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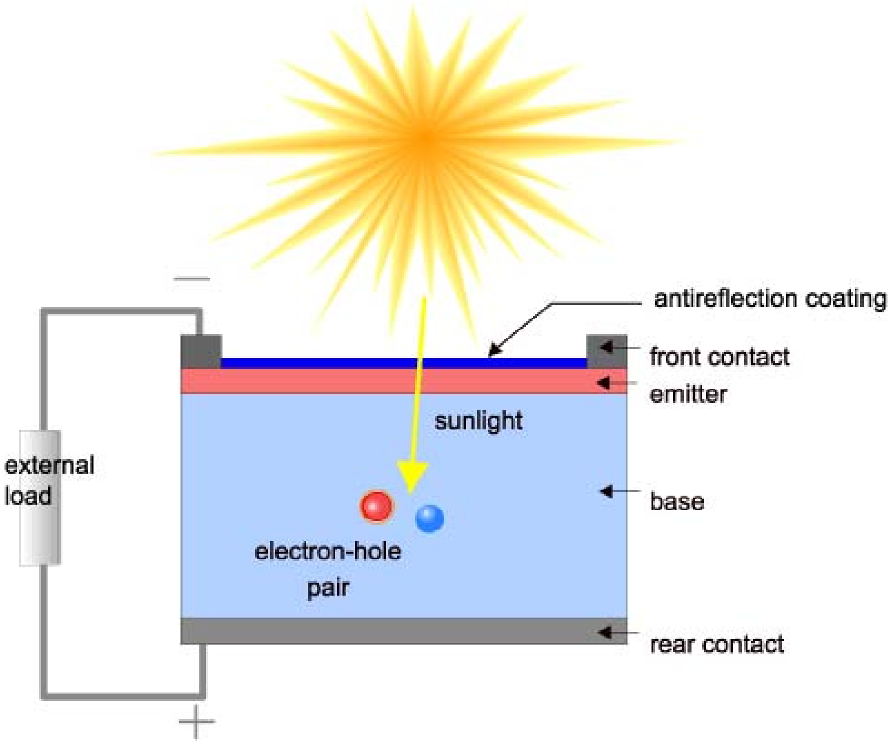
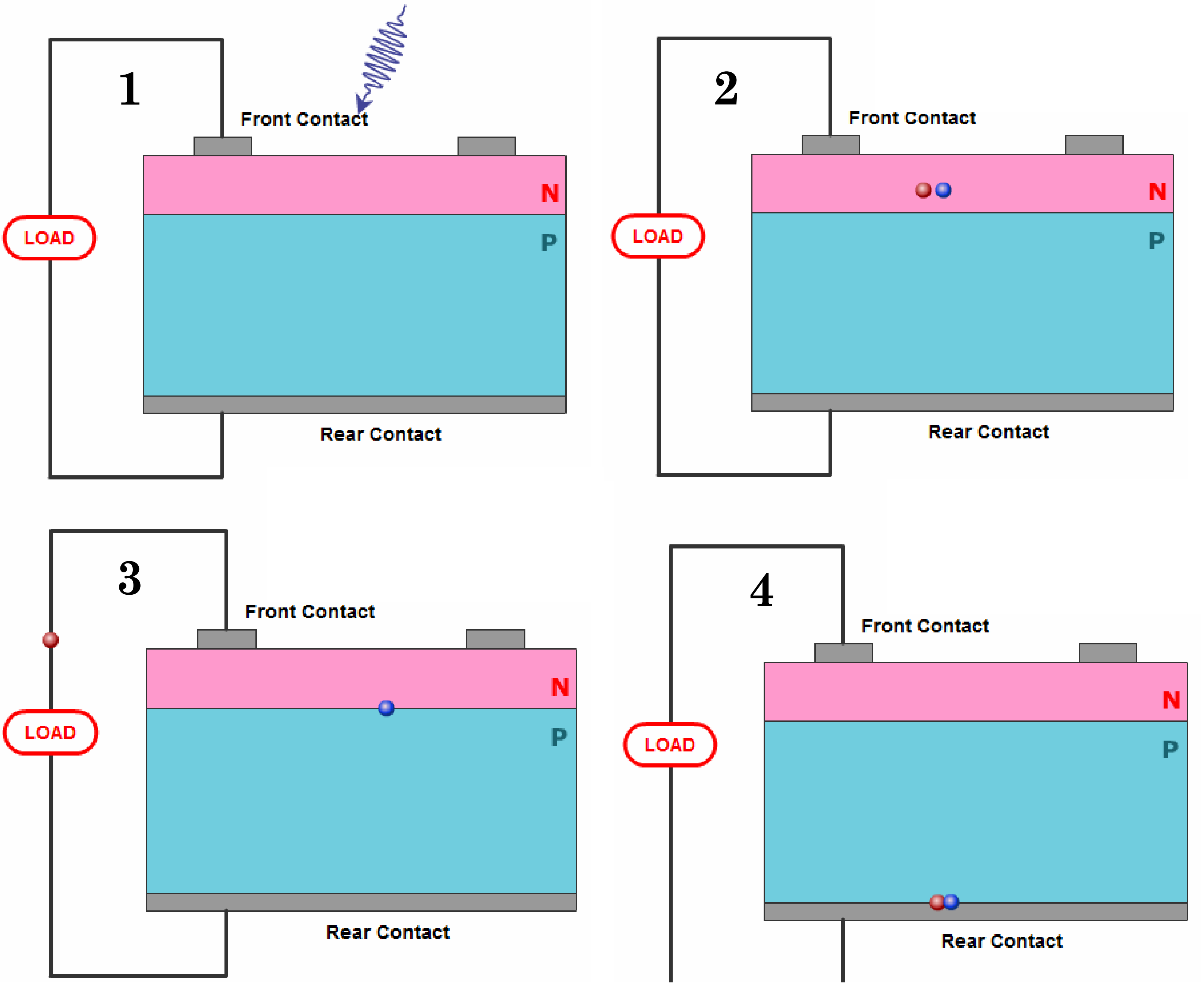
SOLAR CELL STRUCTURE

- Light shining on the solar cell produces both a current and a voltage to generate electric power.
- This process requires a material in which the absorption of light raises an electron to a higher energy state, and the movement of this higher energy electron from the solar cell into an external circuit.
- The electron then dissipates its energy in the external circuit and returns to the solar cell.
- A variety of materials and processes can potentially satisfy the requirements for photovoltaic energy conversion, but in practice nearly all photovoltaic energy conversion uses semiconductor materials in the form of a *p-n* junction.




1
Front Contact
N
P
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2
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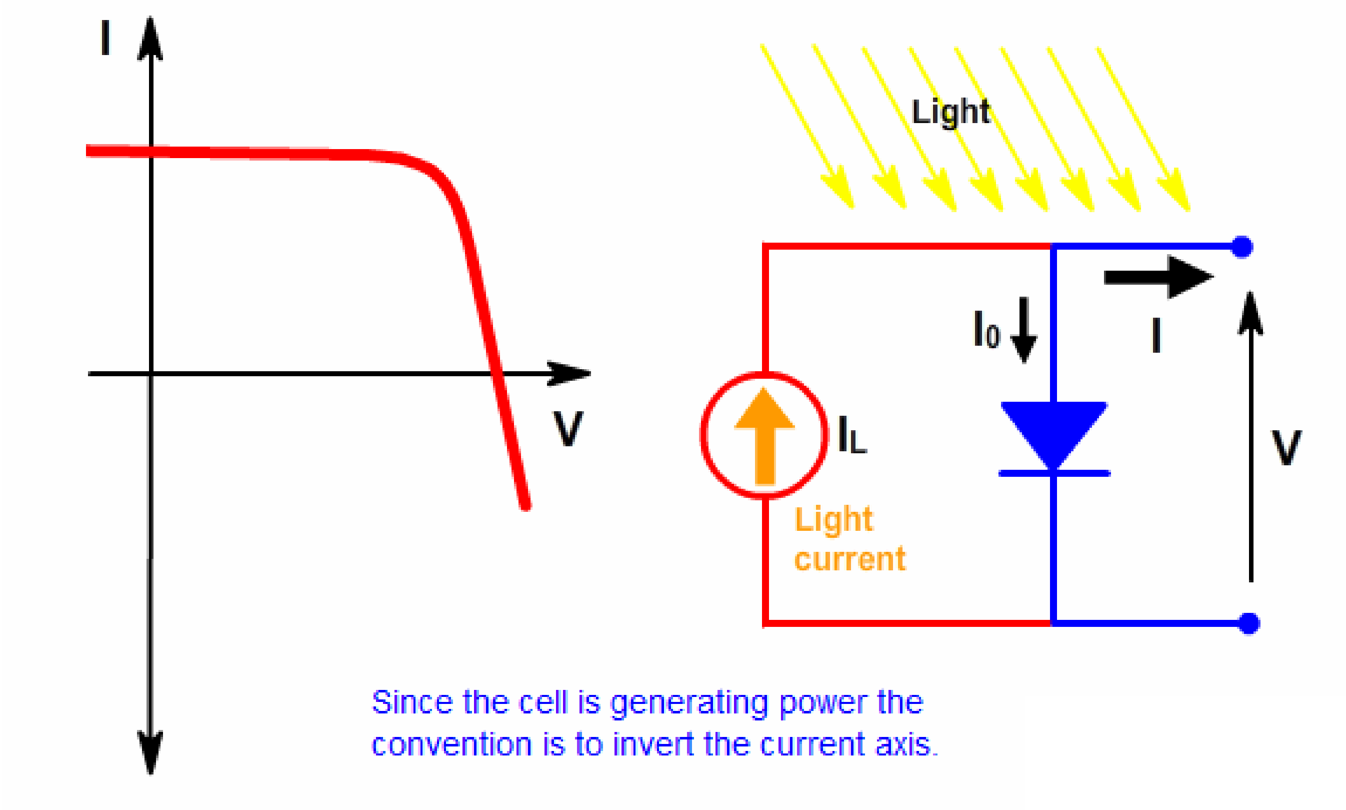
I-V Curve Revisited

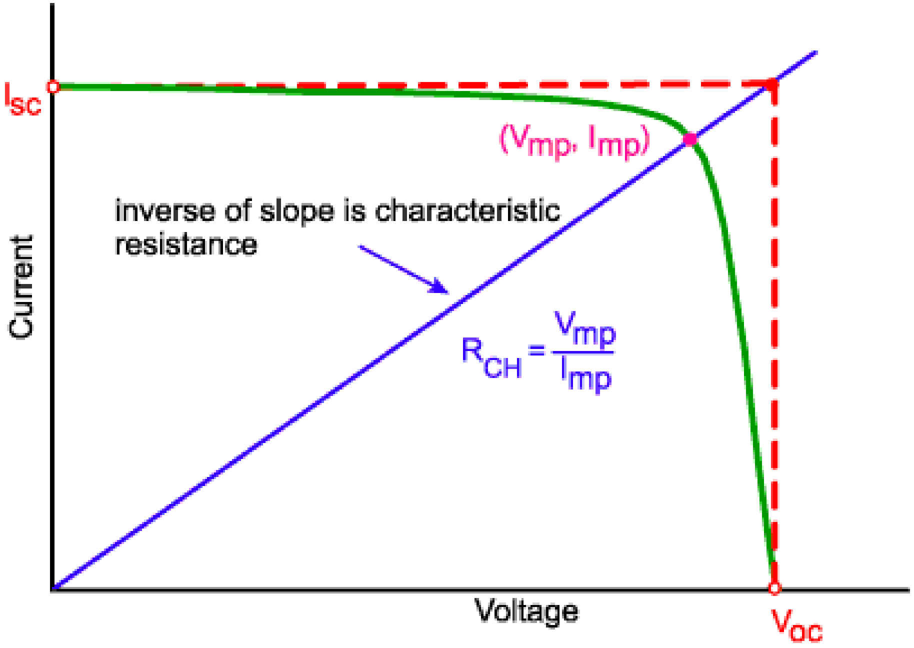


Since the cell is generating power the convention is to invert the current axis.

