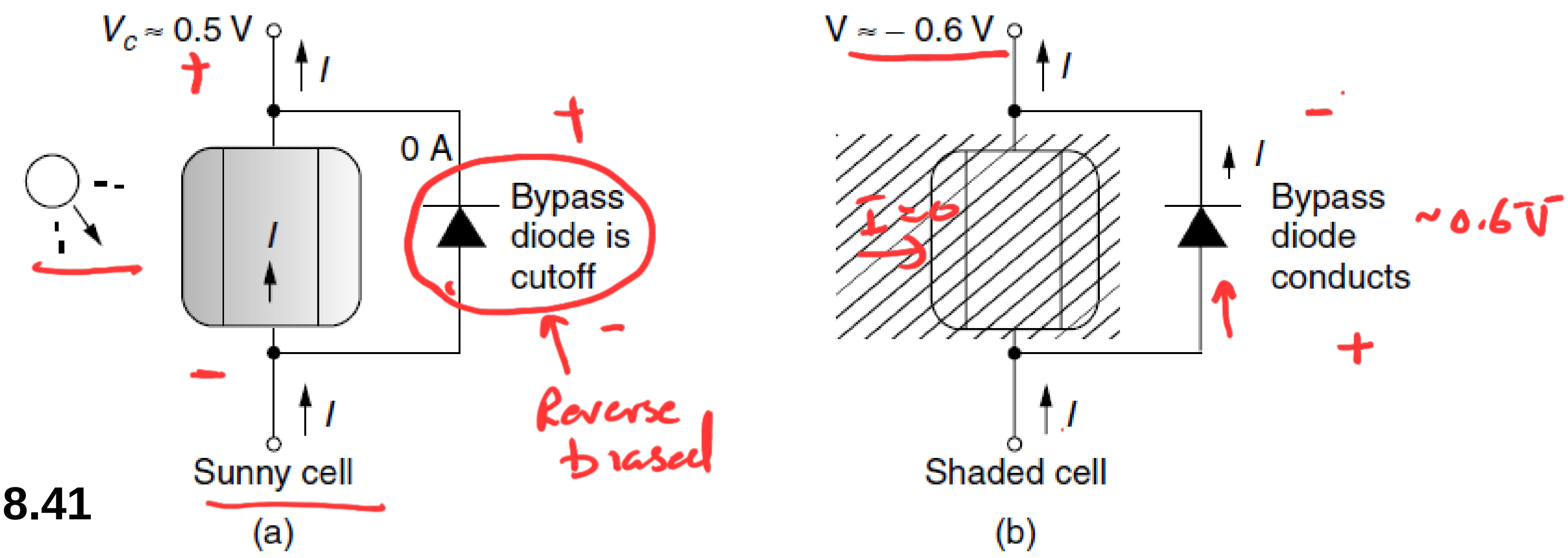


Figure 8.41

- Mitigating the shade problem with a bypass diode.
- In the sun (a), the bypass diode is cut off and all the normal current goes through the solar cell.
- In shade (b), the bypass diode conducts current around the shaded cell, allowing just the diode drop of about 0.6 V to occur.

Bypass Diodes Across Modules

- **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.**

- To see how bypass diodes wired in parallel with modules can help mitigate shading problems, consider Fig. 8.42, 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.

