Energia Fotovoltaica

Parte II - Materiais Fotovoltaicos e Agregações de Células PV

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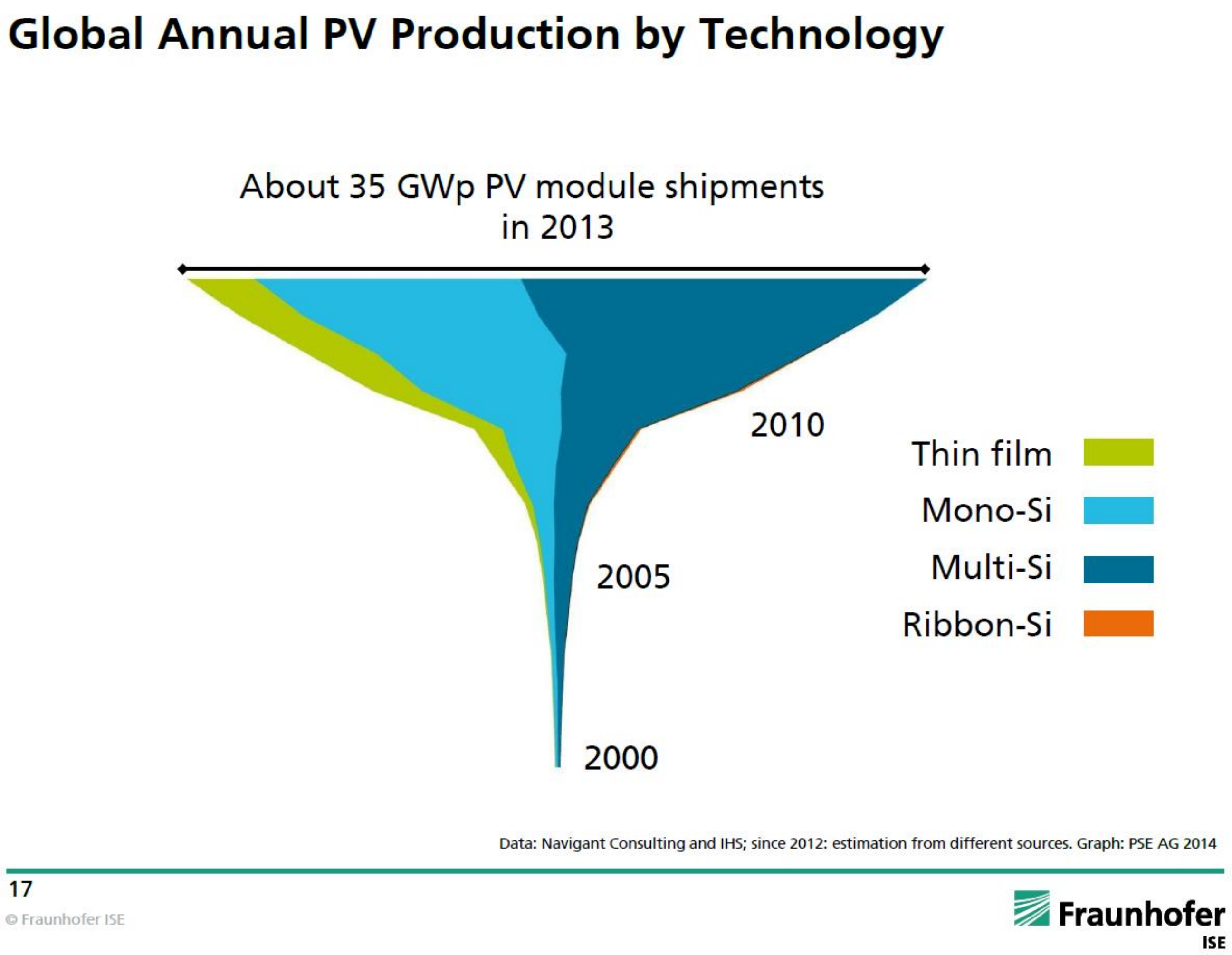
PV Materials

- There are many different materials used for PV cells;
- However the marketplace is dominated by three technologies:
  - *Monocrystalline silicon (mono-si);*
  - *Polycrystalline silicon (p-Si);*
  - *Thin film.*

PV Material Market Share



Note that silicon continues to dominate in market share

Source: http://www.ise.fraunhofer.de/en (Photovoltaics Report, July 2014)

Monocrystalline Silicon (mono-si)

- Also called crystalline silicon
- Made out of high grade silicon ingots that are *cylindrical* in shape (Czochralski method)
  - Their edges are cut ⇒ sq. cross section, significant waste
  - Have a even coloring and a uniform look
- These panels tend to cost more but have higher efficiency and longer life
  - Example: SunPower E20 series with 20% efficiency

Image: http://solargaincommercial.com.au/sites/default/files/sunpower-solar-power-module.png

Polycrystalline Silicon (p-Si) or Multi-cyrstalline Silicon (mc-Si)

- Oldest of the commercial PV panels
- Silicon is melted and poured into square molds
  - Result is square wafers, with no side cuts
- Advantages are that they are less expensive, and result in less waste
- Disadvantage is efficiency is lower (13-16%); more speckled appearance

Image: http://dev.msbs.net/Portals/0/images/PolycrystallineSolarPanel.jpg

Thin-Film Solar Cells

- Thin-film solar cells are created by depositing one or more layers of material onto glass or metal substrate
  - Examples include amorphous silicon (a-Si), gallium arsenide (arsenieto de gálio) (GaAs), cadmium telluride (CdTe), copper indium gallium selenide (CIS) (telureto de cádmio, seleneto de cobre-índio-gálio)
- Advantages are that they are simple to mass produce, have a uniform appearance, and can be flexible
- Disadvantages are they are not very efficient, and may degrade faster

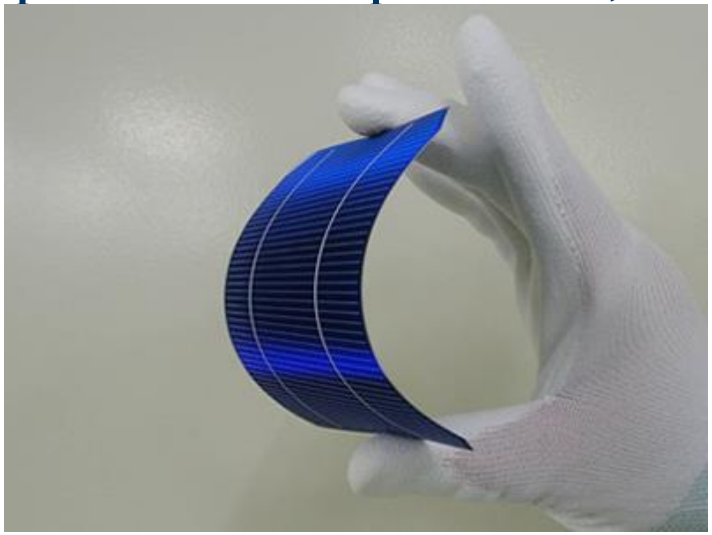
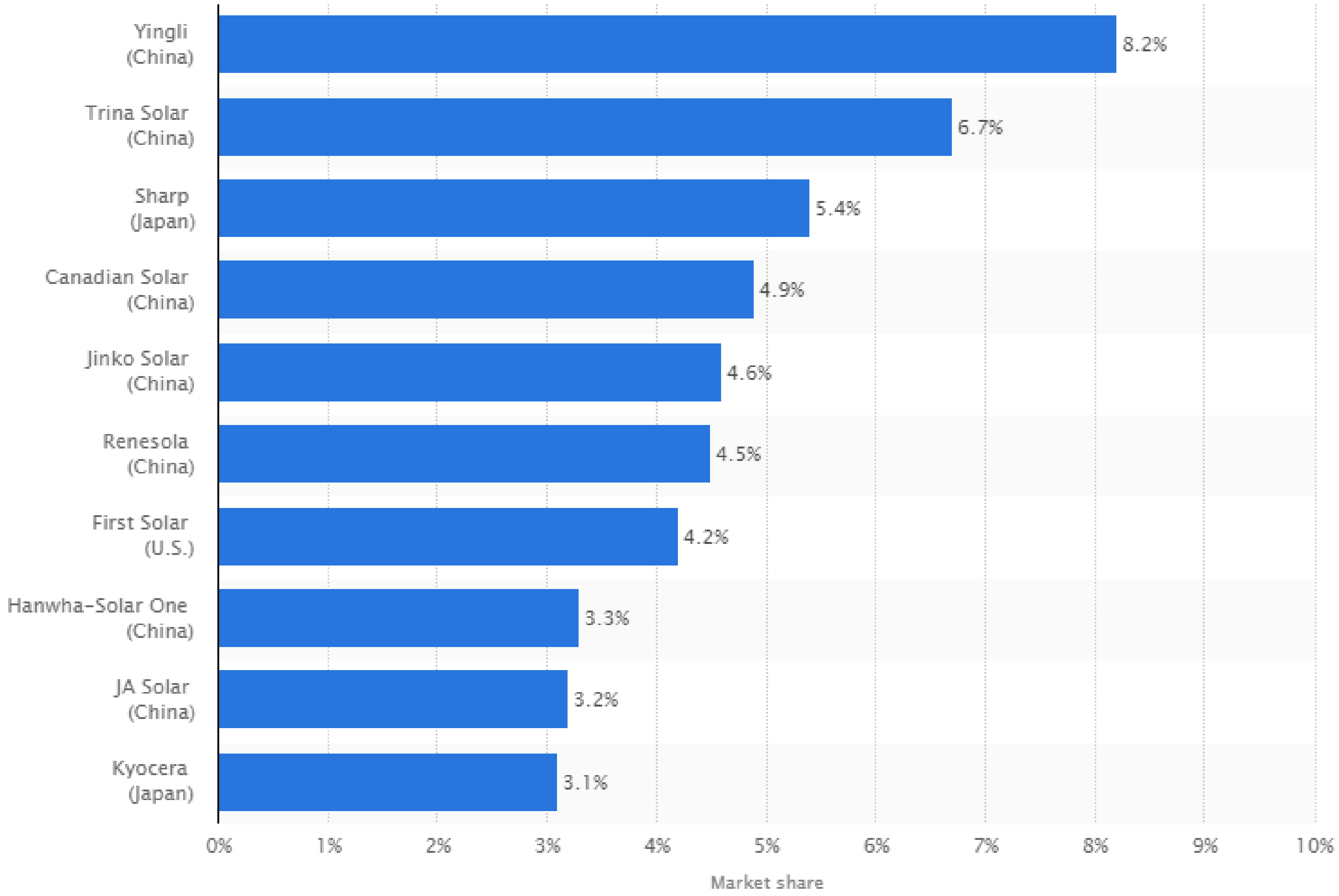