Characteristic Resistance

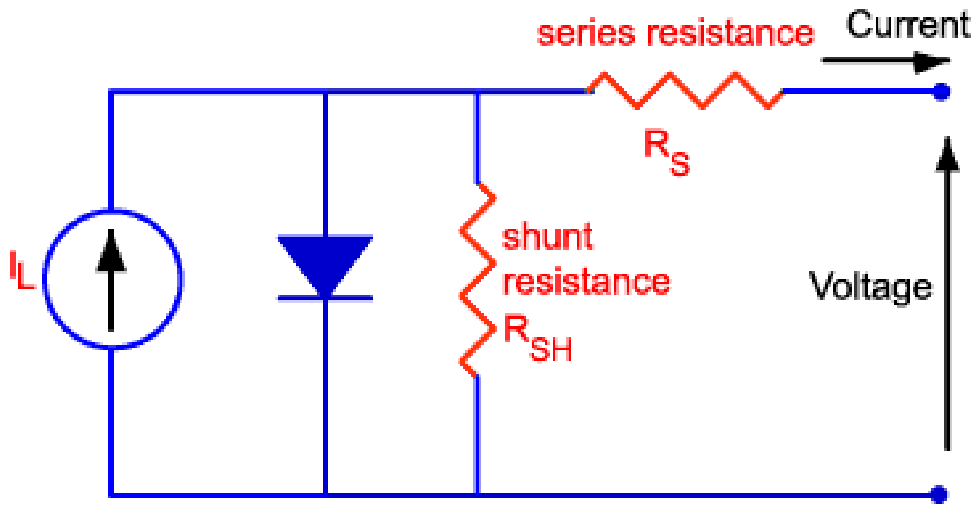
- The characteristic resistance of a solar cell is the output resistance of the solar cell at its maximum power point.
- If the resistance of the load is equal to the characteristic resistance of the solar cell, then the maximum power is transferred to the load and the solar cell operates at its maximum power point.
- The value of this resistance can be approximated by

$$R_{CH} = \frac{V_{OC}}{I_{SC}}$$



Effect of Parasitic Resistances

- Resistive effects in solar cells reduce the efficiency of the solar cell by dissipating power in the resistances. The most common parasitic resistances are series resistance and shunt resistance.
- Series resistance in a solar cell is due to :
  - the movement of current through the p-n materials of the solar cell;
  - the contact resistance between the metal contact and the silicon;
  - the resistance of the top and rear metal contacts.
- The series resistance reduces the fill factor, but has no impact on the open circuit voltage nor on the short-circuit current.



Effect of Series Resistance

- An equation for the FF as a function of series resistance can be determined by noting that for moderate values of series resistance, the maximum power may be approximated as the power in the absence of series resistance minus the power lost in the series resistance.

$$P'_{MP} \approx V_{MP} I_{MP} - I_{MP}^2 R_S = V_{MP} I_{MP} \left(1 - \frac{I_{MP}}{V_{MP}} R_S\right) = P_{MP} \left(1 - \frac{I_{SC}}{V_{OC}} R_S\right)$$

or $$P'_{MP} = P_{MP}(1 - r_S)$$

where $$r_S = \frac{R_S}{R_{CH}}$$

- Also, since the open circuit voltage and short circuit current are not affected:

$$FF' = FF(1 - r_S)$$

- A straight-forward method of estimating the series resistance from a solar cell is to find the slope of the IV curve at the open-circuit voltage point.

Effect of Shunt Resistance

- Power losses caused by the presence of a shunt resistance, R_{SH}, are typically due to manufacturing defects, rather than poor solar cell design.
- Low shunt resistance causes power losses in solar cells by providing an alternate current path for the light-generated current. Such a diversion reduces the amount of current flowing through the solar cell junction and reduces the voltage from the solar cell.
- The effect of a shunt resistance is particularly severe
  - at low light levels, since there will be less light-generated current.
  - at lower voltages where the effective resistance of the solar cell is high, the impact of a resistance in parallel is large.

Effect of Shunt Resistance

- An equation for the FF as a function of shunt resistance can be determined in a similar fashion as in the case of series resistance:

$$P'_{MP} \approx V_{MP} I_{MP} - \frac{V_{MP}^2}{R_{Sh}} = V_{MP} I_{MP} \left(1 - \frac{V_{MP}}{I_{MP}} \frac{1}{R_{SH}}\right) = P_{MP} \left(1 - \frac{V_{SC}}{I_{OC}} \frac{1}{R_{SH}}\right)$$

or $P'_{MP} = P_{MP} \left(1 - \frac{1}{r_{SH}}\right)$

where $r_{SH} = \frac{R_{SH}}{R_{CH}}$

- Also, since the open circuit voltage and short circuit current are not affected:

$$FF' = FF \left(1 - \frac{1}{r_{SH}}\right)$$

- A straight-forward method of estimating the shunt resistance from a solar cell is to find the slope of the IV curve at the short circuit current point.

Impact of Series and Shunt Resistances

- In the presence of both series and shunt resistances, the I-V curve of the solar cell is given by;

$$I = I_L - I_0 \exp\left[\frac{q(V + IR_S)}{nkT}\right] - \frac{V + IR_S}{R_{SH}}$$

- The overall fill factor FF is

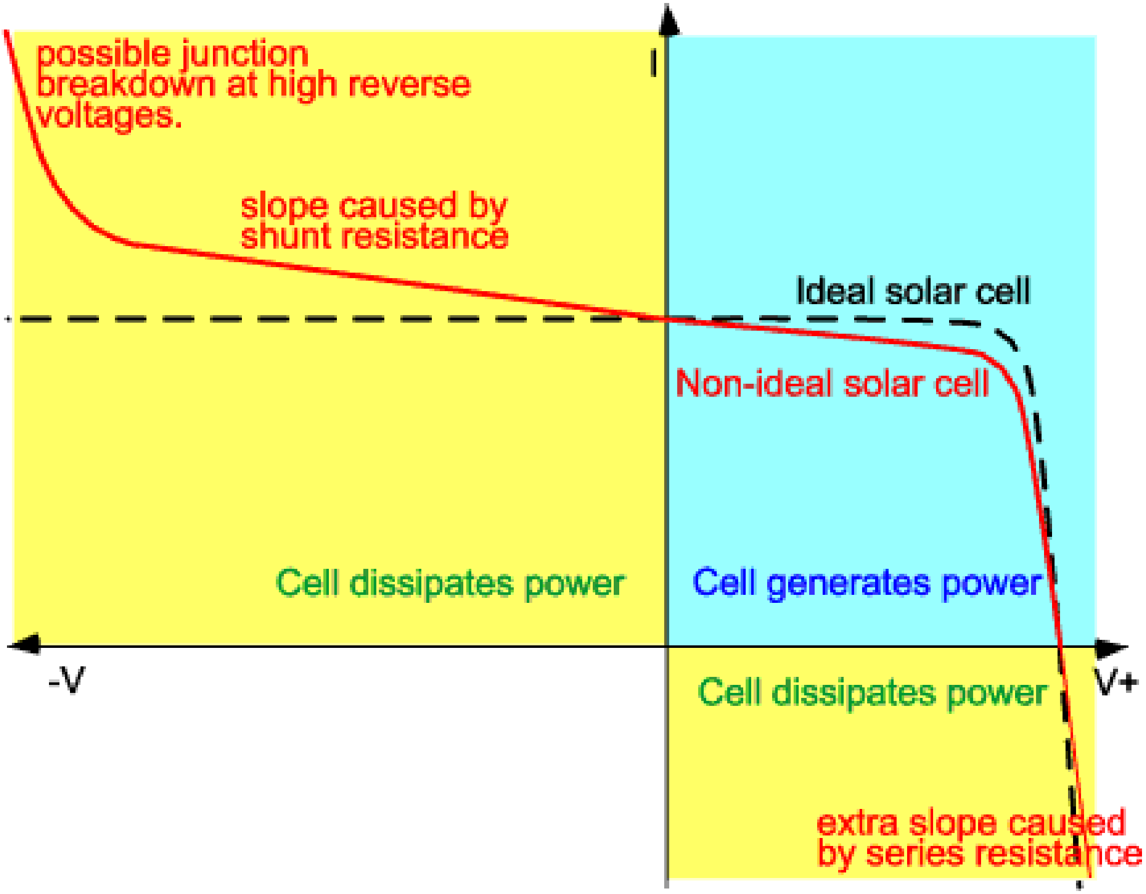
$$FF' = FF(1 - r_s)(1 - \frac{1}{r_{SH}})$$

Mismatch Effects

- Mismatch losses are caused by the interconnection of solar cells or modules which do not have identical properties or which experience different conditions from one another.
- Mismatch losses are a serious problem in PV modules and arrays under some conditions because the output of the entire PV module under worst case conditions is determined by the solar cell with the lowest output.
- For example, when one solar cell is shaded while the remainder in the module are not, the power being generated by the "good" solar cells can be dissipated by the lower performance cell rather than powering the load.
- This in turn can lead to highly localized power dissipation and the resultant local heating may cause irreversible damage to the module.

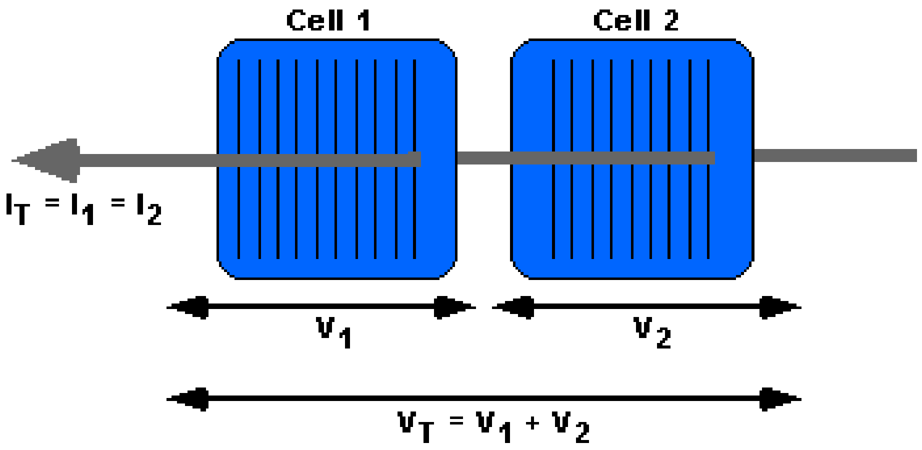
Mismatch Effects

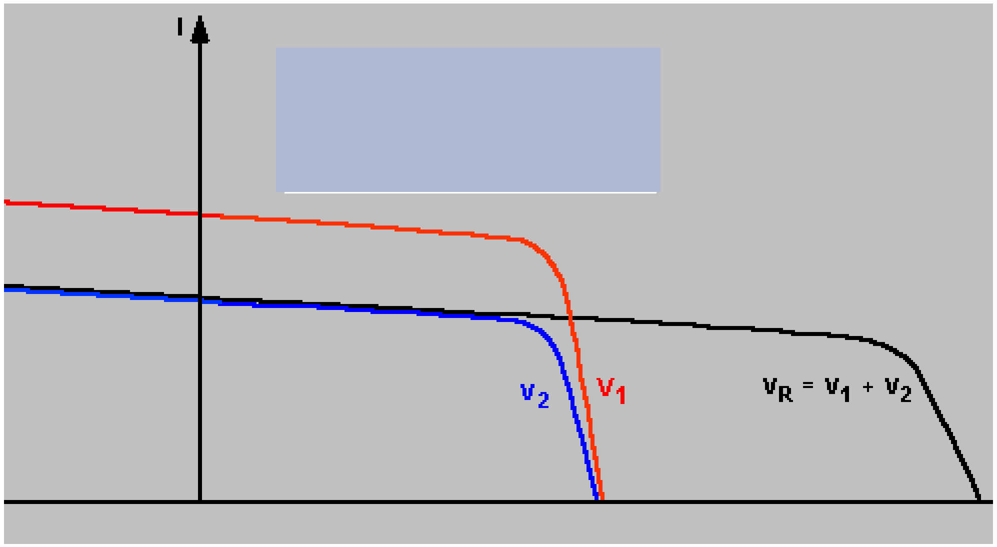
- The impact and power loss due to mismatch depend on (a) the operating point of the PV module; (b) the circuit configuration; and (c) the parameter (or parameters) which are different from the remainder of the solar cells.