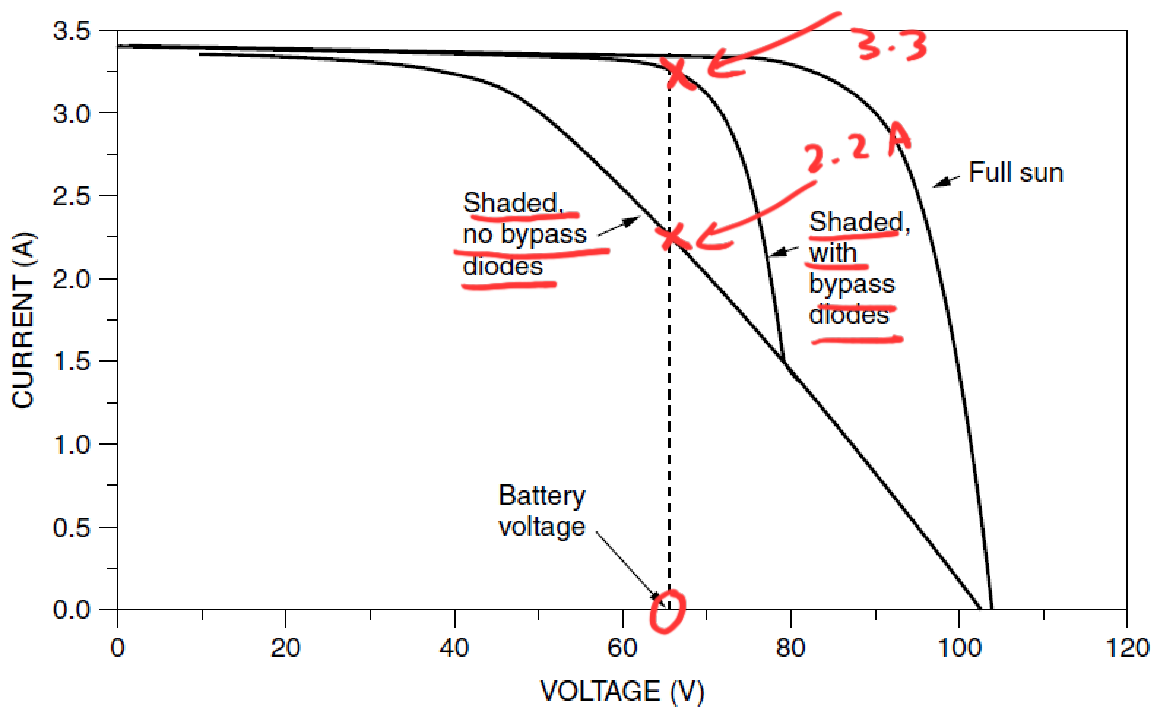


Fig. 8.42

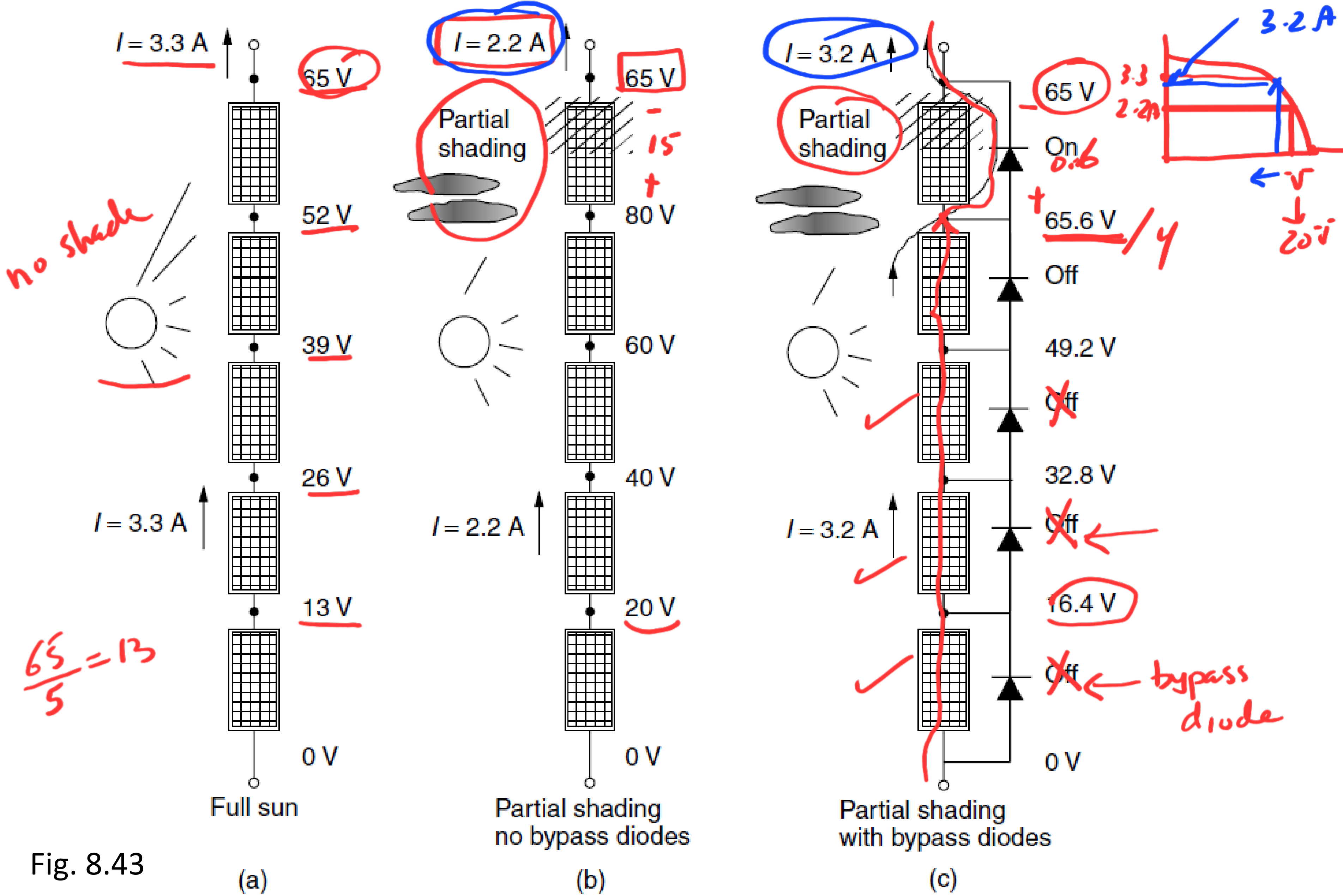


Fig. 8.43

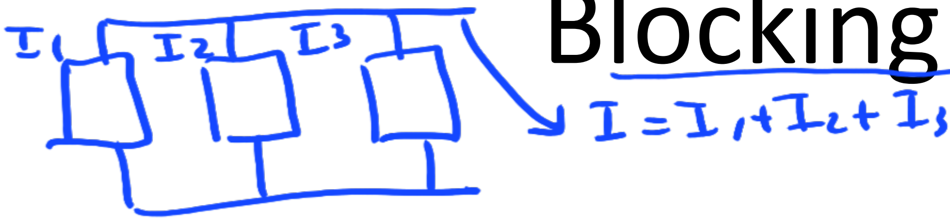
Without bypass diodes, a partially shaded module constricts the current delivered to the load (b). With bypass diodes, current is diverted around the shaded module.

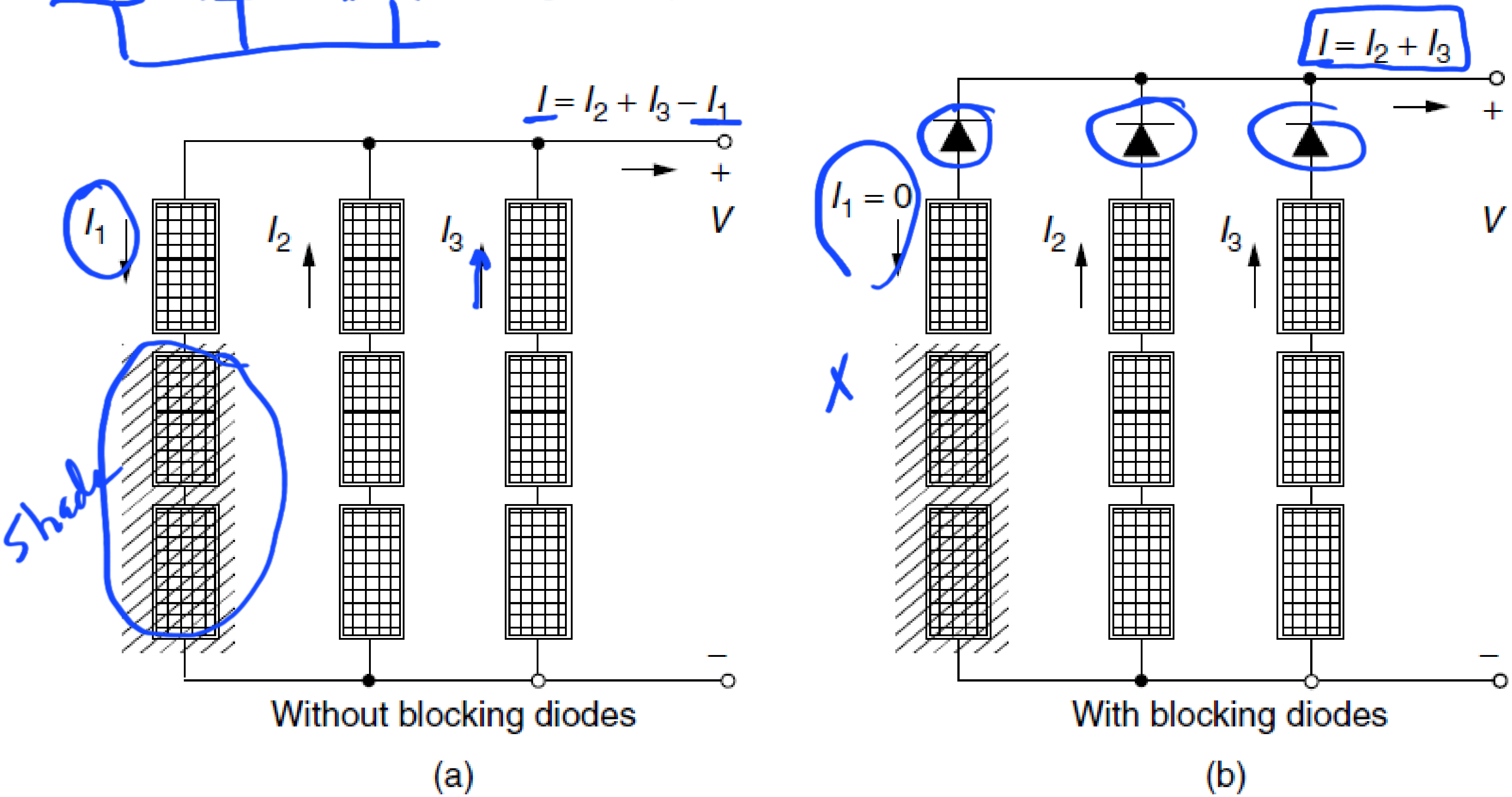
- Figure 8.43 (previous slide) helps explain how the bypass diodes do their job. Imagine five modules, wired in series, connected to a battery that forces the modules to operate at 65 V.
- In full sun the modules deliver 3.3 A at 65 V. When any of the cells are shaded, they cease to produce voltage and instead begin to act like resistors (6.6 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 Fig. 8.43c, 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.