Image: http://www.thesolarco.com/images/Why-Choose-Monocrystalline-Technology_amorphous.jpg

Global Market Share PV Manufacturers, 2013



Solar PV Prices Have Recently Dropped

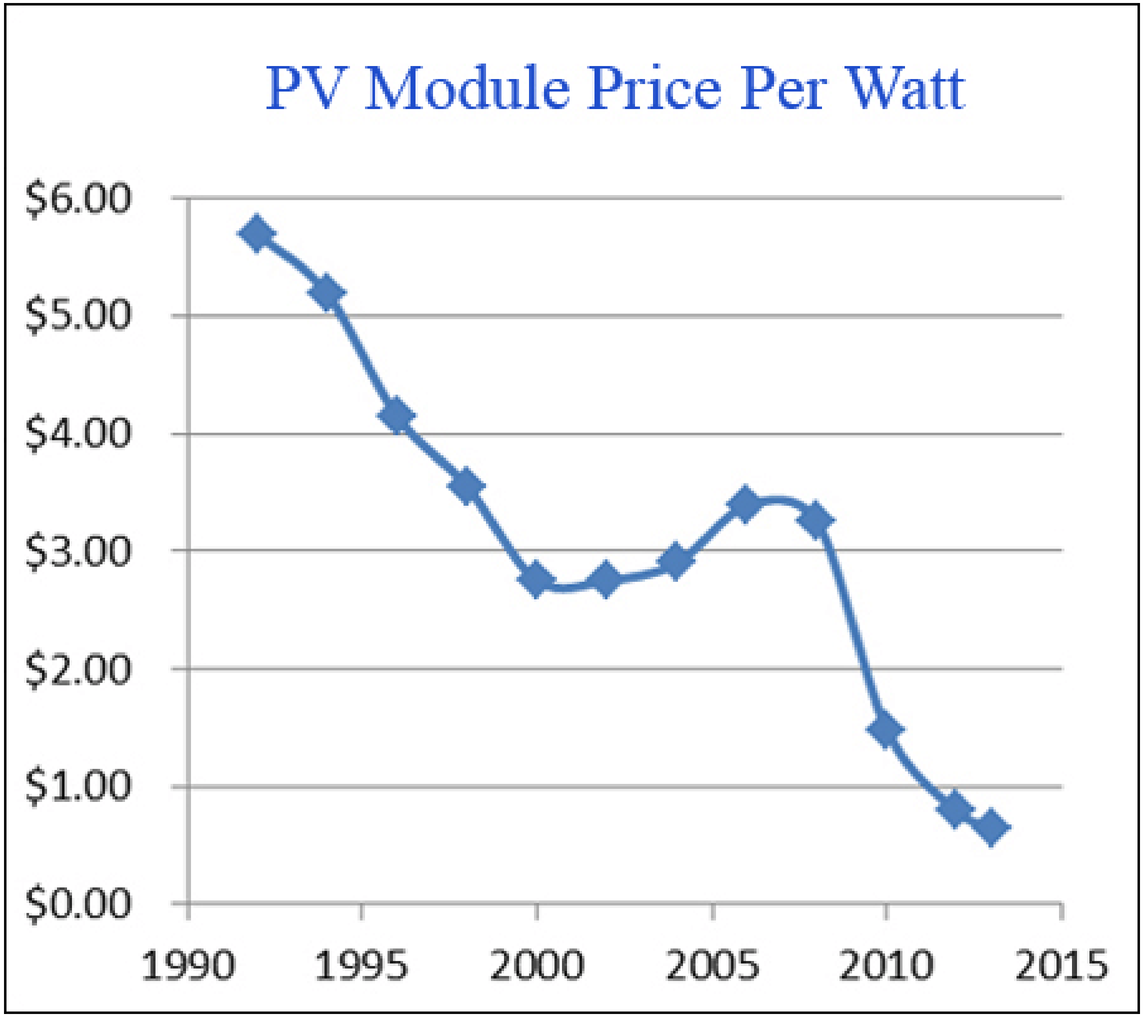
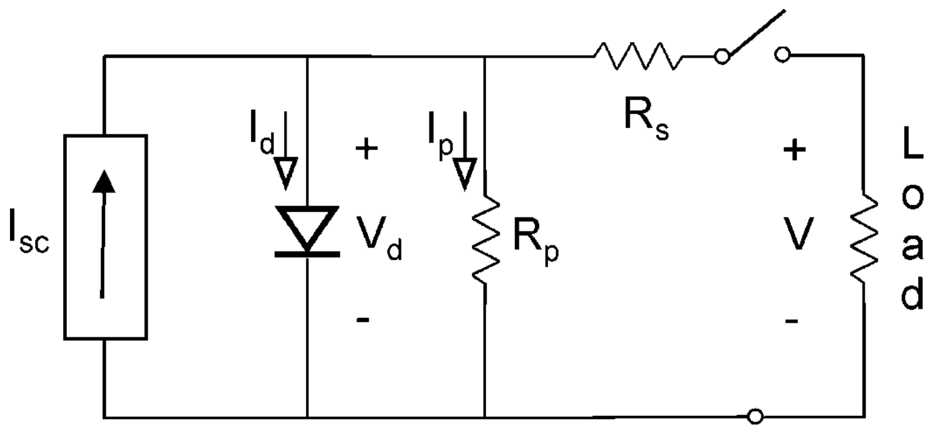


Image: http://solarcellcentral.com/markets_page.html

Single Cell Example

Equivalent Circuit:



Assume $I_0 = 5\times10^{-11}$ A, I_{sc}=5A, R_p=5Ω, R_s=0.01 Ω.
At 25°C what is V_{oc}?