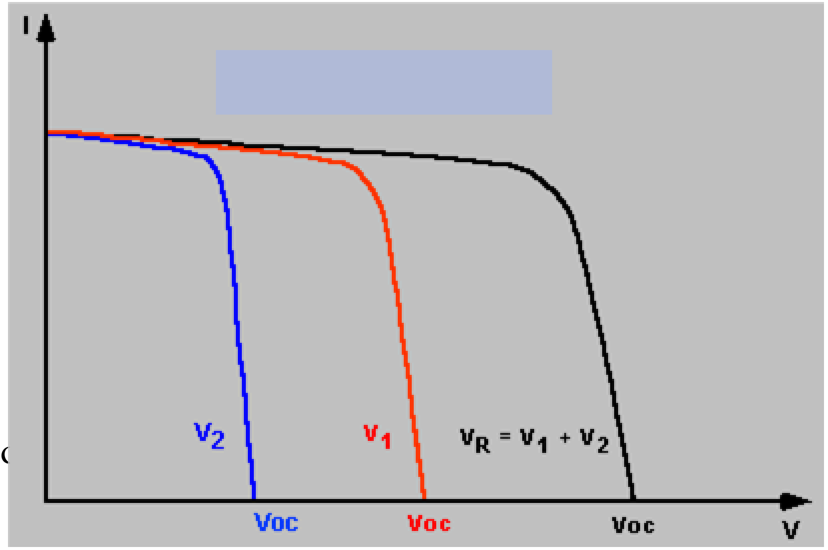


A non-ideal I-V curve and operating regime of a solar cell

Mismatch for Cells Connected in Series

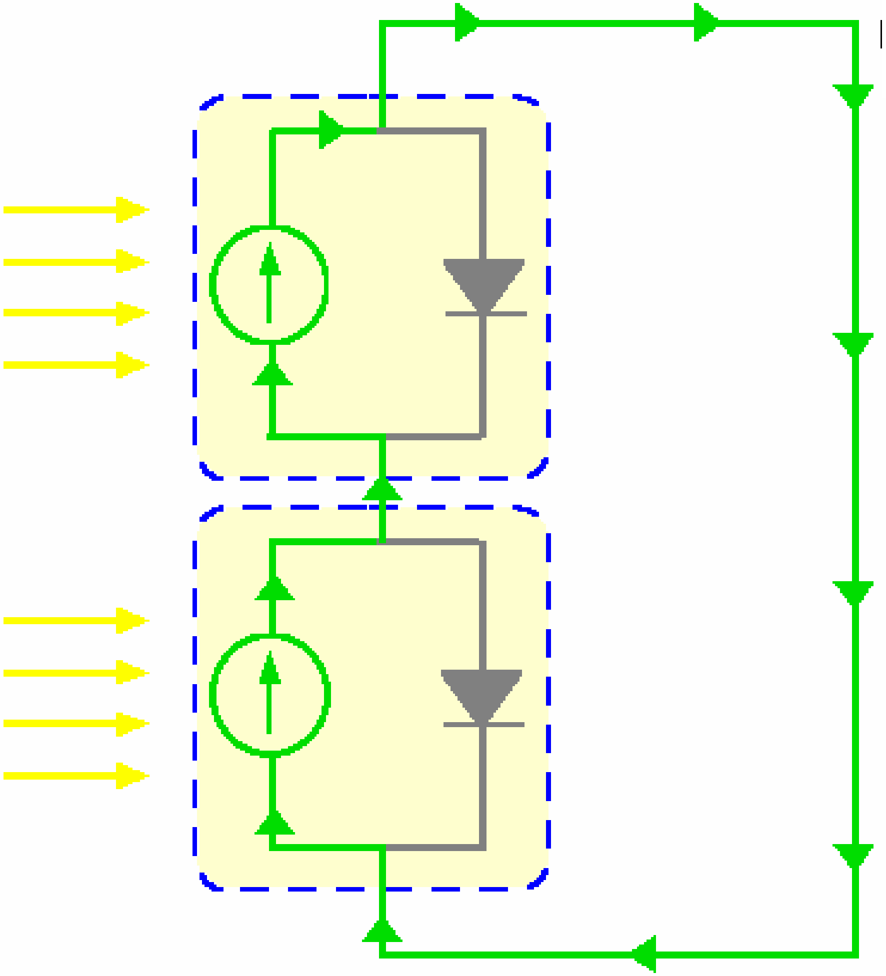






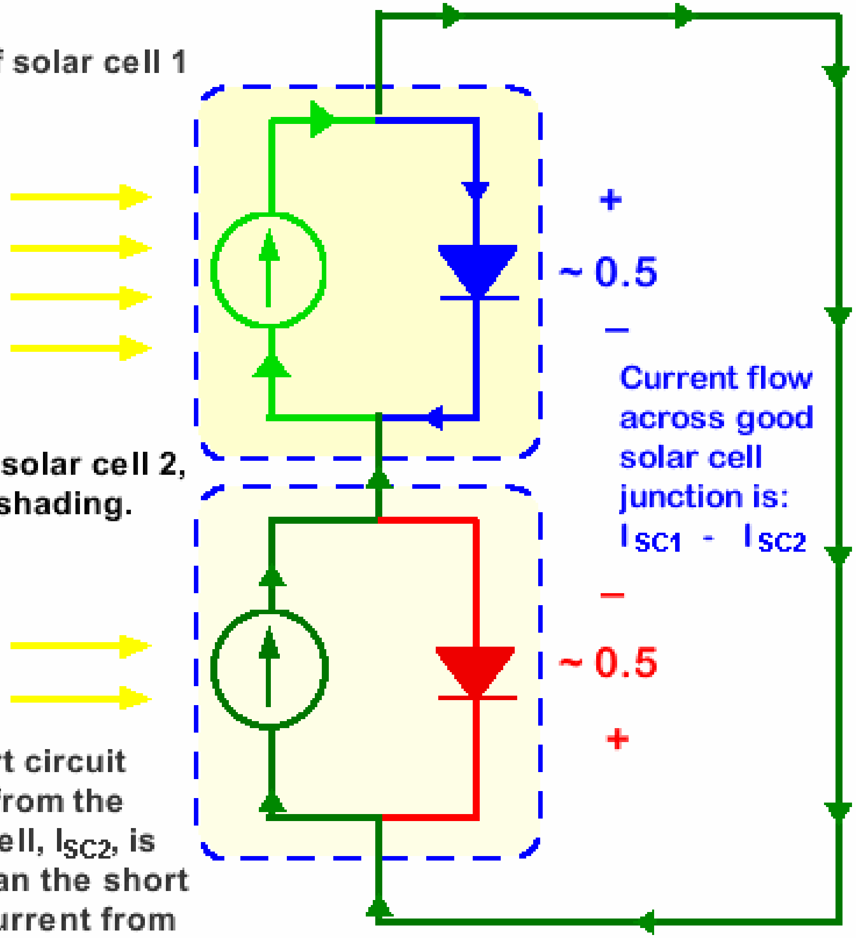
Series Connected Cells with Identical I_{SC}.

The circuit elements contained within the blue dotted lines model a solar cell. The current source is the light generated current, I_{SC} . The solar cells are at short-crcuit, so the forward bias current flowing across the solar cell is zero and threfore the voltage across them is also zero.



Series Connected Cells with Different I_{SC}.

The short circuit current from the poor cell, I_{SC2}, is the maximum current that can flow in the external circuit. Therefore, extra current from the good cell, mathematically given by $I_{SC1} - I_{SC2}$, is forced to flow across the good solar cell junction, forward biasing it and generating a voltage.



Model of solar cell 1

Model of solar cell 2, with 50% shading.

The short circuit current from the "poor" cell, I_{SC2}, is lower than the short circuit current from the "good" cell, I_{SC1}.

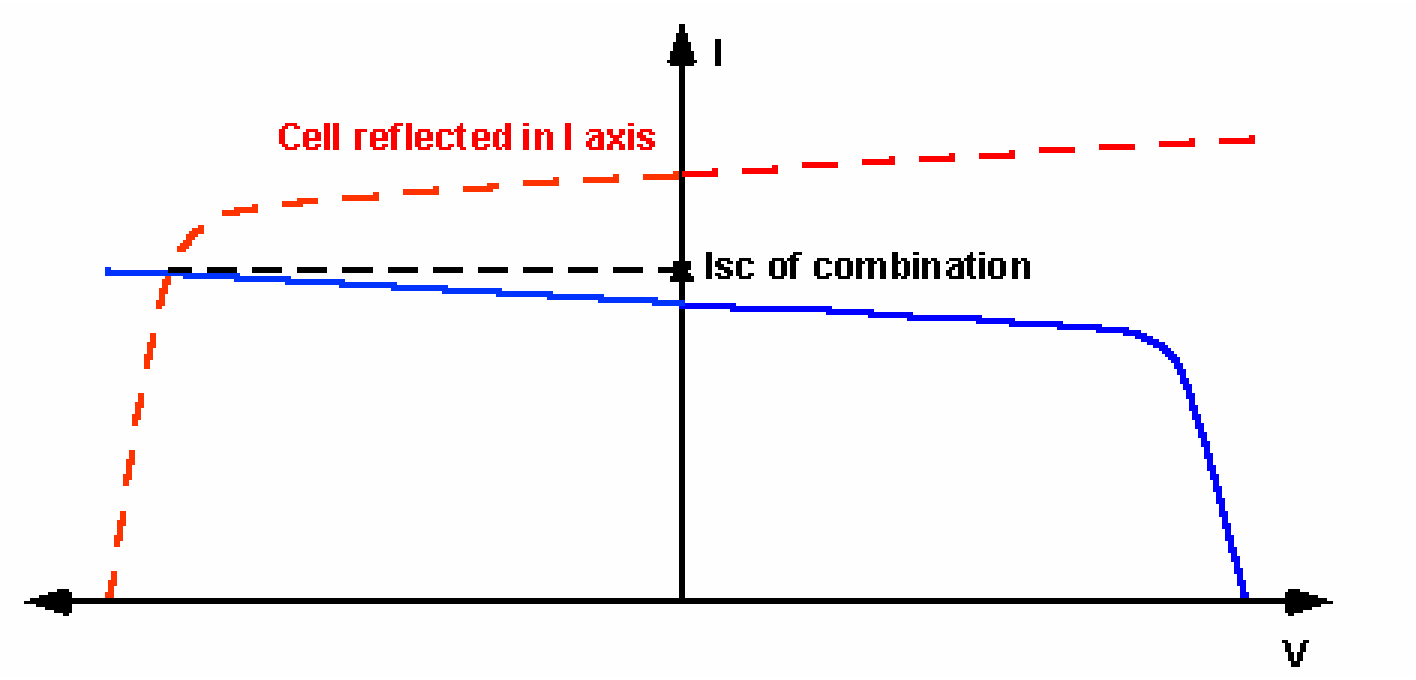
Current flow across good solar cell junction is: $I_{SC1} - I_{SC2}$

The two solar cells are short-circuited, such that the net voltage across them is zero.