Blocking Diodes

- When strings of modules are wired in parallel, a 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 Fig. next slide, the reverse current drawn by a shaded string can be prevented

Blocking Diodes





Blocking diodes prevent reverse current from flowing down malfunctioning or shaded strings.

Few more Notes

- The current of a PV device is directly proportional to surface area and solar irradiance.
- In other words, for a given device, doubling the surface area exposed to solar radiation will double the current output.
- Likewise, doubling solar irradiance on the device surface will double current.

- The maximum power point is located on the knee of the I-V curve and is the highest efficiency operating point for a PV device for the given conditions of solar irradiance and cell temperature.
- Due to the shape of the curve, maximum power voltage is typically about 70% to 80% of the value of the open-circuit voltage, while maximum power current is typically about 90% of the value of the short circuit current.

$$\begin{cases} V_{mpp} \approx (0.7-0.8)\, V_{oc} \\ I_{mpp} \approx 0.9\, I_{sc} \end{cases}$$

- Maximum power voltage and current can be measured only while the PV device is connected to a load that operates the device at maximum power.

- Most commercial crystalline silicon PV cells have fill factors exceeding 70%, while the fill factor for many thin-film materials is somewhat less.
- For a higher fill factor cell, the current decreases much less with increasing voltage up to the maximum power point, and decreases much more with increasing voltage beyond maximum power.

- A decrease in fill factor over time indicates problems with PV devices, including degradation of the cells or, more commonly, increased resistance of the wiring or connections in the system.

Efficiency

- *Efficiency is the ratio of power* output to power input.
- The efficiency of PV devices compares the solar power input to the electrical power output.
- Solar irradiance is multiplied by the area of the PV device to determine watts of solar power, which can then be directly compared to watts of electrical power.
- PV cell efficiencies vary considerably among different PV technologies, and for the same material and technology, efficiencies vary widely between laboratory samples and commercial devices.

- Efficiency is expressed as a percentage and is calculated with the following formula:

$$\eta = \frac{P_{mp}}{E \times A}$$

→ @ max power point

- *Pm - maximum power (in W)*
- *E = solar irradiance (in W/m^2)*
- *A = area (in m^2)* ← of the module (cell)

Example

- For example, what is the efficiency of a PV module with a surface area of 1.2 m^2 and a maximum power output of 160 W when exposed to 1000 W/m^2 solar irradiance?

$$\eta = \frac{P_{mp}}{E \times A}$$

$$\eta = \frac{160}{1000 \times 1.2}$$

$$\eta = \frac{160}{1200}$$

$$\eta = \mathbf{0.133} \text{ or } \mathbf{13.3\%}$$

- Cells with higher efficiencies require less surface area to produce each watt of power, which saves some costs for raw materials, mounting structures, and other equipment.
- However, higher efficiency modules are generally no less expensive than less efficient ones, because the price for modules is generally based on the maximum power rating and not on the size.
- For modules, efficiencies are often based on the entire module laminate area including the frame, and spacing between individual cells in the module.
- For individual cells, there is none of this extra area to affect the efficiency.
- This is one reason why module efficiencies are lower than their associated best cell efficiencies.

Operating point

- The operating point on an I-V curve is determined by the electrical load of the system.
- For example, if a battery is connected to a PV module, the battery voltage sets the operating voltage of the module. It also establishes the operating current that flows between the device and battery.
- If an incandescent lamp or DC motor is connected to a PV device, the effective resistance of the lamp filament or motor determines the operating point.
- Short-circuit current is associated with zero load resistance and open-circuit voltage is associated with infinite load resistance.
- Every point in between the two states has a specific load resistance that increases from left to right along the I-V curve.

Operating point

- PV cells operate most efficiently at their maximum power points. However, the maximum power point is constantly changing due to changes in solar irradiance and cell temperature.
- Consequently, some systems use maximum power point tracking (MPPT) to dynamically match the electrical loads to PV output in order to maximize the performance.
- This function is included in most interactive inverters and some battery charge controllers.
- The electrical load resistance required to operate a PV device at any point can be calculated using Ohm's law.

- For the maximum power point, the formula is:

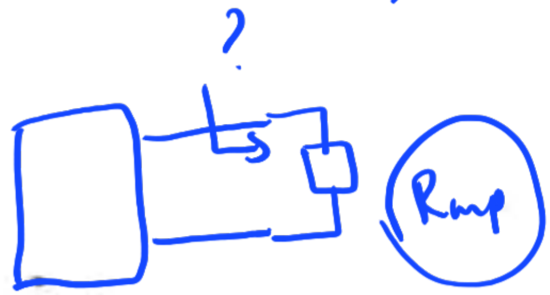
$$R_{mp} = \frac{V_{mp}}{I_{mp}}$$

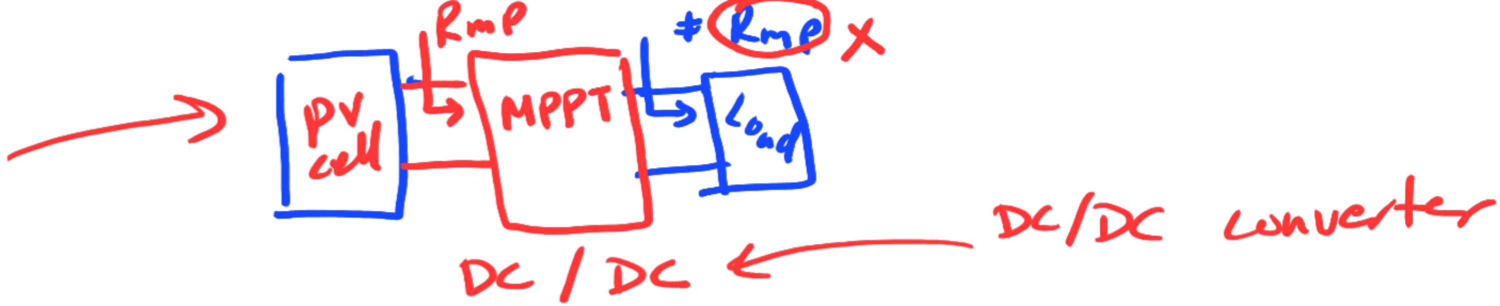
where

R_{mp} = resistance at maximum power point (in Ω)

V_{mp} = maximum power voltage (in V)

I_{mp} = maximum power current (in A)





- For example, a module has maximum power voltage of 15 V and maximum power current of 3 A.
- What resistance is required to operate the module at the maximum power point, and what is its maximum power?