$$I_{sc} = I_d + \frac{V_d}{5}$$

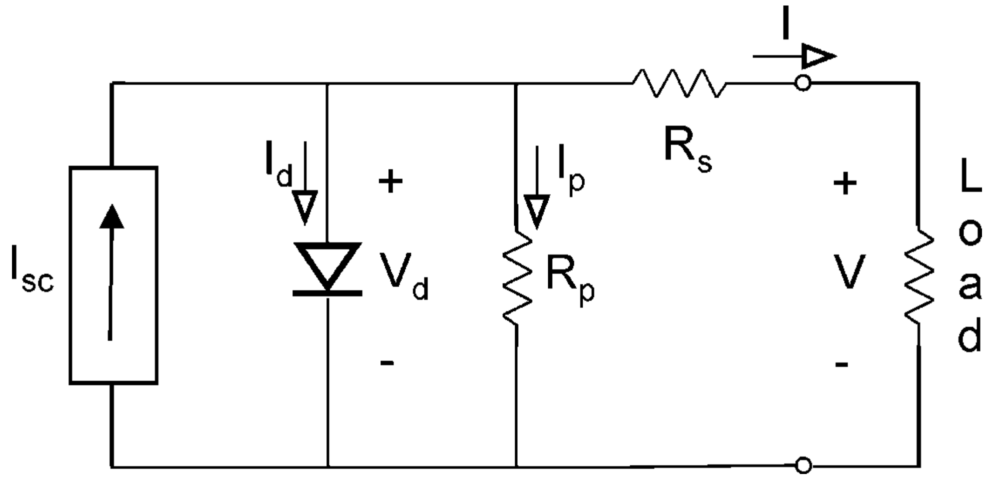
$$5 = 5\times 10^{-11}(e^{38.9V_d} - 1) + \frac{V_d}{5}$$

That equation cannot be solved directly, but an iterative solution can be found (guess a V_d and solve with Newton's method). Guess V_d = 0.65, next iteration is 0.6504.

Single Cell Example Continued: V-I Curve

- To generate the output V-I Curve
  - Pick a value of V_d
  - Solve for I_d
  - Solve for I_p
  - $I=I_{sc} - I_d - I_p$
  - $V=V_d-R_s*I$

Equivalent Circuit:



Assume V_d=0.64, I_{sc} = 5A

$$I_d = 5\times 10^{-11}(e^{38.9V_d} - 1) = 3.245$$

$$I_p = \frac{0.64}{5} = 0.128$$

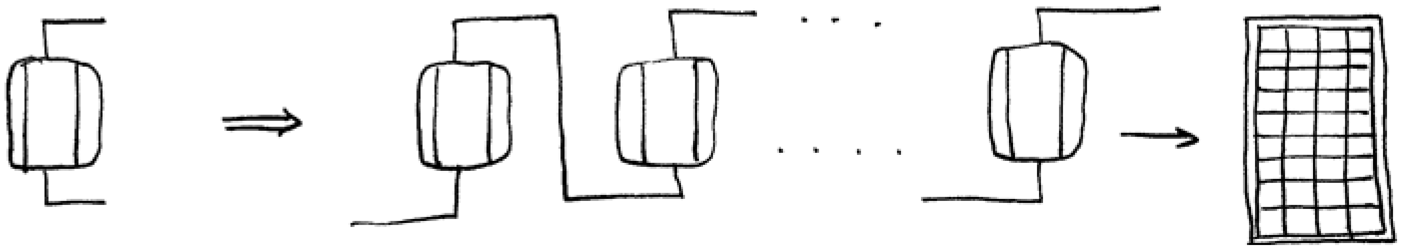
$$I = 5 - 3.245 - 0.128 = 1.627$$

$$V = 0.64 - 0.01\times 1.558 = 0.624$$

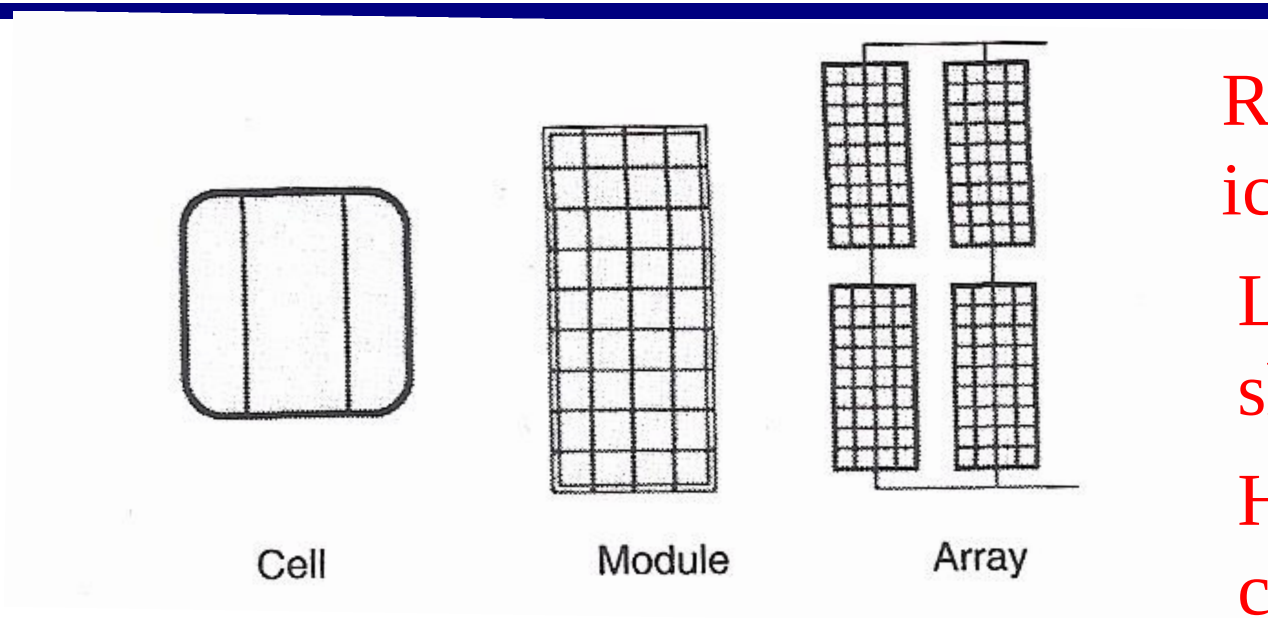
This is one point on the curve

Cells as Building Blocks

- The *open circuit voltage* of a solar cell is ≅ 0.6 V and ≅ 0.5 V when the cell is loaded
- Since 0.5 V is rather low for power applications, it is rare that we use one individual cell
- Instead, we use ***modules***, which consist of a bunch of individual cells in series, encased in a tough, weather-resistant package
- The modules are commonly connected into ***arrays***



Cells to Modules to Arrays



Rain, hail, ice, snow

Local failures, shadows

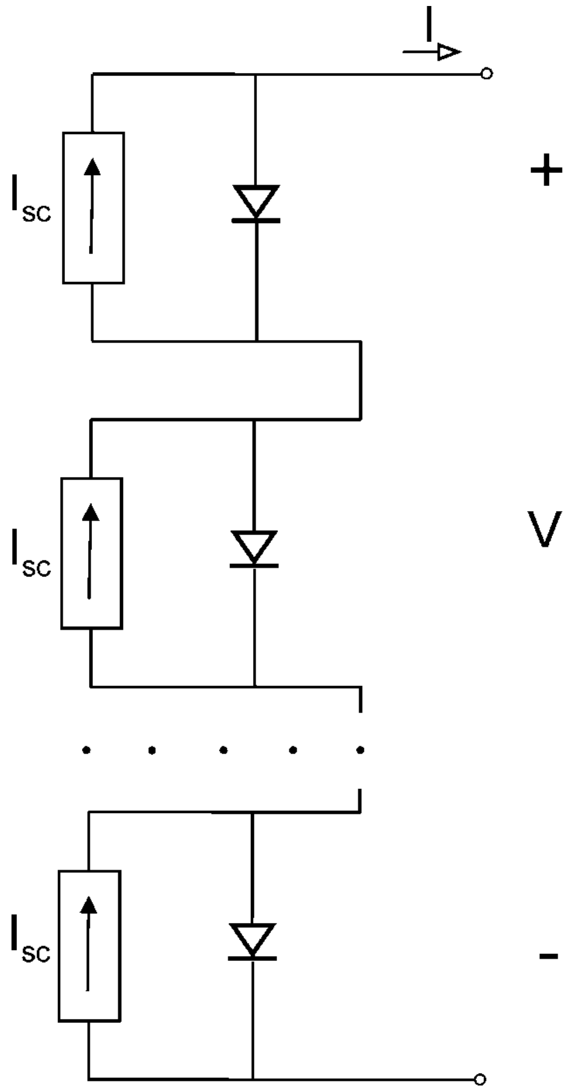
Heat, humidity, corrosive gases

Modules – A 12V module has 36 cells wired in series, each cell ~ 0.5 V

72-cell modules are also common (usually 24 V)