The forward bias votlage generated by the "good" cell reverse biases the "poor" cell.

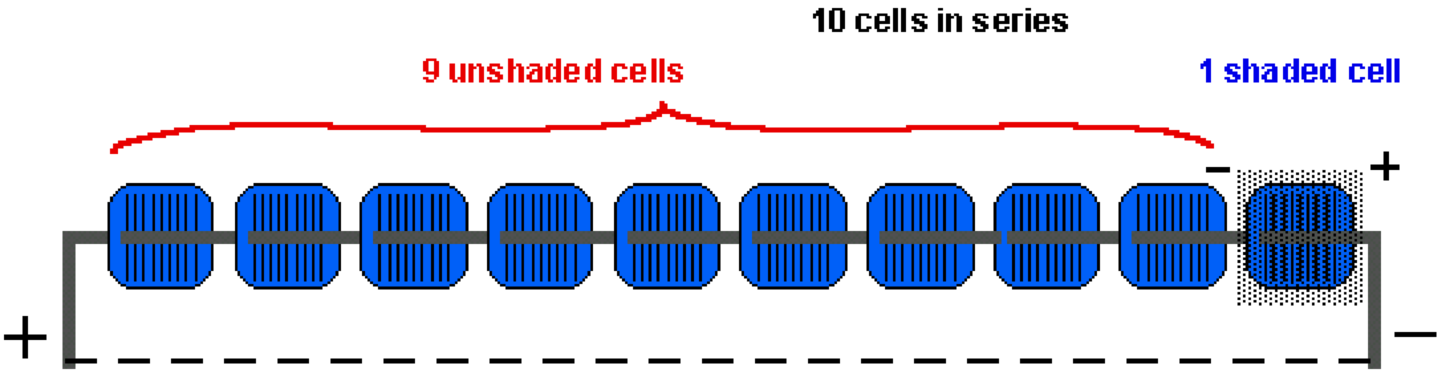
Mismatch for Cells Connected in Series

- An easy method of calculating the combined short-circuit current of series connected mismatched cells. The current at the point of intersection represents the short-circuit current of the series combination (i.e. , V1+V2=0).



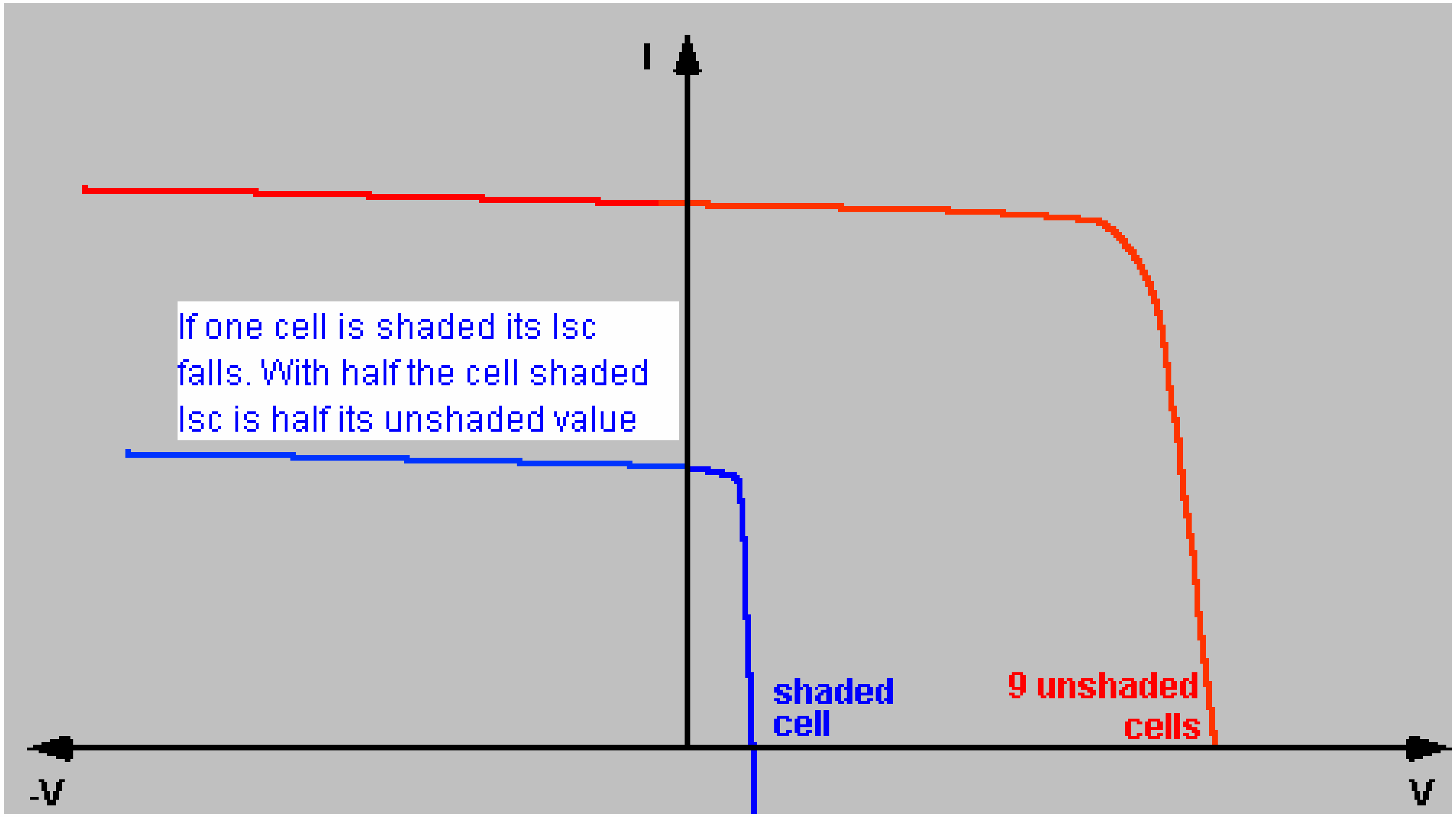
Hot-Spot Heating

- If the series string is short circuited, then the forward bias across all of these cells reverse biases the shaded cell.

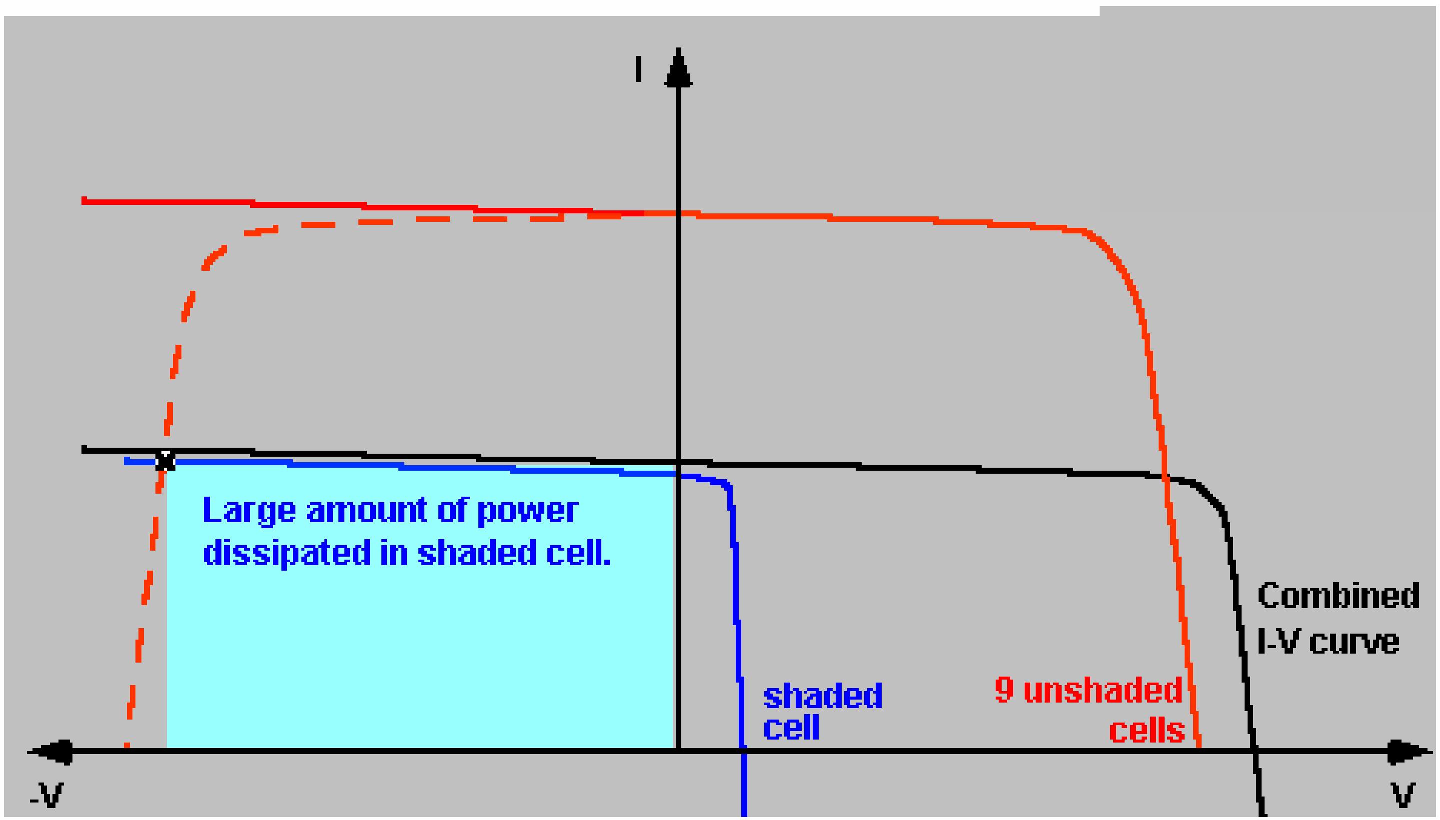


- Hot-spot heating occurs when a large number of series connected cells cause a large reverse bias across the shaded cell, leading to large dissipation of power in the poor cell.
- The enormous power dissipation occurring in a small area results in local overheating, or "hot-spots", which in turn leads to destructive effects, such as cell or glass cracking, melting of solder or degradation of the solar cell.