$$R_{mp} = \frac{V_{mp}}{I_{mp}}$$

$$R_{mp} = \frac{15}{3}$$

$$R_{mp} = \mathbf{5\ \Omega}$$

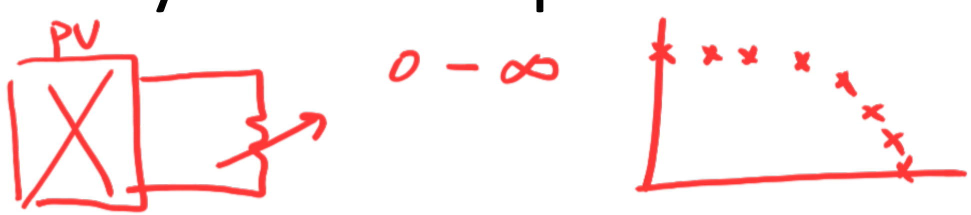
$$P_{mp} = V_{mp} \times I_{mp}$$

$$P_{mp} = 15 \times 3$$

$$P_{mp} = \mathbf{45\ W}$$

I-V Curve Measurement

- A variable resistive load, such as a rheostat or adjustable resistor, can be used to load a PV device over nearly its entire I-V curve.
- When combined with meters measuring voltage and current, this method can be used to generate the I-V curves of small PV devices or individual modules which can be then used to identify the key I-V curve parameters

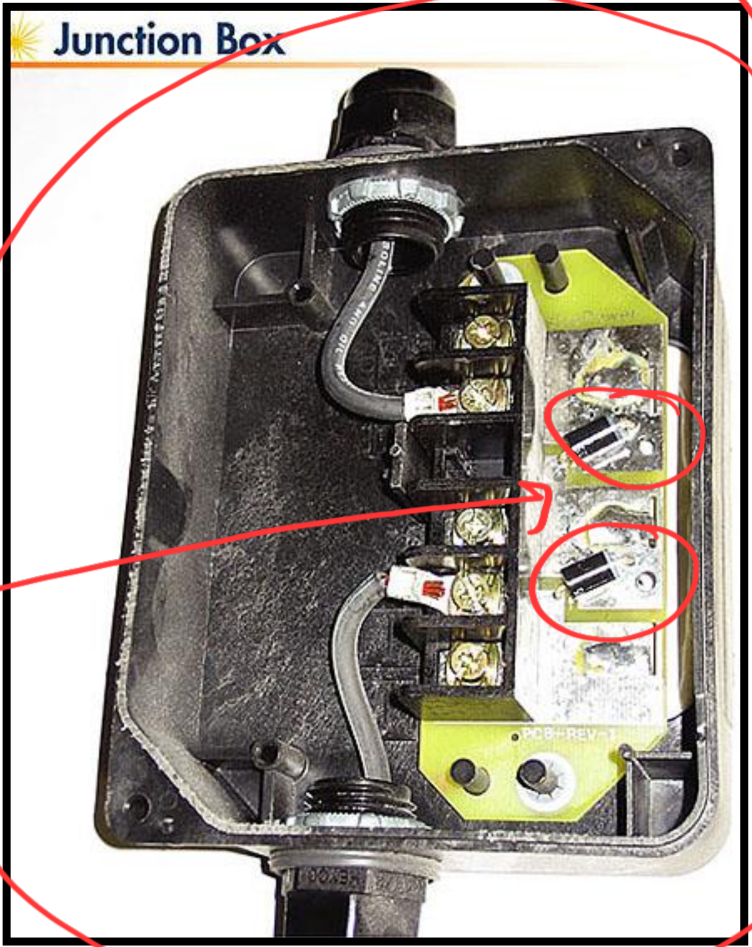


Automated I-V Curve Measurement

- Automatic Measurement of I-V curve can be done using an electronic load
- This electronic load can be implemented using commercially available electronic loads
- Many other techniques can be used to implement the electronic load using capacitive charging, MOSFET , DC-Dc converter

Junction Box

- A junction box on the back of a module provides a protected location for electrical connections and bypass diodes.



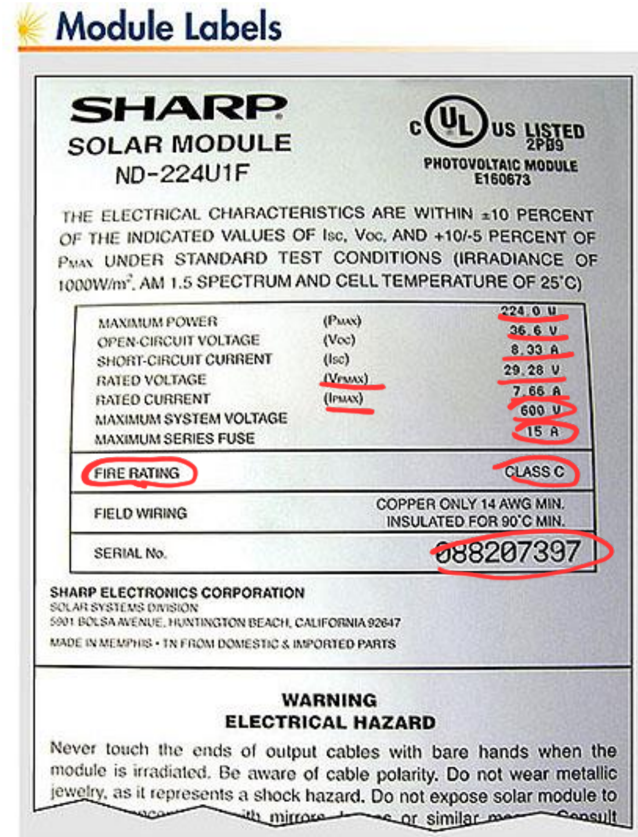
Reliability

tests

- Reliability of modules is assured through series Design qualification tests which include thermal cycling, humidity and freezing, impact and shock, immersion, cyclic pressure, twisting, vibration and other mechanical tests, and excessive and reverse current electrical tests.
- Design qualification has important implications for product warranties offered by manufacturers.
- As a result, most major module manufacturers offer warranties of 20 years or more, guaranteeing module peak power output of at least 80% of initial nameplate ratings.
- This equates to a degradation rate of no more than 1% per year.
- These exceptionally long warranty periods are not typical among other electrical equipment and appliance warranties, but are offered to assure buyers of the long term performance of PV systems.

Module Label

- Module labels must include performance ratings for the module and may include other information used to design a PV system.



https://www.sharp.co.uk/cps/rde/xbcr/documents/documents/Marketing/Datasheet/NDR250A5_NDR245A5_Flyer_0414_en.pdf

https://www.sharp.co.uk/cps/rde/xbcr/documents/documents/Marketing/Datasheet/1901_NDAH330H_Poly_Datasheet_EN.pdf

https://www.sharp.co.uk/cps/rde/xbcr/documents/documents/Marketing/Datasheet/1902_NU-AH360_370_Mono_Datasheet_EN_v1.pdf