Arrays – combination of modules connected in series and/or in parallel

Module with Simple Cell Model



Using the ***simplest model*** of a cell:

$$V = V_1 + V_2 + \ldots + V_n = nV_d$$

$$I = I_{SC} - I_d$$

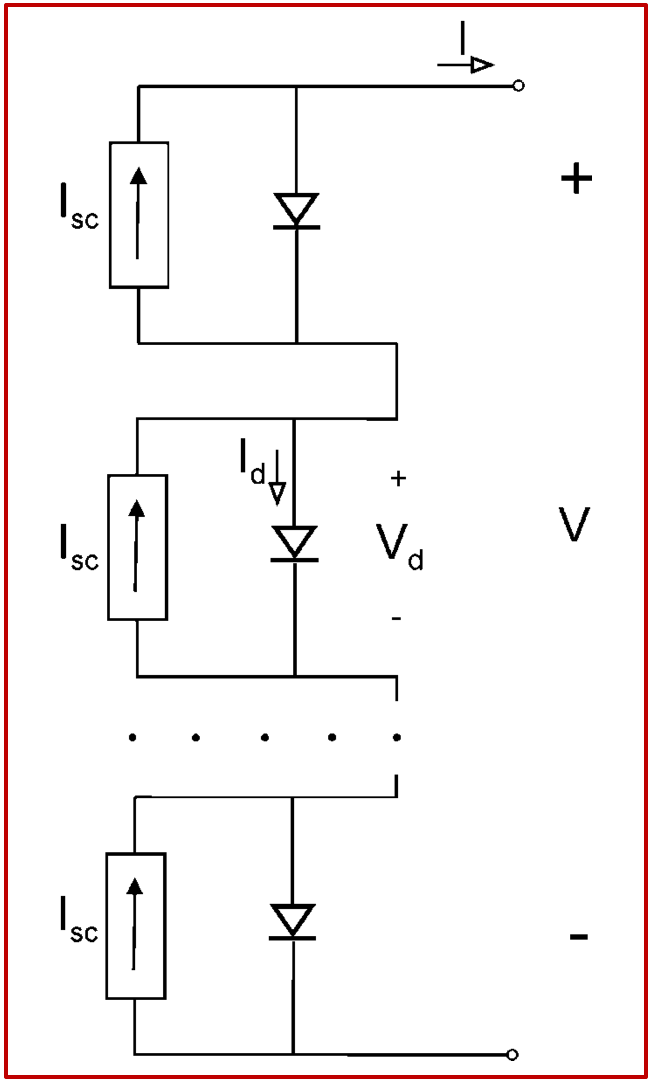
For one cell (in the sun):

$$I = I_{SC} - I_0 (e^{qV_d/kT} \text{-}1)$$

$$e^{qV_d/kT} = \frac{I_{SC} - I}{I_0} + 1$$

$$V_d = \frac{kT}{q} \ln\left(\frac{I_{SC} - I + I_0}{I_0}\right)$$

Module with Simple Cell Model



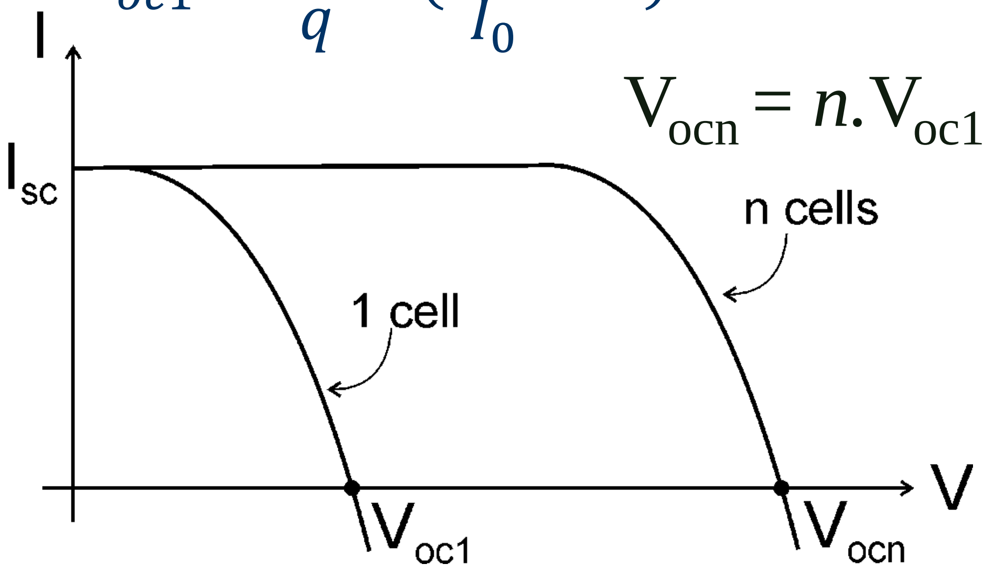
For the entire module

$$V = n \cdot \frac{kT}{q} \ln\left(\frac{I_{SC} - I + I_0}{I_0} \right)$$

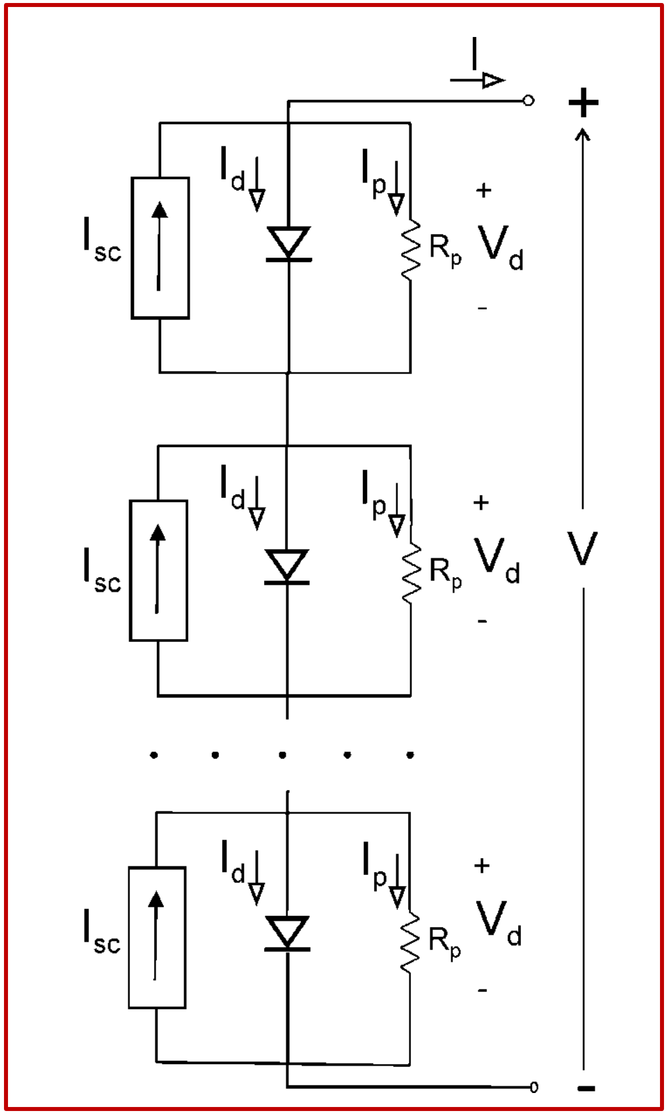
$$I = I_{SC} - I_0 (e^{qV/nkT} \text{-}1)$$

$$V_{oc1} = \frac{kT}{q} \ln(\frac{I_{SC}}{I_0} + 1)$$

$$\mathrm{V_{ocn}} = n.\mathrm{V_{oc1}}$$



Module with Parallel-Only Cell Model



For one cell (in the sun)

$$V = nV_d$$

$$I_d = I_{SC} - I - \frac{V_d}{R_P}$$

$$V_d = \frac{kT}{q}\ln\left(\frac{I_d}{I_0} + 1\right)$$

For the entire module

$$V = n \cdot \frac{kT}{q}\ln\left(\frac{I_{SC} - I - V/(nR_P)}{I_0} + 1\right)$$