I-V Curve of 9 Cells and One Partially Shaded Cell (with no Bypass Diode)



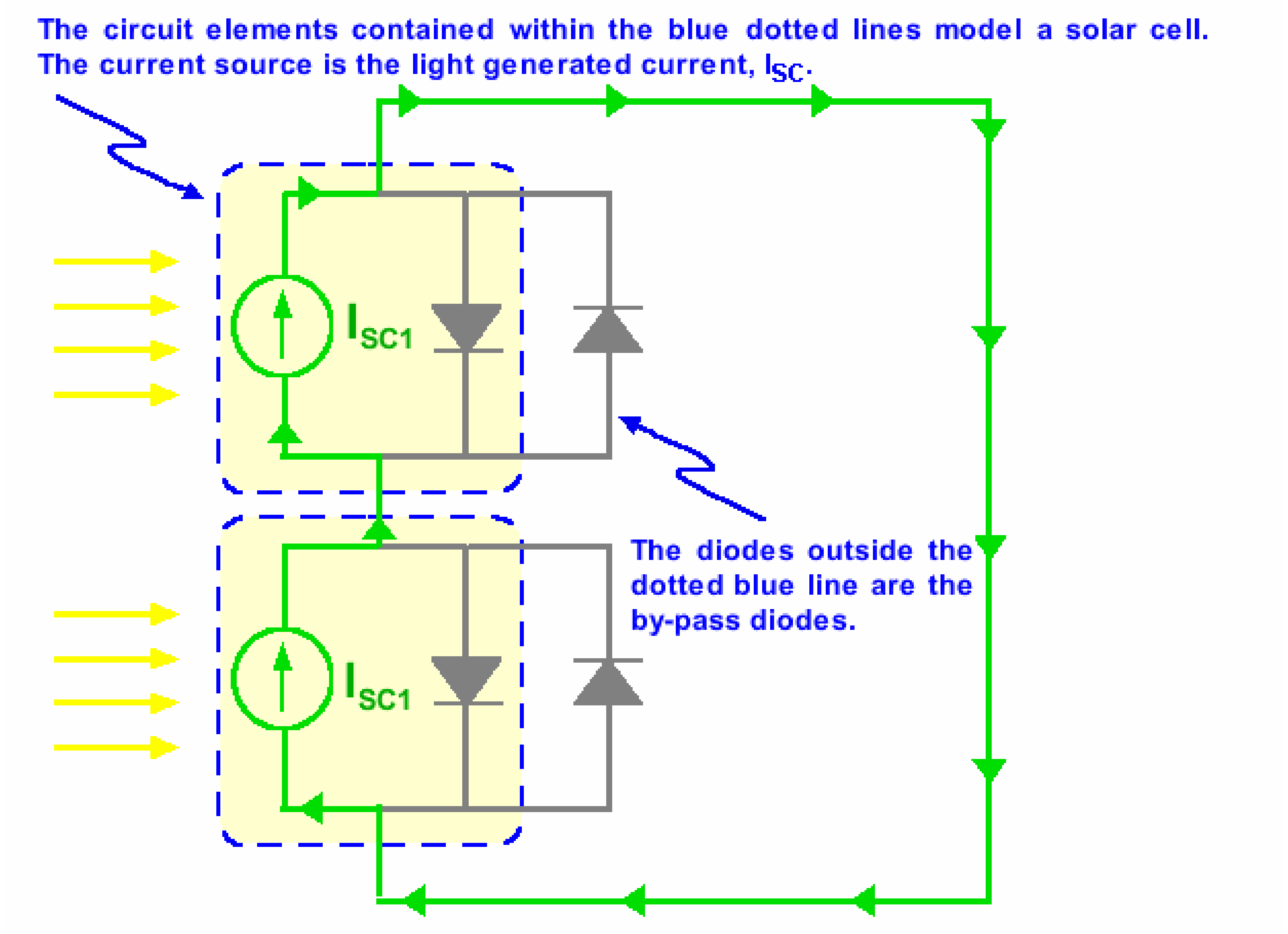
I-V Curve of 10 Cells (One Partially Shaded Cell with no Bypass Diode)



Bypass Diodes

- The destructive effects of hot-spot heating may be circumvented through the use of a bypass diode.
- A bypass diode is connected in parallel, but with opposite polarity to a solar cell.
- Under normal operation, each solar cell will be forward biased and therefore the bypass diode will be reverse biased and will effectively be an open circuit.
- However, if a solar cell is reverse biased due to the a mismatch in short-circuit current between several series connected cells, then the bypass diode conducts, thereby allowing the current from the good solar cells to flow in the external circuit rather than forward biasing each good cell.
- The maximum reverse bias across the poor cell is reduced to about a single diode drop, thus limiting the current and preventing hot-spot heating.

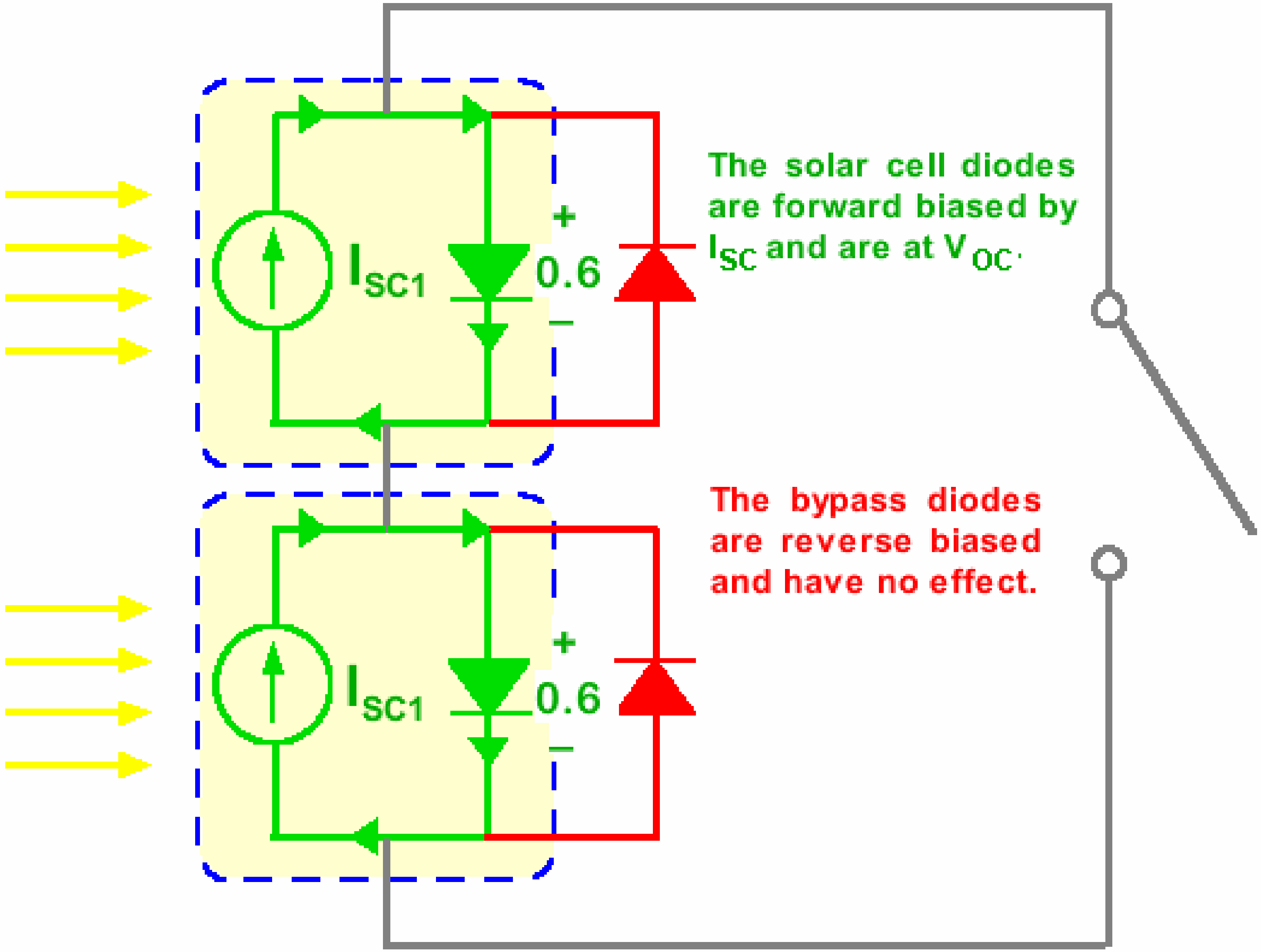
Matched Currents at Short Circuit



The circuit elements contained within the blue dotted lines model a solar cell. The current source is the light generated current, I_{SC}.

The diodes outside the dotted blue line are the by-pass diodes.

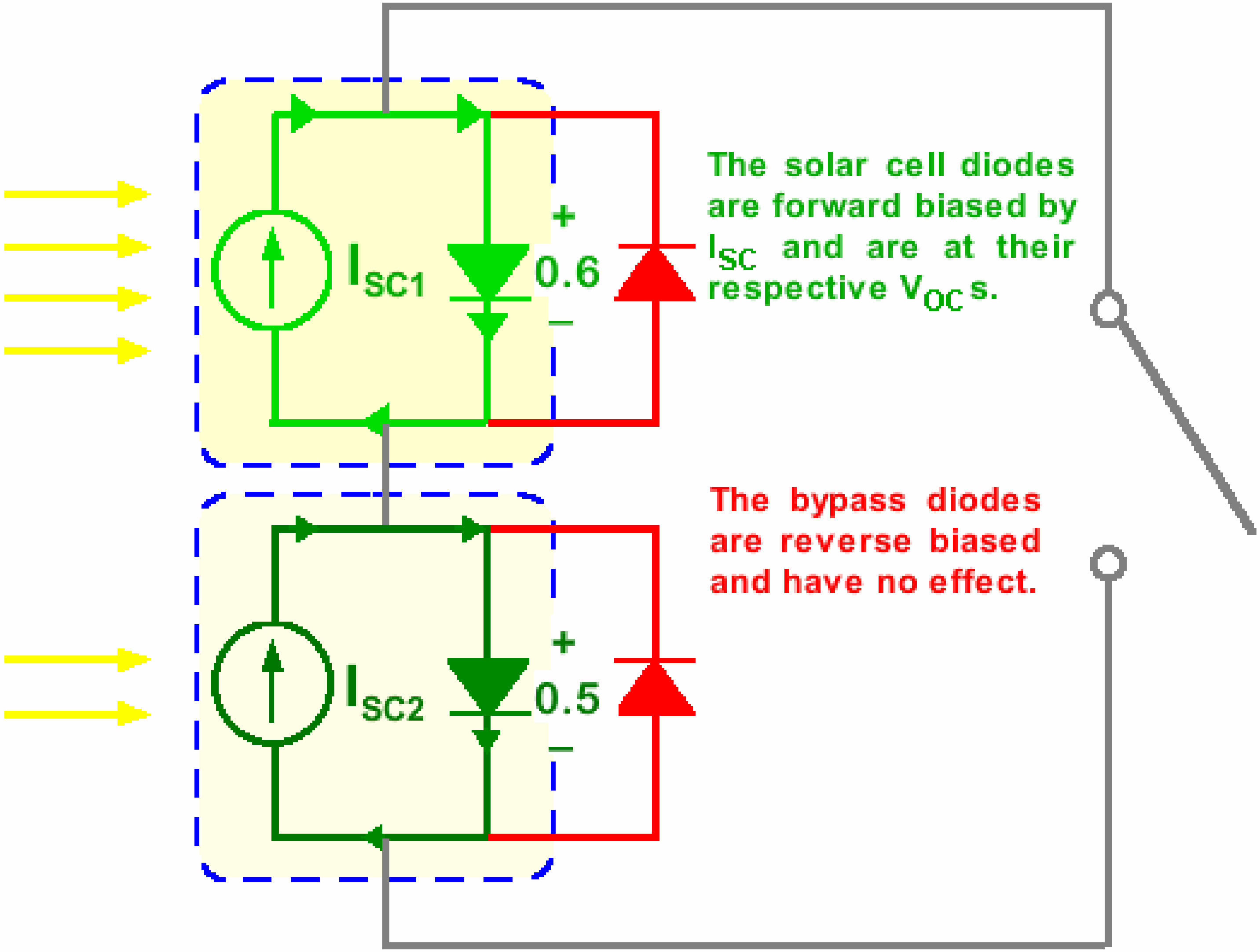
Matched Current at Open Circuit



The solar cell diodes are forward biased by I_{SC} and are at V_{OC}.