Example Data Sheet

ND-R250A5 | 250W
ND-R245A5 | 245W
Polycrystalline silicon photovoltaic modules

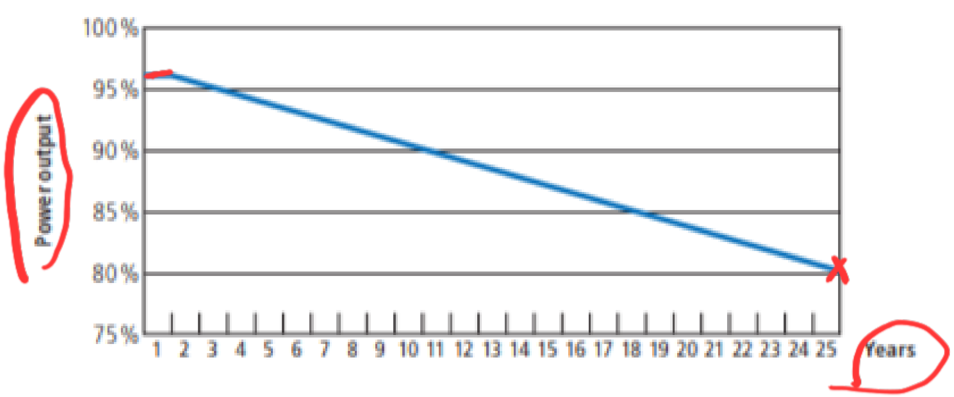
Product features

- High-performance photovoltaic modules made of polycrystalline (156.5 mm)² silicon solar cells with module efficiencies of up to 15.2%.
- 3 busbar technology for enhancing the power output.
- Anti-reflex coating to increase light absorption.
- Production controlled positive power tolerance from 0 to +5%. Only modules will be delivered that have the specified power or more for high energy yield.
- Improved temperature coefficient to reduce power losses at higher temperatures.
- High power performance even at lower irradiations.

Quality from Sharp

Continual checks guarantee a consistently high level of quality. Every module undergoes visual, mechanical, and electrical inspection. This is recognisable by means of the original Sharp label, the serial number, and the Sharp guarantee:

- 10-year product guarantee
- 25-year linear performance guarantee
  - Minimum 96% of the specified minimum power output during the first year
  - Maximum 0.667% annual reduction of the power output for the following 24 years



https://www.sharp.co.uk/cps/rde/xbcr/documents/documents/Marketing/Datasheet/NDR250A5_NDR245A5_Flyer_0414_en.pdf

ELECTRICAL DATA (AT STC)

		ND-R250A5	ND-R245A5	
Maximum power	P_{max}	250	245	W_p
Open-circuit voltage	V_{oc}	37.6	37.3	V
Short-circuit current	I_{sc}	8.68	8.62	A
Voltage at point of maximum power	V_{mpp}	30.9	30.7	V
Current at point of maximum power	I_{mpp}	8.10	7.99	A
Module efficiency	η_m	15.2	14.9	%

STC = Standard Test Conditions: irradiance 1,000 W/m², AM 1.5, cell temperature 25 °C.
Rated electrical characteristics are within ±10% of the indicated values of I_{sc}, V_{oc} and 0 to +5% of P_{max} (power measurement tolerance ±3%).

ELECTRICAL DATA (AT NOCT)

		ND-R250A5	ND-R245A5	
Maximum power	P_{max}	180.2	176.6	W_p
Open-circuit voltage	V_{oc}	36.7	36.4	V
Short-circuit current	I_{sc}	7.0	6.96	A
Voltage at point of maximum power	V_{mpp}	27.7	27.5	V
Nominal Operating Cell Temperature	NOCT	47.5	47.5	°C

NOCT: Module operating temperature at 800 W/m² irradiance, air temperature of 20 °C, wind speed of 1 m/s.

NOCT: Module operating temperature at 800 W/m² irradiance, air temperature of 20 °C, wind speed of 1 m/s.

LIMIT VALUES

Maximum system voltage	1,000 V DC
Over-current protection	15 A
Temperature range	−40 to +90 °C
Maximum mechanical load	2,400 N/m²

MECHANICAL DATA

Length	1,652 mm (+/−3.0 mm)
Width	994 mm (+/−2.0 mm)
Depth	46 mm (+/−0.8 mm)
Weight	19 kg

TEMPERATURE COEFFICIENT

P_{max}	−0.440 % / °C
V_{oc}	−0.329 % / °C
I_{sc}	+0.038 % / °C

GENERAL DATA

Cells	polycrystalline, 156.5 mm × 156.5 mm, 60 cells in series
Front glass	low iron tempered glass, 3 mm
Frame	anodized aluminium alloy, silver
Connection box	PPE/PPO resin, IP65 rating, 58 × 125 × 15 mm, 3 bypass diodes
Cable	4 mm², length 1,000 mm
Connector	SMK (MC4 compatible), Type CCT9901-2361F/2451F (Catalogue no. P51-7H/R51-7), IP67 rating To extend the module connection leads, only use SMK connector from the same series or MultiContactAG MC4 connector (PV-KST04/PV-KBT04)

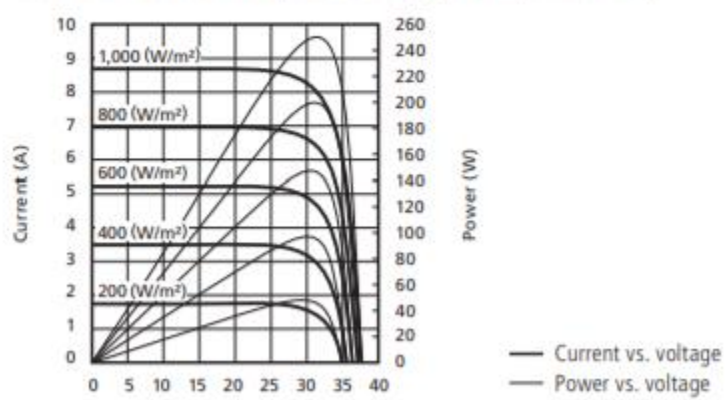
PACKING DATA

Modules per palette	30 pcs
Palette size (length × width × height)	1,670 × 1,010 × 1,840 (mm)
Palette weight	626 kg

2 modules are packed in one carton.

CHARACTERISTIC CURVES ND-R250A5

Characteristic curves: current/power vs. voltage (cell temperature: 25 °C)



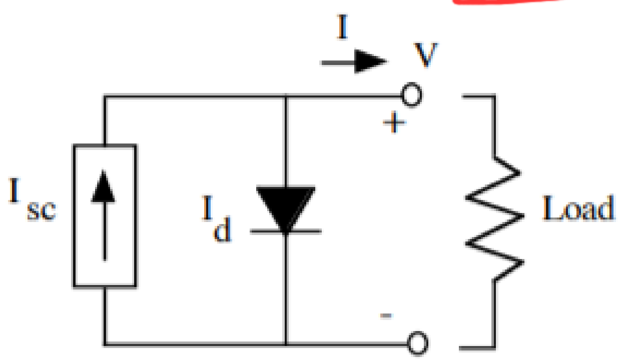
Degradation-and-failure-modes

- https://www.pveducation.org/pvcdrom/modules/degradation-and-failure-modes (FOR SELF STUDY)

Problems and Solutions

- Problems

For the simple equivalent circuit of a 0.017 m² photovoltaic cell shown below, the reverse saturation current is $I_0 = 4 \times 10^{-11}$ A and at an insolation of 1-sun the short-circuit current is $I_{SC} = 6.4$ A. At 25°C, find the following:



a. The open-circuit voltage.

b. The load current and output power when the output voltage is $V = 0.55$ V.

c. The efficiency of the cell at $V = 0.55$V.