$$I = I_{SC} - I_0(e^{qV/nkT} \text{-}1) - \frac{V}{R_P n}$$

Module Example

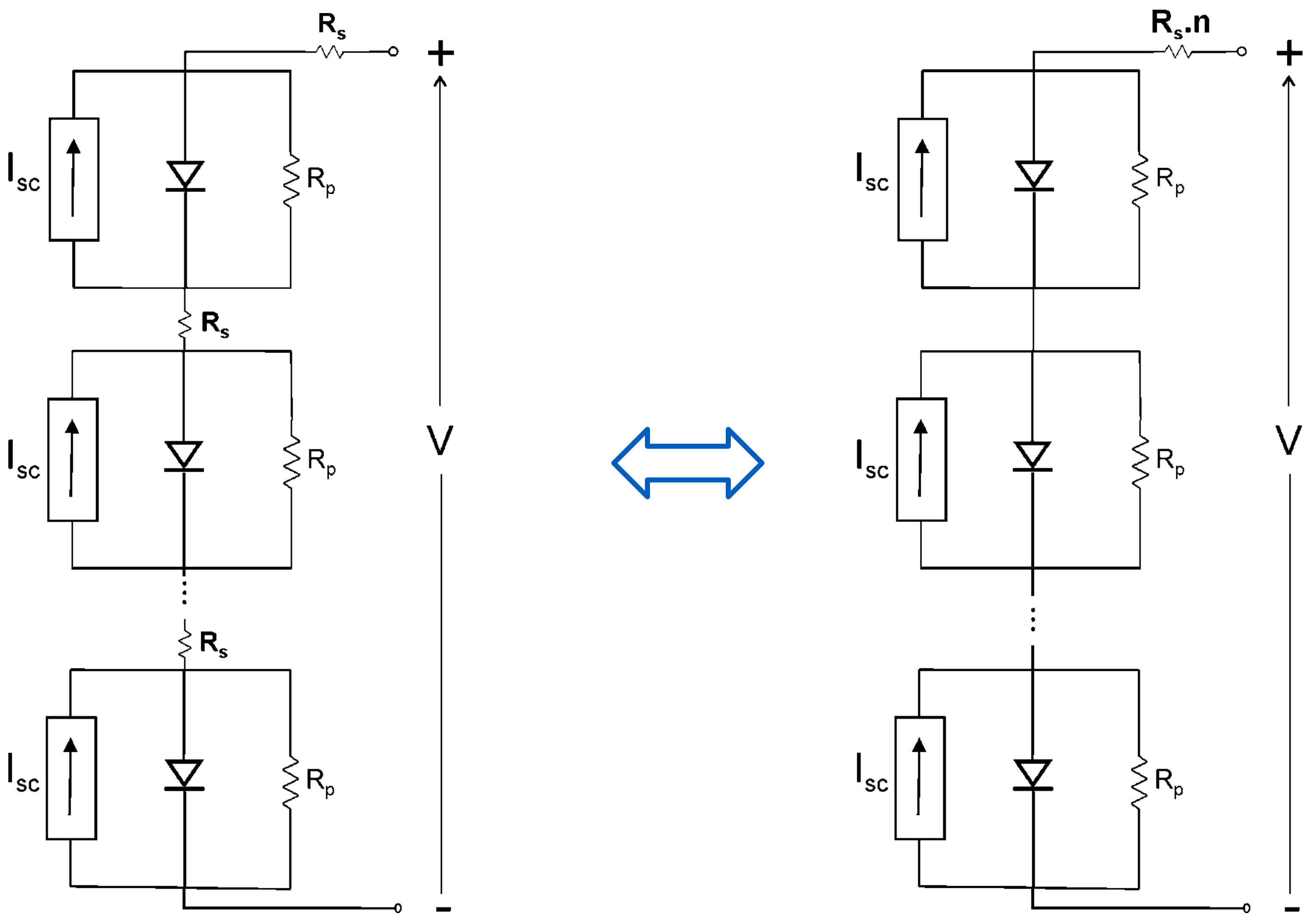
Assume 36 identical cells in series with $I_0 = 5\times10^{-11}$ A, I_{sc}=5 A, R_p=5 Ω, R_s=0 Ω. At 25°C what is V_{oc}?

$$I_{sc} = I_d + \frac{V}{5\times 36}$$

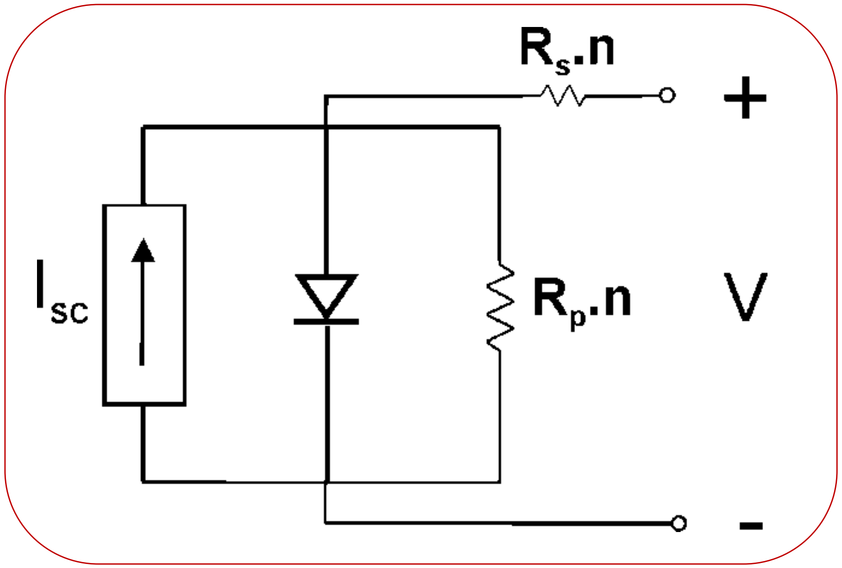
$$5 = 5\times 10^{-11}(e^{38.9V/36} - 1) + \frac{V}{5\times 36}$$

That equation again cannot be solved directly, but an iterative solution can be found: V=23.41 V

Module with General Cell Model



Module with General Cell Model



For the entire module:

$$V = n\left(V_d - IR_S\right)$$

$$V + nIR_S = nV_d$$

Writing the equations in terms of V and I:

$$I = I_{SC} - I_0\left(e^{q(V+I\cdot nR_S)/nkT} - 1\right) - \frac{V + I\cdot nR_S}{R_P n}$$

Module Example Continued: V-I Curve

- Generating the V-I Curve again requires picking a V_d
  - Pick a value of V_d
  - Solve for I_d
  - Solve of I_p
  - $I = I_{sc} – I_d - I_p$
  - $V = n(V_d - R_s * I)$

Assume $V_d = 0.64$, $I_{sc} = 5A$

$$I_d = 5 \times 10^{-11}(e^{38.9V_d} - 1) = 3.245$$

$$I_p = \frac{0.64}{5} = 0.128$$

$$I = 5 - 3.245 - 0.128 = 1.627$$

$$V = 36 \times \left(0.64 - 0.01 \times 1.627\right) = 22.45$$

Modules in Parallel

- Modules in parallel increase the current

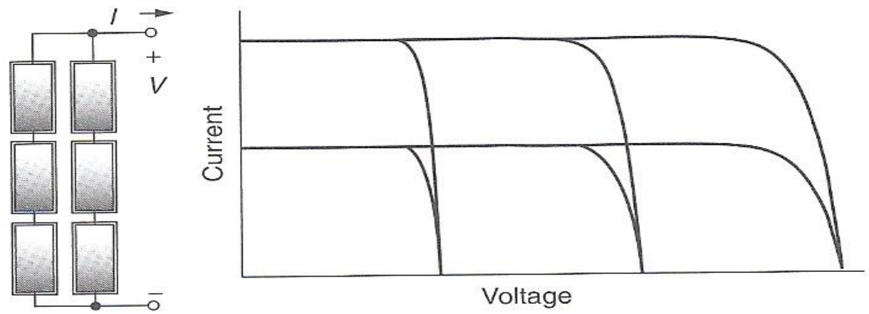


FIGURE 5.37 The total *I–V* curve of an array consisting of two strings of three modules each.