The bypass diodes are reverse biased and have no effect.

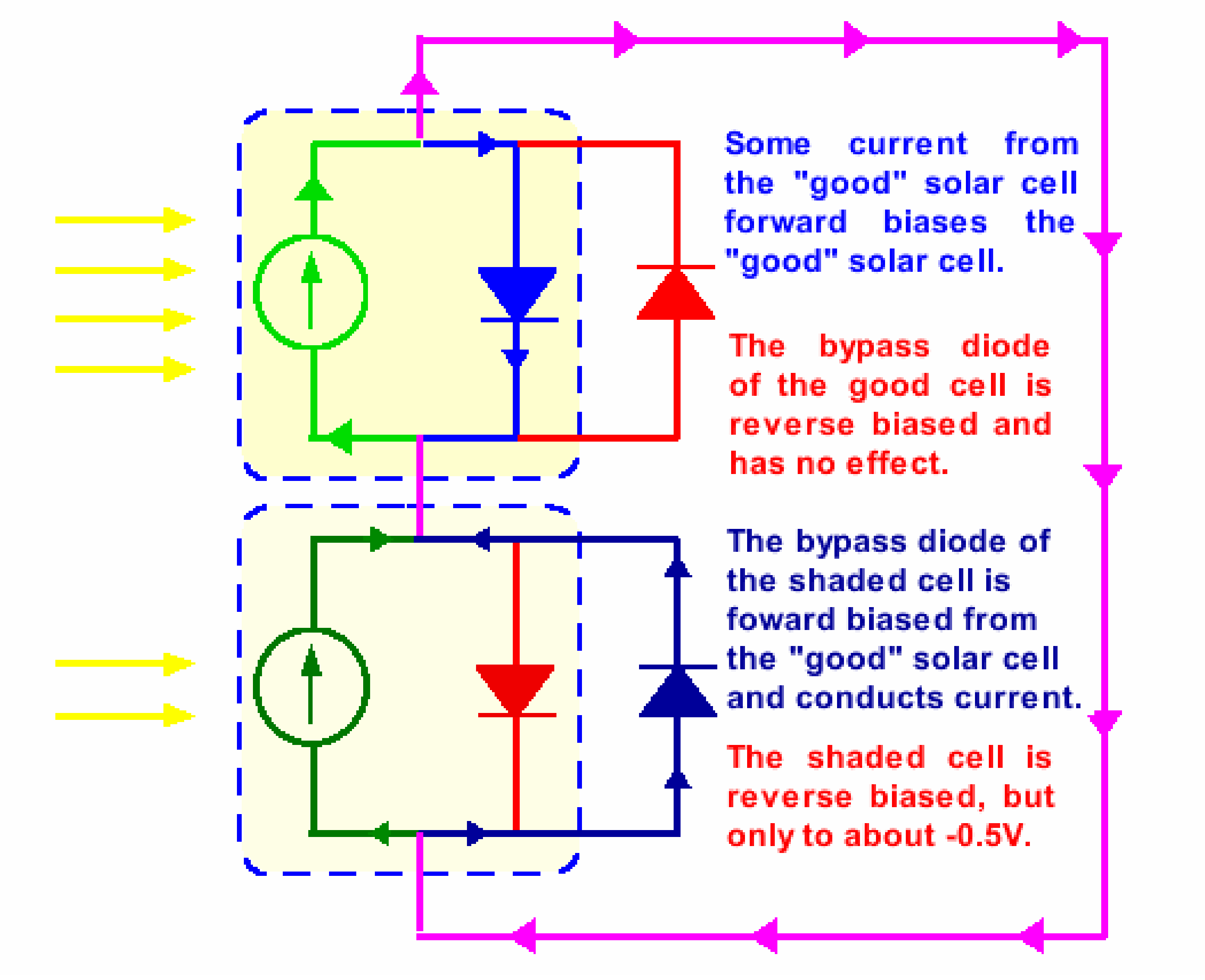
Mismatched Current at Open Circuit



The solar cell diodes are forward biased by I_{SC} and are at their respective V_{OC} s.

The bypass diodes are reverse biased and have no effect.

Mismatched Currents at Short Circuit



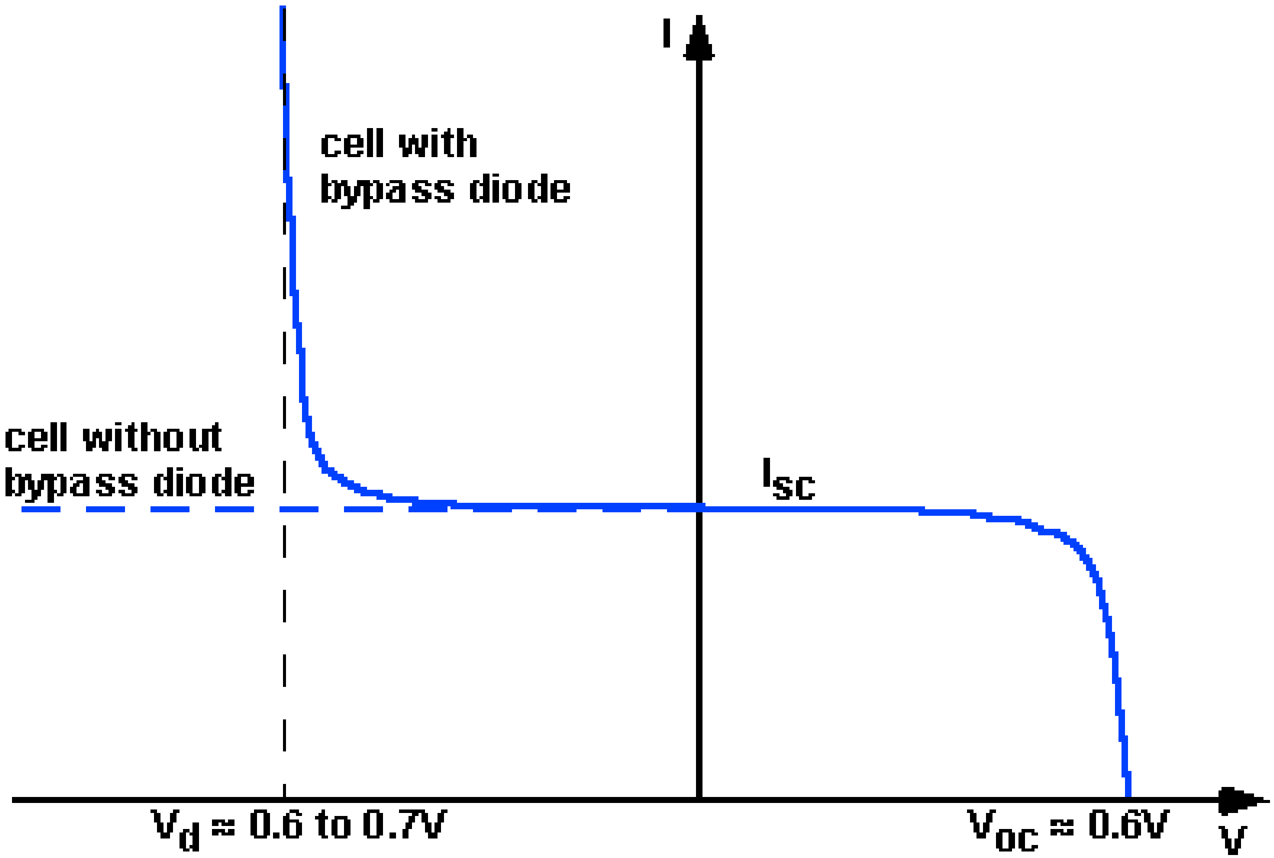
Some current from the "good" solar cell forward biases the "good" solar cell.

The bypass diode of the good cell is reverse biased and has no effect.

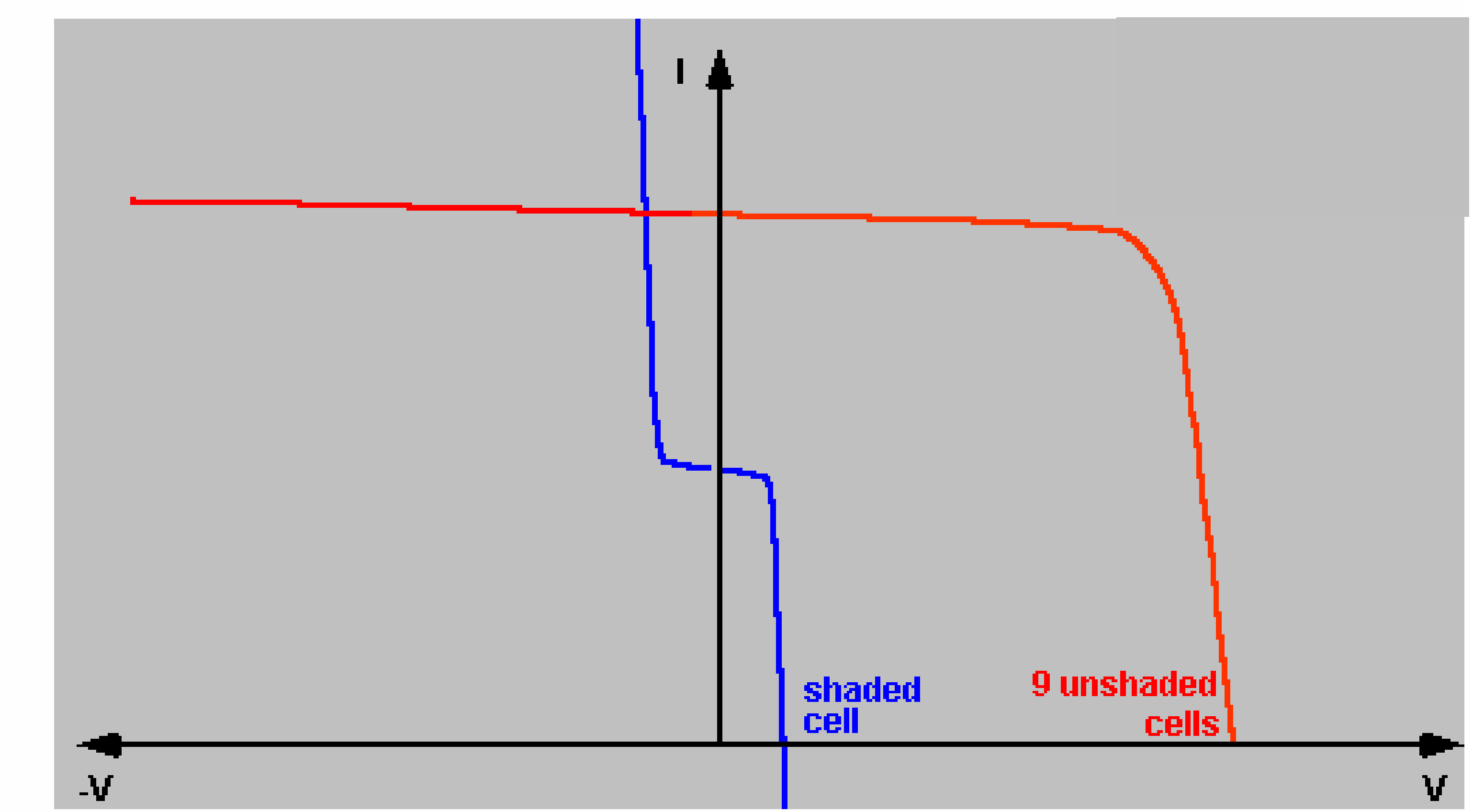
The bypass diode of the shaded cell is foward biased from the "good" solar cell and conducts current.