a. Open circuit voltage from (5.11) is

$$V_{OC} = 0.0257 \ln\left(\frac{I_{SC}}{I_0}+1\right) = 0.0257 \ln\left(\frac{6.4}{4x10^{-11}}+1\right) = 0.663V$$

b. When the output voltage is 0.57 V, the load current will be

$$I_L = I_{SC} - I_d = I_{SC} - I_0\left(e^{38.9V}-1\right)$$

$$= 6.4 - 4x10^{-11}\left(e^{38.9x0.57}-1\right) = 6.23A$$

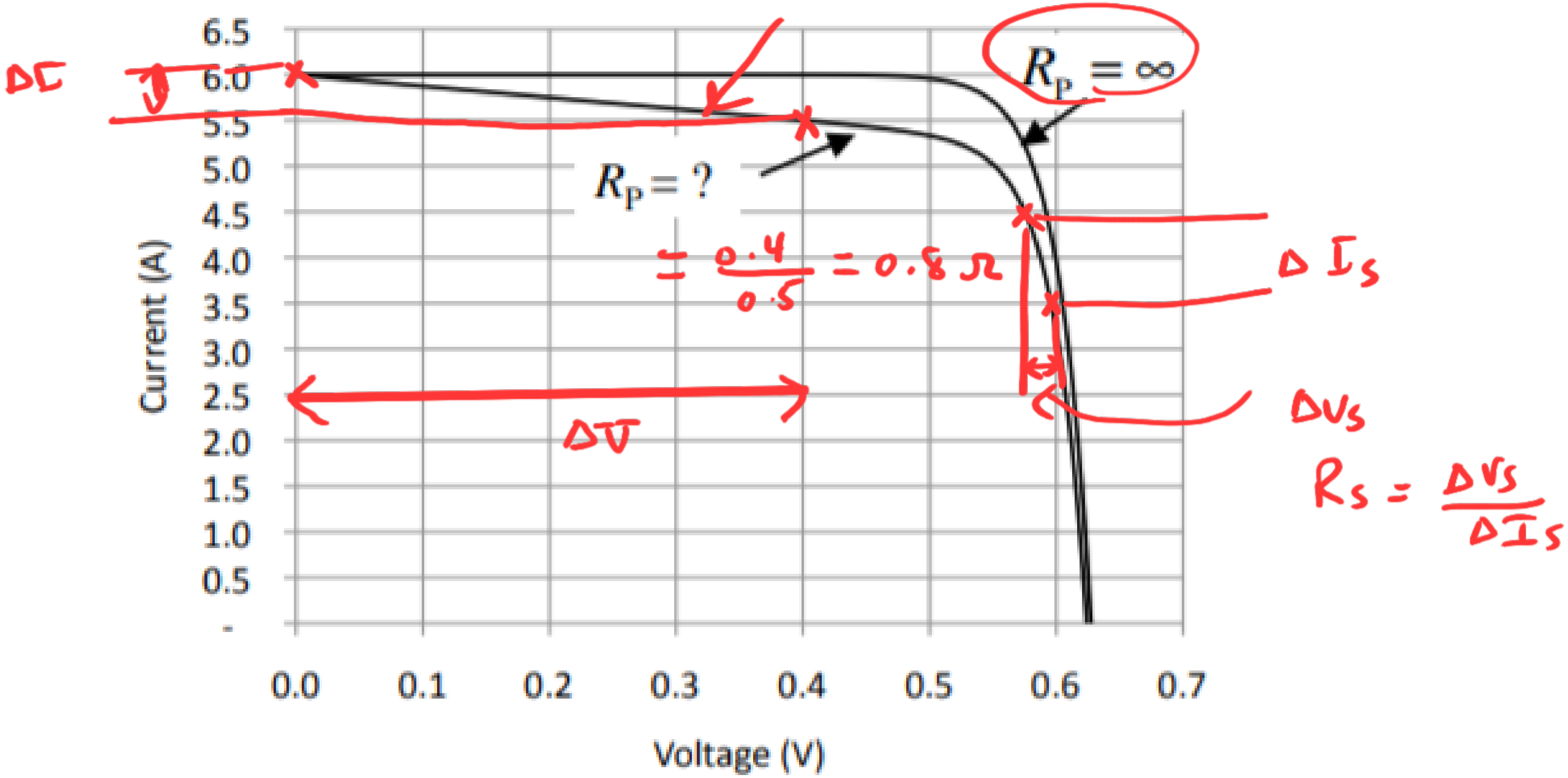
$$P = IV = 6.23A \cdot 0.57V = 3.55W$$

c. Cell efficiency

$$\eta = \frac{output}{input} = \frac{3.55W}{0.017m^2 x 1000W/m^2} = 0.209 = 20.9\%$$

The following figure shows two I-V curves. Both have zero series resistance. One is for a PV cell with an equivalent circuit having an infinite parallel

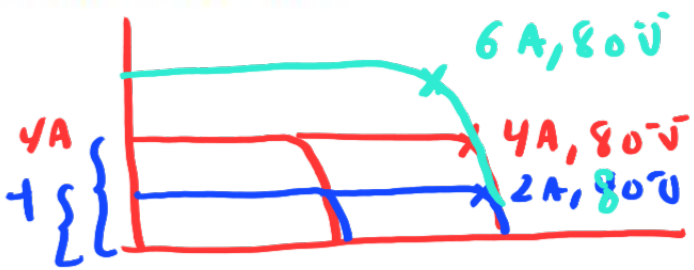
resistance. For the other, what is the parallel resistance in its equivalent circuit?

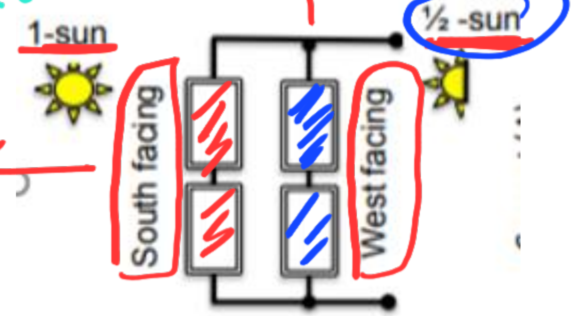


The slope of the drop off in current can be estimated from the point where V = 0.4V and ΔI = 6.0 – 5.5 = 0.5 A:

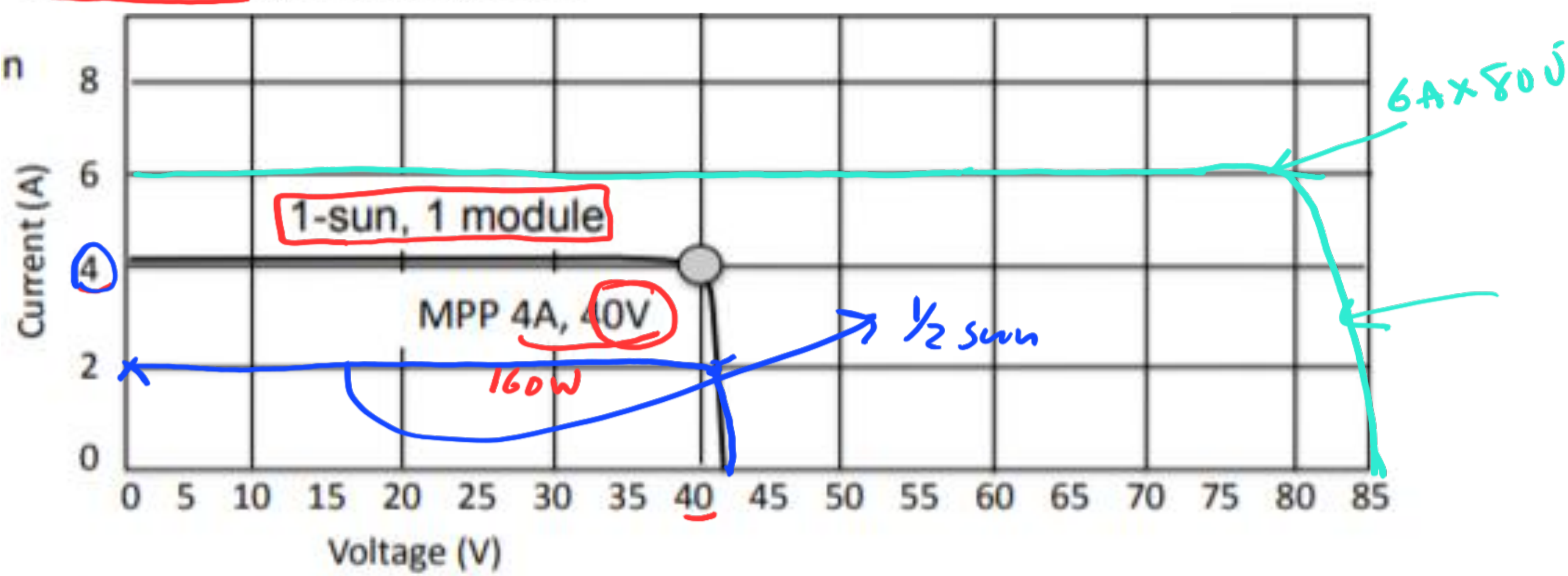
$$R_p = \frac{\Delta V}{\Delta I} = \frac{0.4}{0.5} = 0.8\Omega$$

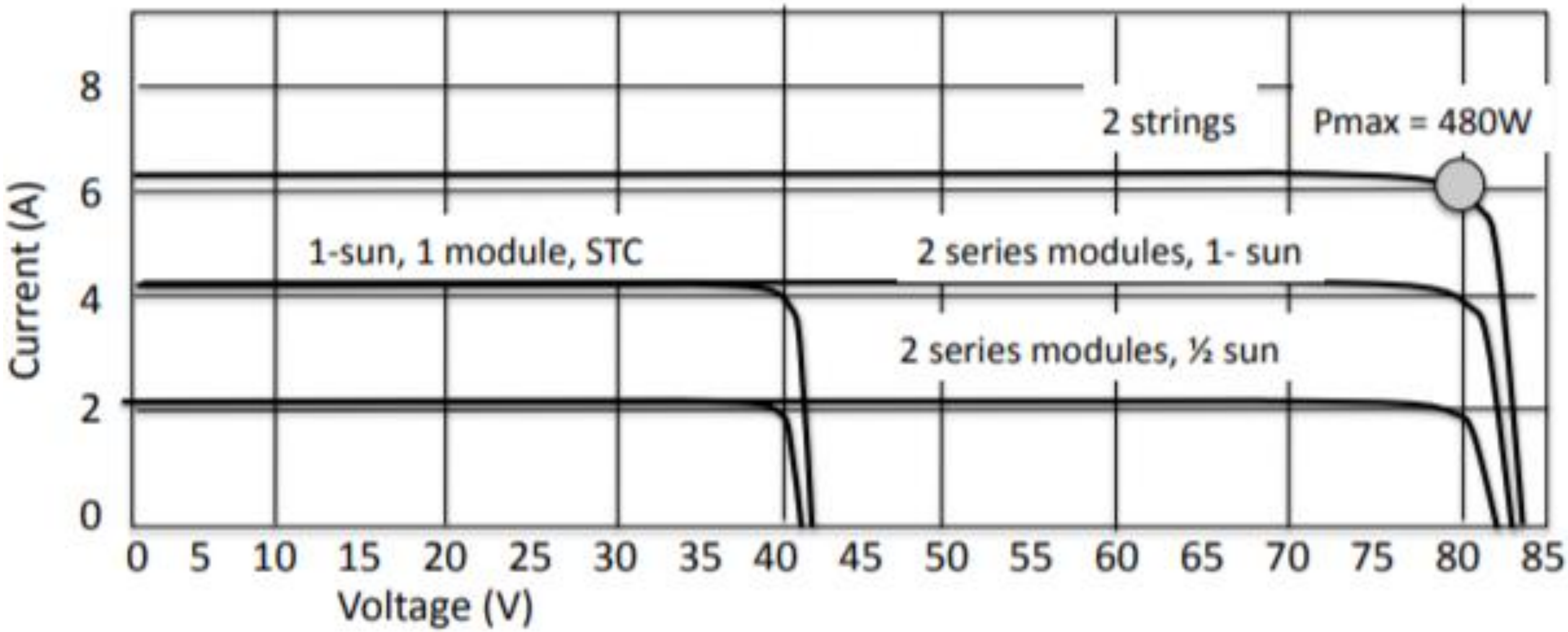
A 4-module array has two south-facing modules in series exposed to 1000 W/m² of insolation, and two west-facing modules exposed to 500 W/m². The 1-sun *I-V* curve for a single module with its maximum power point at 4A, 40V is shown below.





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





8
6
4
2
0
Current (A)
2 strings
Pmax = 480W
1-sun, 1 module, STC
2 series modules, 1- sun
2 series modules, ½ sun
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85
Voltage (V)

SOLN: 480 W

A 200-W c-Si PV module has NOCT = 45°C and a temperature coefficient for rated power of -0.5%/°C.