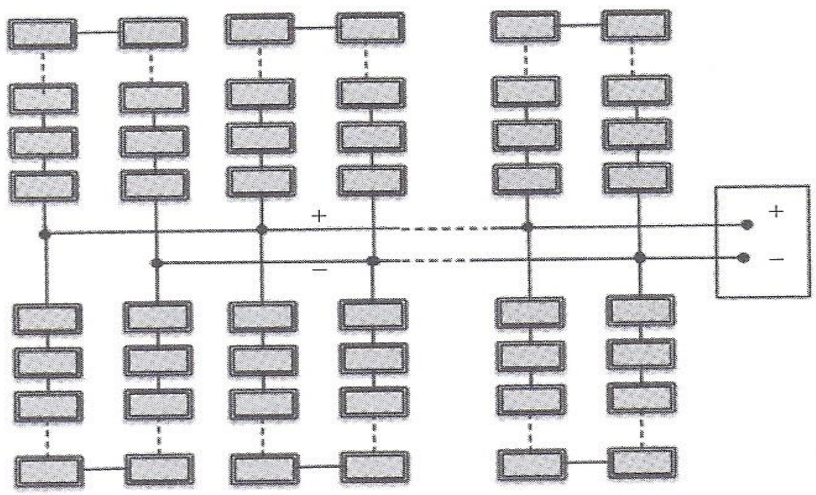


FIGURE 5.38 Multiple strings in parallel for large power arrays.

Standard Test Conditions

- PV modules are tested under standard conditions of 1 kW/m^2 and a cell temperature of 25°C.
- Rating is the power at the maximum power point (MPP); fill factor is ratio of MPP to $V_{oc} \times I_{sc}$

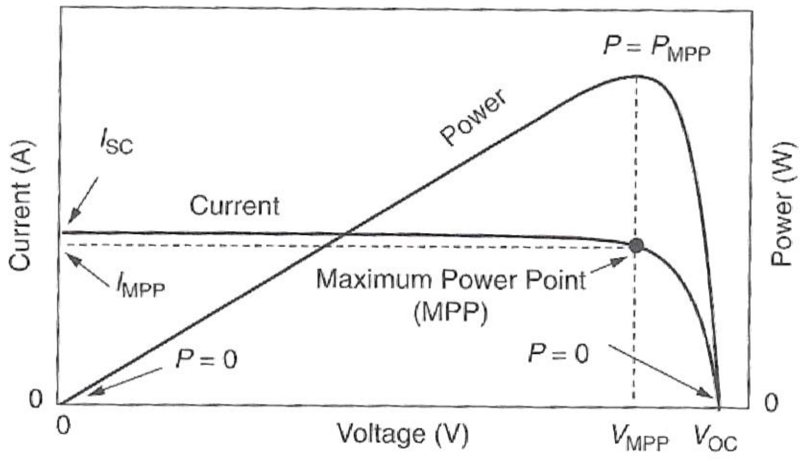
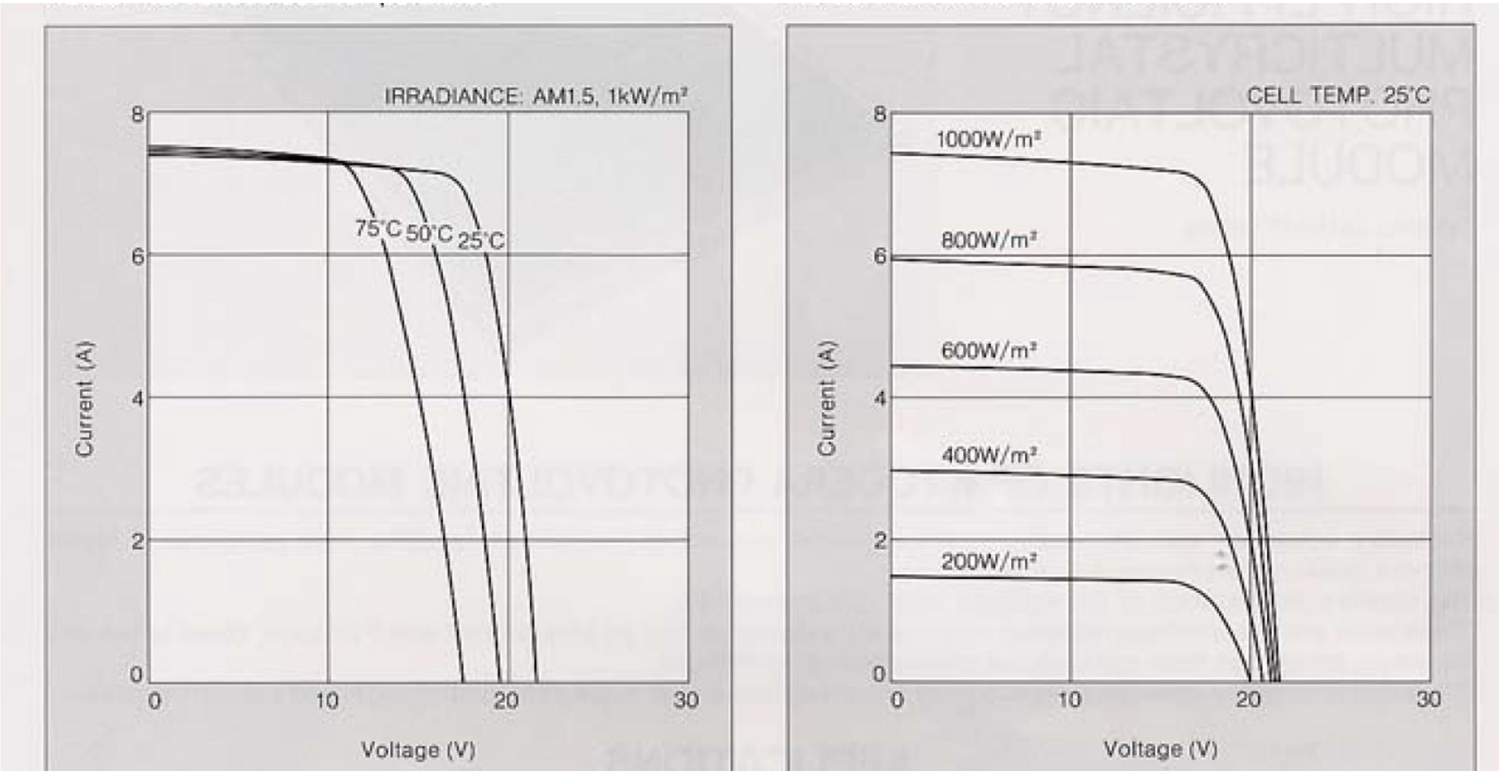


FIGURE 5.40 The *I–V* curve and power output for a PV module. If drawn under standard test conditions, the MPP identifies the rated voltage V_R, current I_R, and power P_R for the module.

Impact of Temperature and Insolation

- Cell output is sensitive to both temperature and insolation (might be on the order of 0.3% per degree C
  - Temperature for cell, which might be well above ambient!