The shaded cell is reverse biased, but only to about -0.5V.

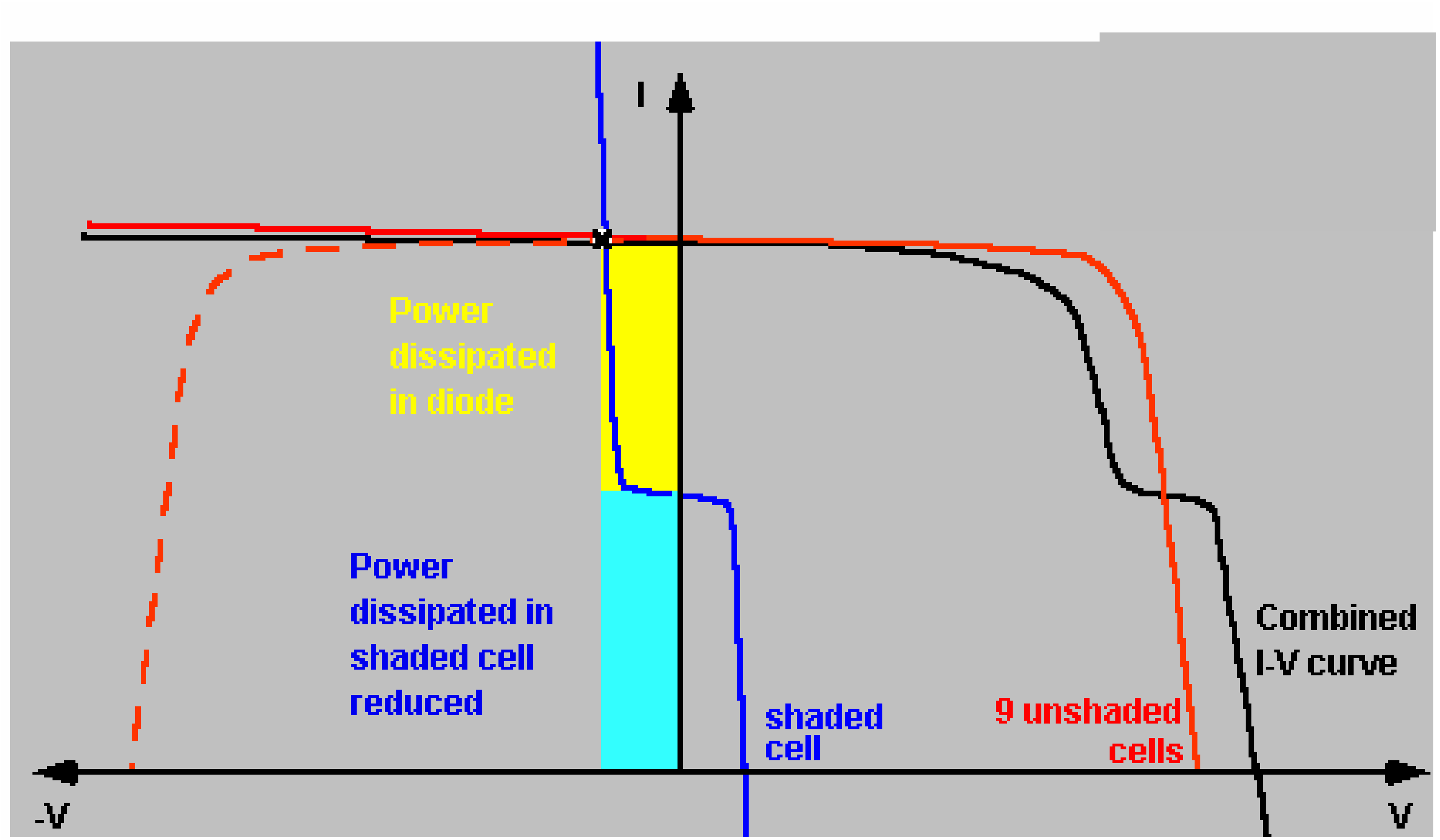
I-V Curve of Cell with Bypass Diode



I-V Curve of 9 Cells and One Partially Shaded Cell (with Bypass Diode)

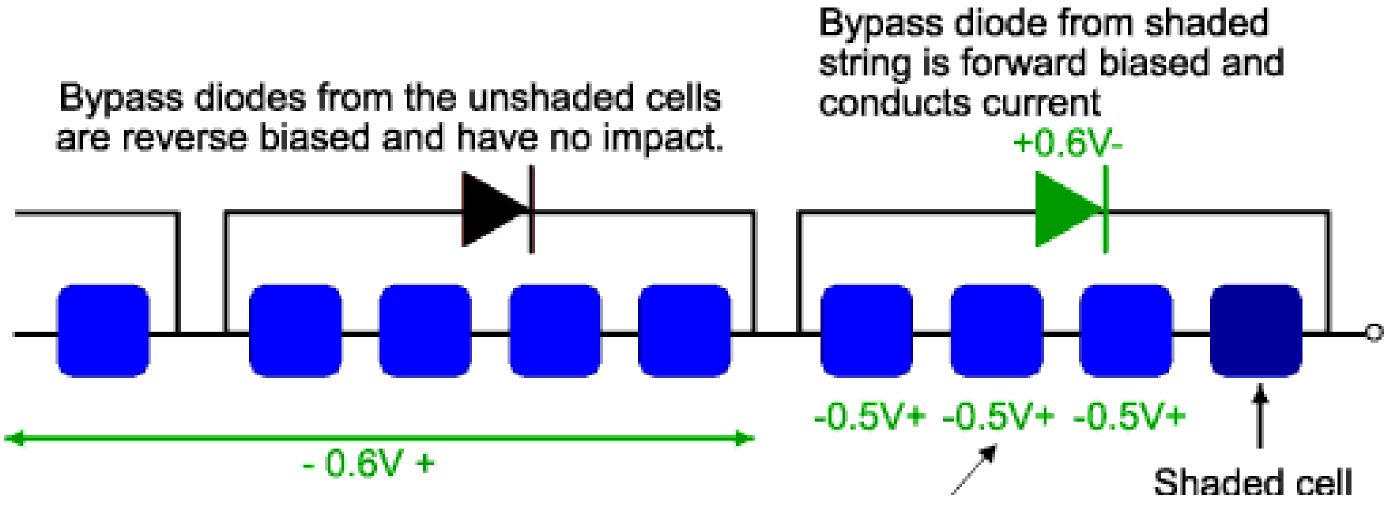


I-V Curve of 10 Cells and One Partially Shaded Cell (with Bypass Diode)

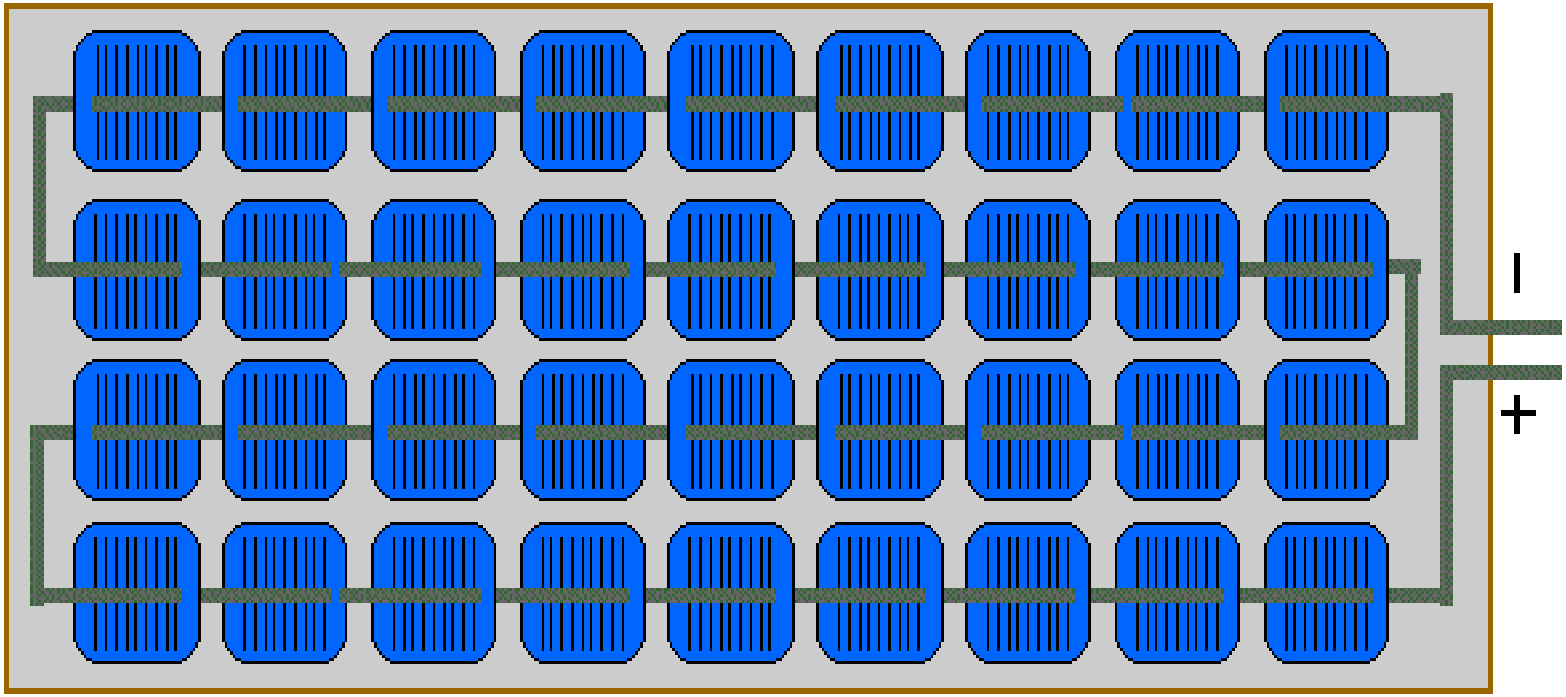


Bypass Diodes

- In practice, however, one bypass diode per solar cell is generally too expensive and not easy to install. Instead, bypass diodes are usually placed across groups of solar cells.
- The maximum power dissipation in the shaded cell is approximately equal to the total power of all cells in the group.
- The maximum group size per diode, without causing damage, is about 15-18 cells/bypass diode, for silicon cells. For a 36 cell module, 2 bypass diodes are used to ensure the module will not be vulnerable to "hot-spot" damage.