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

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

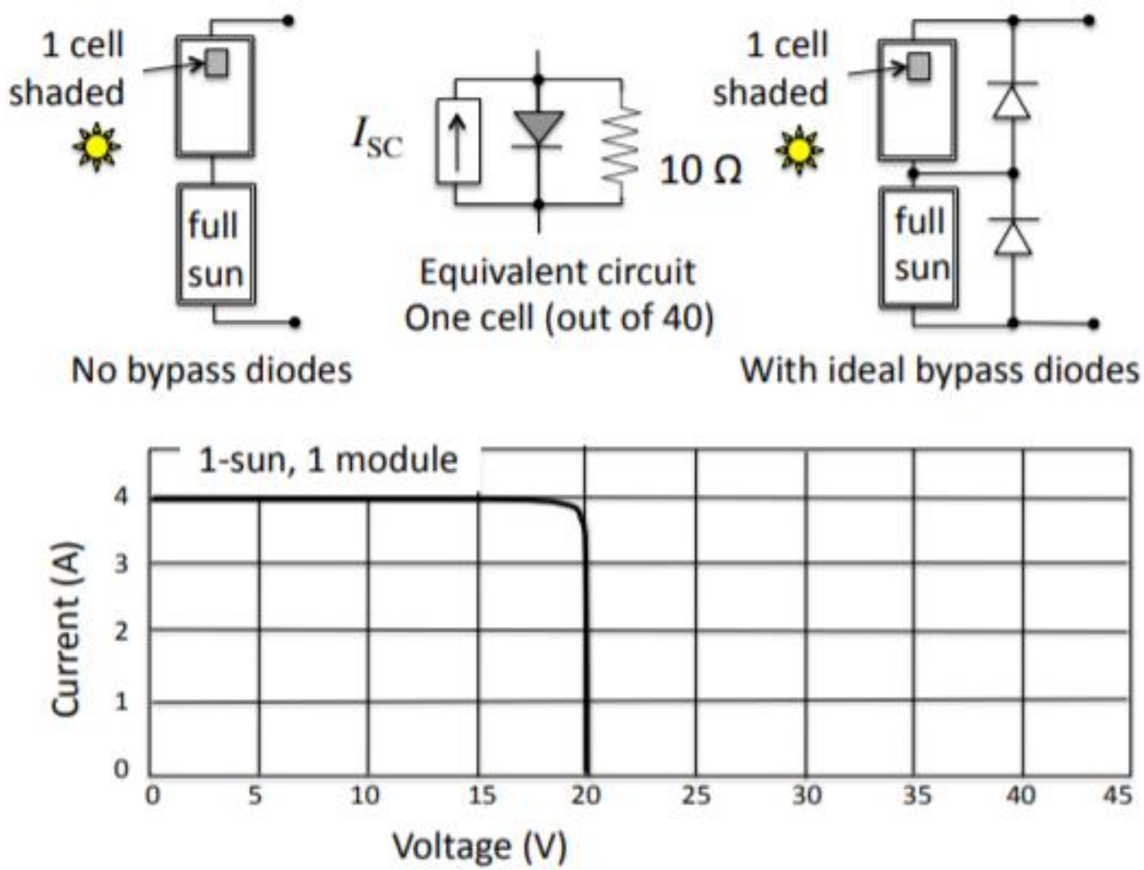
$$P_{max} = 200\text{W}\left[1\text{-}0.5\%/^\circ\text{C}(56.25\text{-}25)^\circ\text{C}\right] = 168.8\text{ W} \quad \text{... a drop of } 15.6\%$$

End of L13

24/4/2021

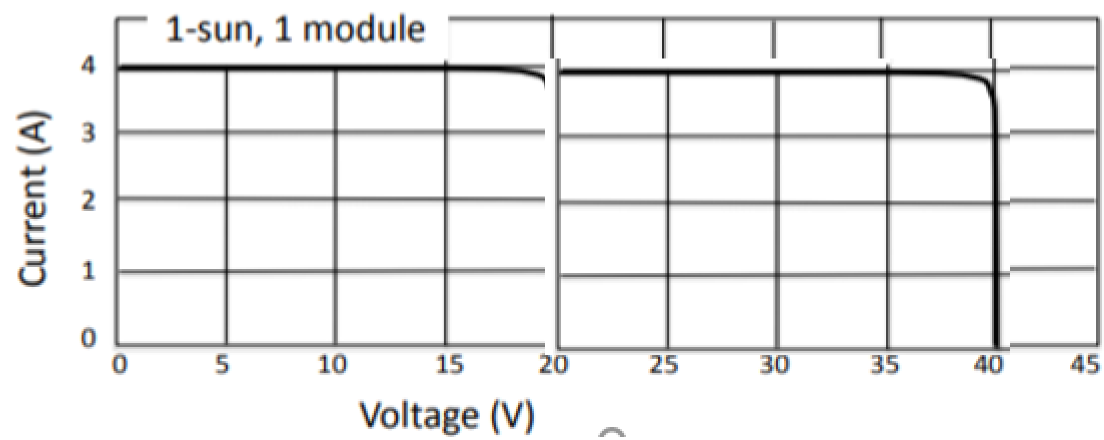
The 1-sun *I-V* curve for a 40-cell PV module in full sun is shown below along with an equivalent circuit for a single cell (including its 10Ω parallel resistance).

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.



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.

b. Sketch the 1-sun *I-V* curve when the bypass diodes are included. Estimate the maximum power output now (close is good enough).



MPP without diodes is at 2A x 20V = 40W could guess, which is fine or prove it by

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

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

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

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

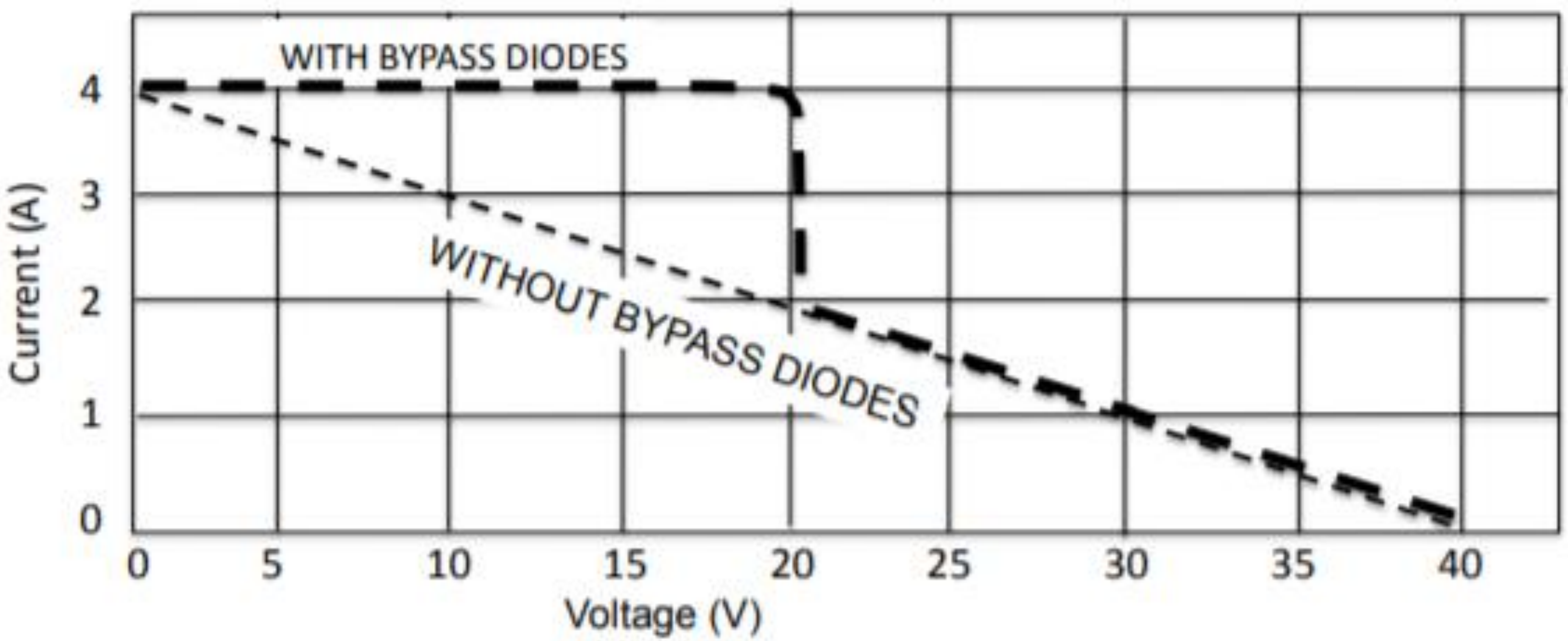
MPP without diodes is at 2A x 20V = 40W could guess, which is fine or prove it by

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

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

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

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



b. MPP with diodes is at about 4A x 20V = 80 W. Still lost half of the 160 W output when there is no shading.