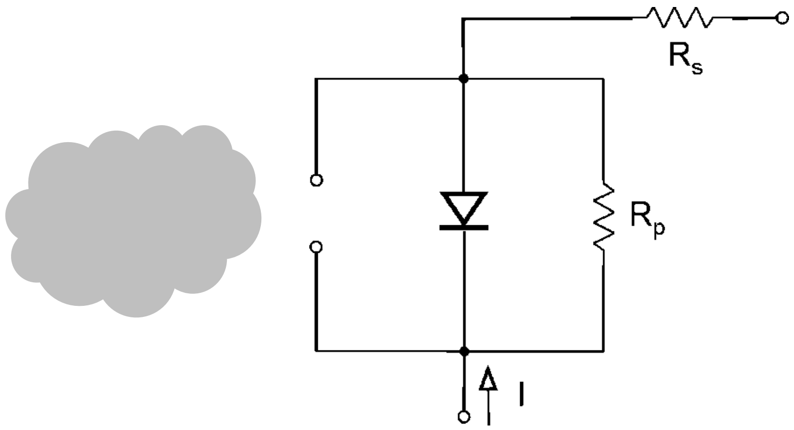


Figures are for a Kyocera KC120 module using mc-Si

Image: http://www.kyocerasolar.com/assets/001/5180.pdf

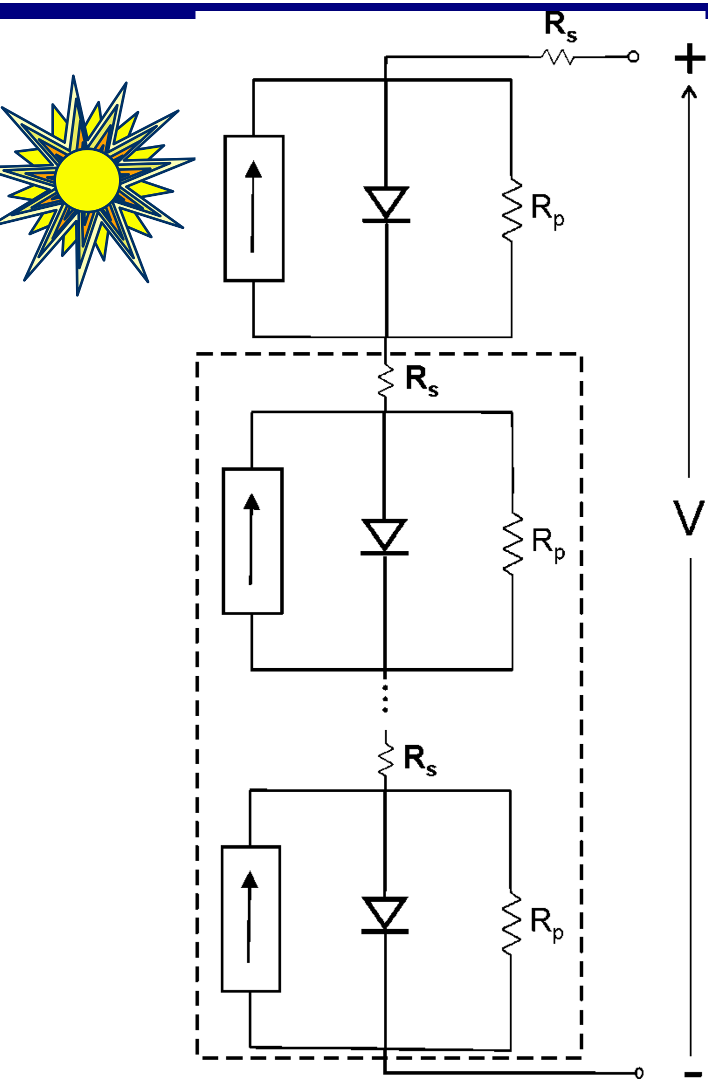
Impact of Shading

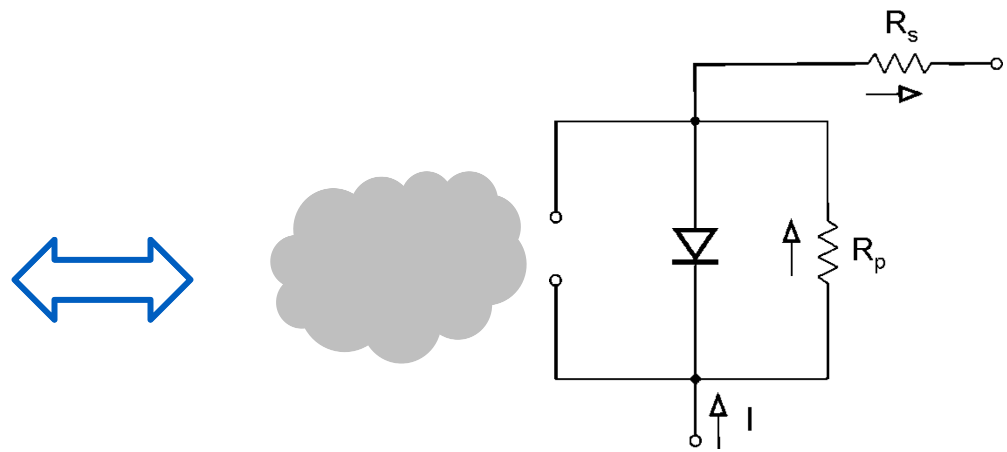
- The output of a PV module can be severely reduced (>50%) if even a small portion is shaded
- A single cell in a long string of cells that is shaded limits the current of the entire string, since cells in series must carry the same current
- Essentially, a PV cell in the shade acts like a resistor instead of a current source in parallel with a diode:



- I_{SC} is zero;
- Diode is reverse biased (off);
- I flows through R_P, R_S

Shading Impact on Output Voltage





Voltage across n non-shaded cells:

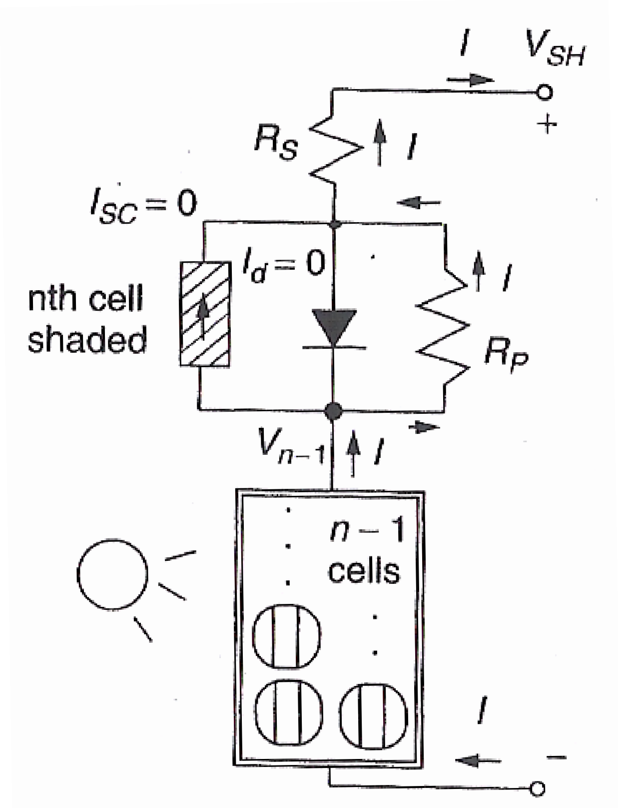
$$V_n = nV_i = V$$

or n-1 non-shaded cells:

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

Voltage Drop due to Shading

- Drop in output voltage due to shading = a loss in what it would produce (V/n) plus a resistive drop (IR)

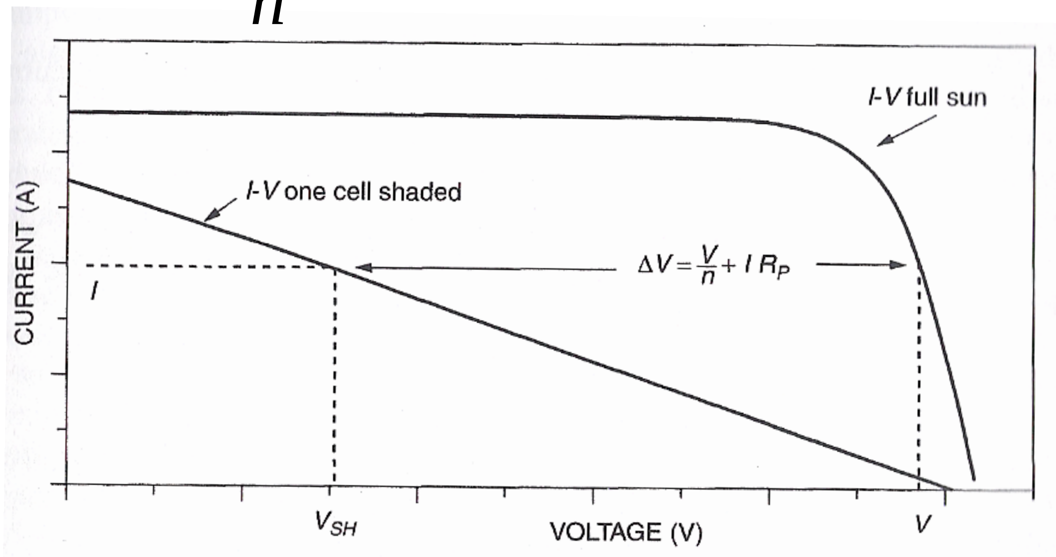


(b) Top cell shaded

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

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

R_p is >> R_s !



Shading Example

- Assume a 36 cell PV module with per cell R_p = 6.6 Ω. In full sun the output current is 2.14 A and the output voltage is 19.41 V. P_{out} = 41.5 W. If one cell is shaded, and the current stays the same, what is the new output voltage and power?