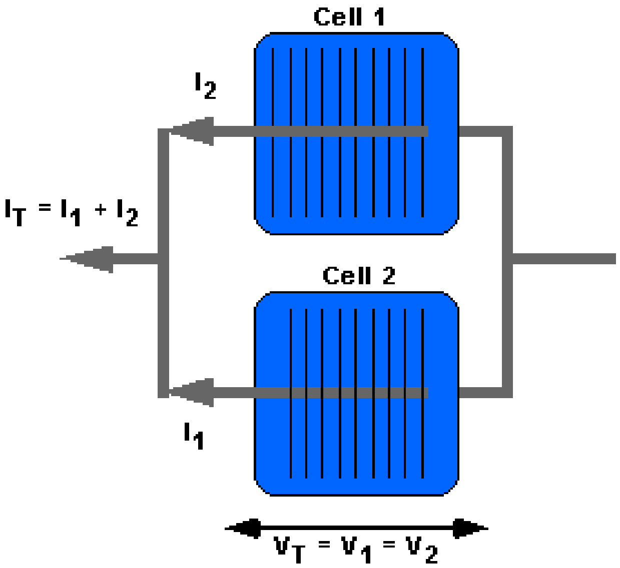


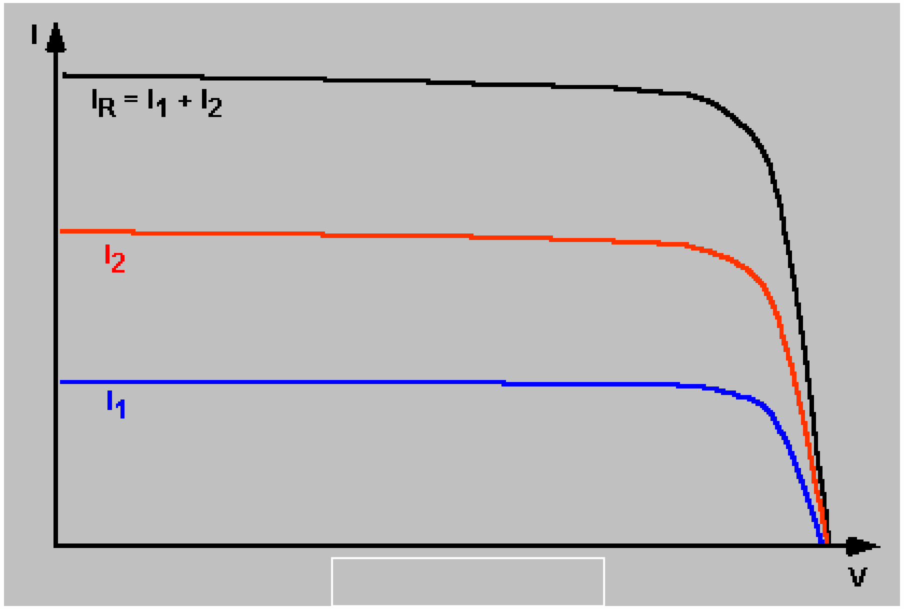
Placement of Bypass Diodes



Mismatch for Cells Connected in Parallel

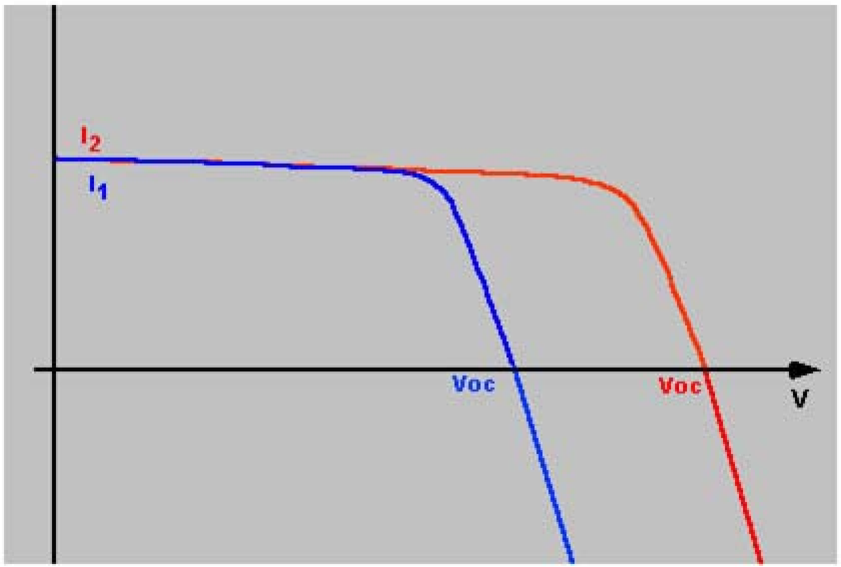
- In small modules the cells are in placed in series so parallel mismatch is not an issue. Modules are paralleled in large arrays so the mismatch usually applies at a module level rather than at a cell level.
- Cells connected in parallel: The voltage across the cell combination is always the same and the total current from the combination is the sum of the currents in the individual cells. .

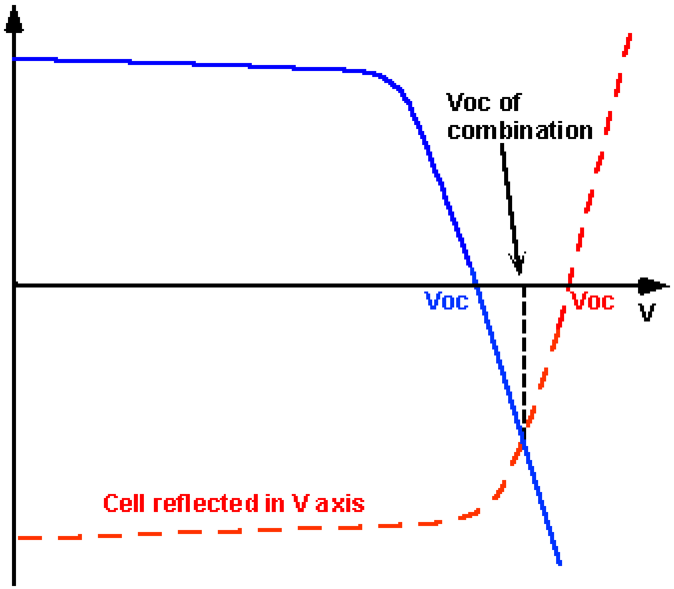




Voltage Mismatch

- Easy method of calculating the combined open circuit voltage (Voc) of mismatched cells in parallel: The curve for one of the cells is reflected in the voltage axis so that the intersection point (where $I_1+I_2=0$) is the V_{oc} of the parallel configuration.

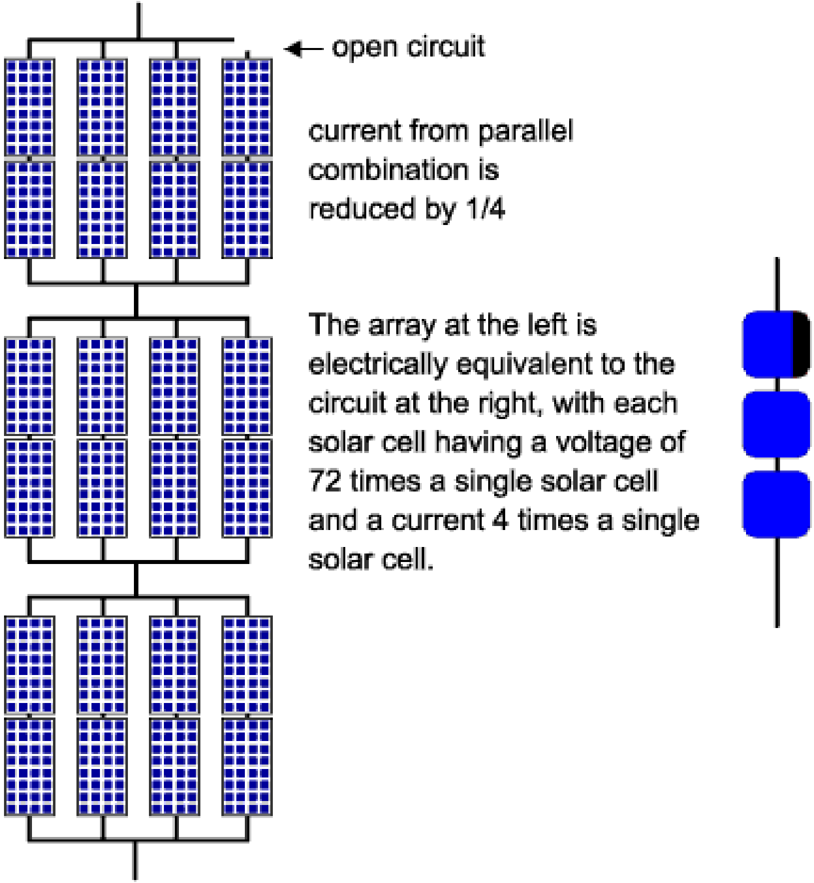




The addition of cell 2 (red) actually reduces Voc below that for good cell.

Mismatch Effects in Arrays

- In a larger PV array, individual PV modules are connected in both series and parallel.
- A series-connected set of solar cells or modules is called a "string".
- The combination of series and parallel connections may lead to several problems in PV arrays.
- One potential problem arises from an open-circuit in one of the series strings.
- The current from the parallel connected string (called a "block") will then have a lower current than the remaining blocks in the module.
- This is electrically identical to the case of one shaded solar cell in series with several good cells, and the power from the entire block of solar cells is lost. The figure below shows this effect.
- Although all modules may be identical and the array does not experience any shading, mismatch and hot spot effects may still occur.

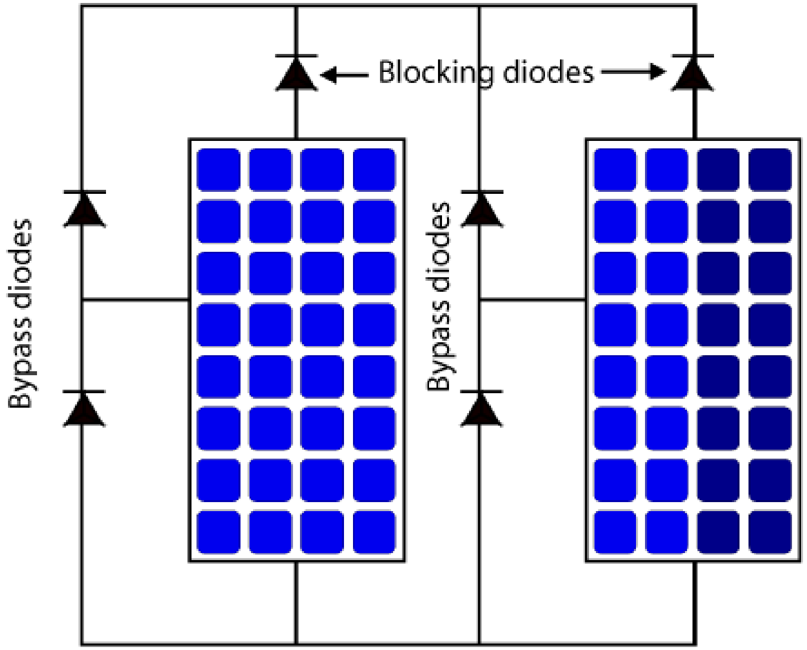


current from parallel combination is reduced by 1/4

The array at the left is electrically equivalent to the circuit at the right, with each solar cell having a voltage of 72 times a single solar cell and a current 4 times a single solar cell.

Mismatch Effects in Arrays

- In addition to the use of by-pass diodes to prevent mismatch losses, an additional diode, called a blocking diode, may be used to minimize mismatch losses.
- With parallel connected modules, each string to be connected in parallel should have its own blocking diode.
- This not only reduces the required current carrying capability of the blocking diode, but also prevents current flowing from one parallel string into a lower-current string and therefore helps to minimize mismatch losses arising in parallel connected arrays.



The blocking diode on shaded module prevents current flow into shaded module from the parallel module.

Bypass diodes reduce the impact of mismatch losses from modules connected in series.