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

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

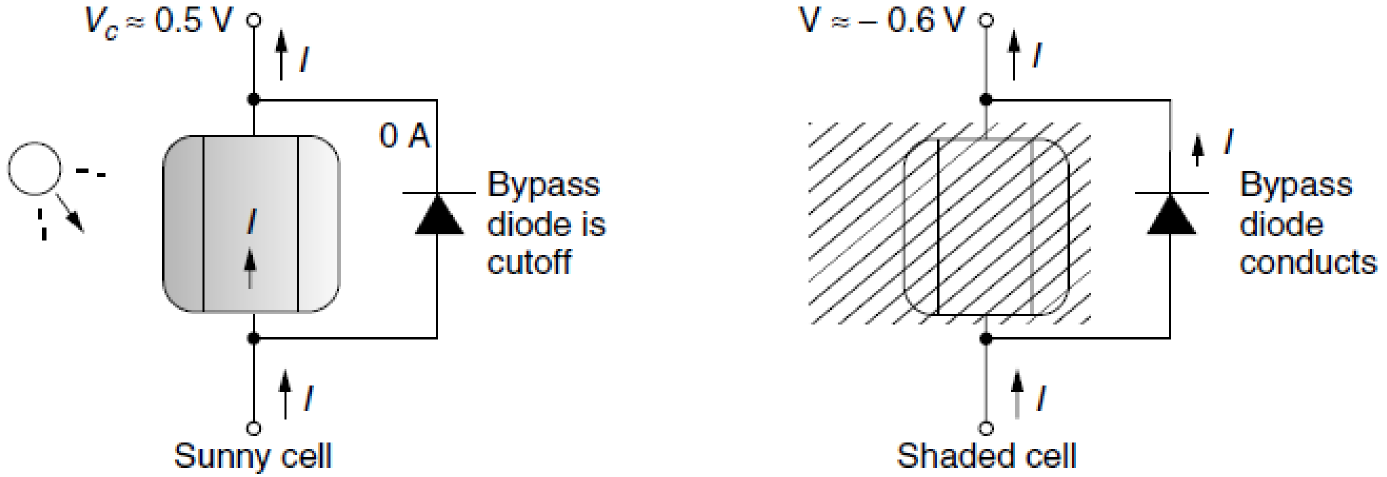
$$V_{new} = 19.41 - 14.66 = 4.75\ V$$

$$P_{new} = 4.75 \times 2.14 = 10.2\ \text{W}$$

With one cell shaded the output is < 25% of original! Lost power is dissipated as heat in the shaded cell.

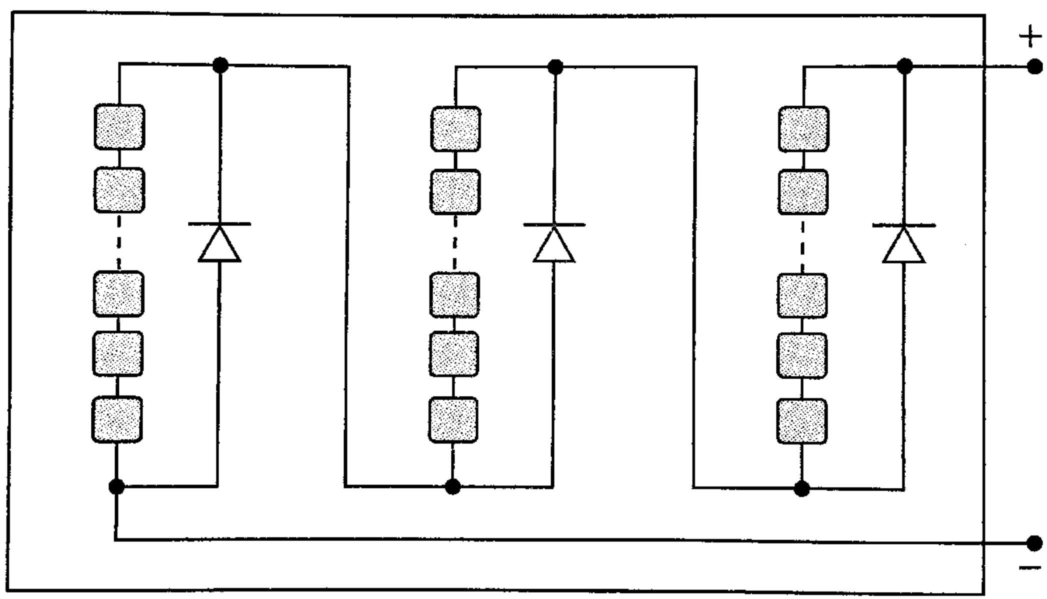
Shading Mitigation

- Solution - bypass diodes to bypass the shaded cell
- Instead of an $I(R_P+R_S)$ voltage drop across the resistors, only a fixed voltage drop due to the diode, about 0.6 V (or even smaller with special diodes)
- No effect during normal operation



Bypass Diodes

- It may be difficult to add one bypass diode to each cell;
- Instead, add the diode to a group of cells such as a module or string:



For example, with three diodes for a module the voltage would drop by about 1/3

Bypass Diode Impact on Module

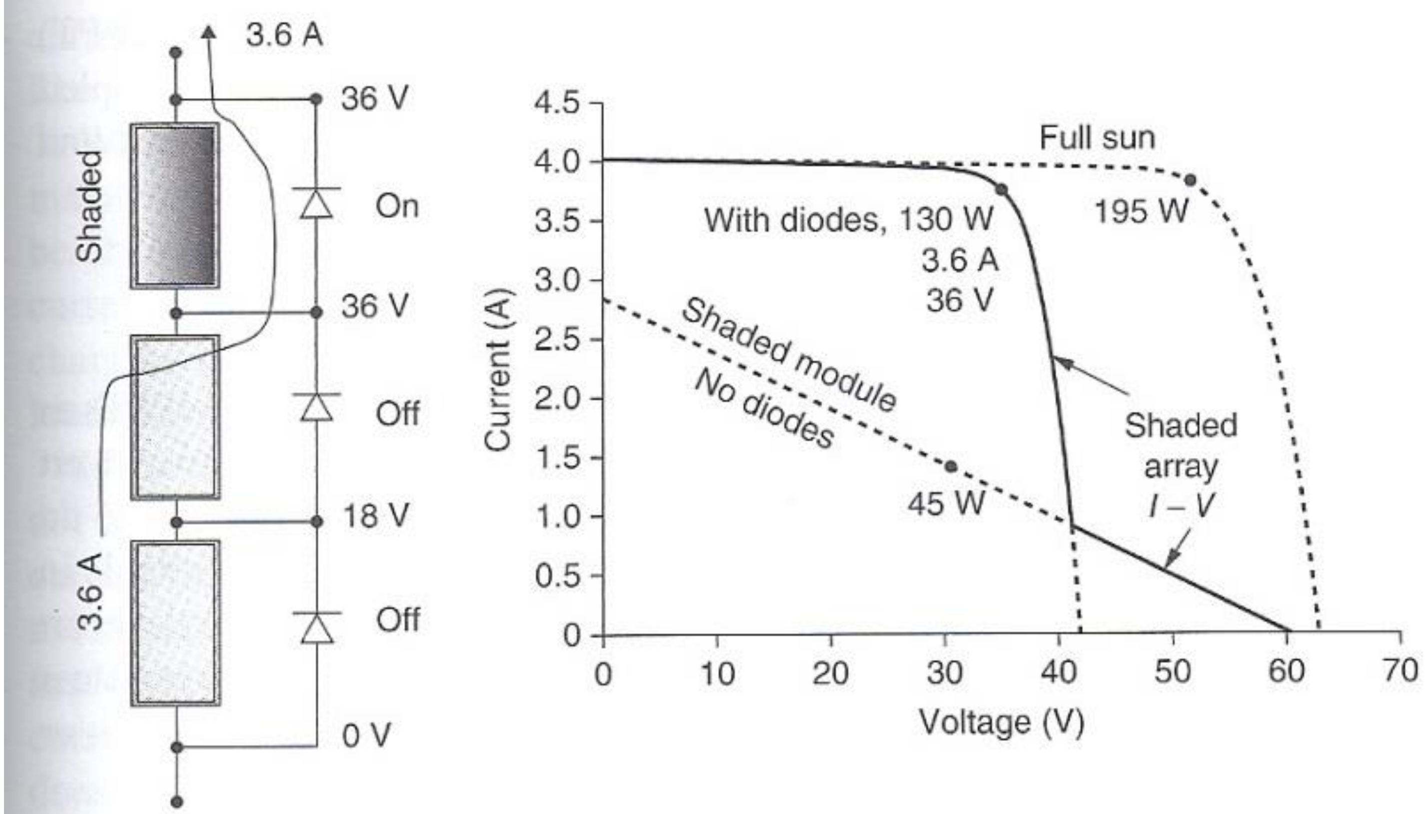


FIGURE 5.50 Showing the ability of bypass diodes to mitigate shading problems in a string of modules.

Bypass diodes also prevent overheating of shaded cells