EELE408 Photovoltaics
Lecture 17 Photovoltaic Modules

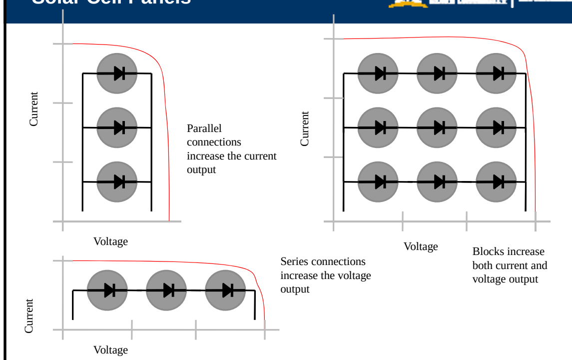
Dr. Todd J. Kaiser
tjkaiser@ece.montana.edu

Department of Electrical and Computer Engineering
Montana State University - Bozeman

Linking Cells

- Solar cells are not usually used individually because they do not output sufficient voltage and power to meet typical electrical demands
- The amount of voltage and current they output can be increased by combining cells together with wires to produce larger area solar modules
- Cells can be connected in a number of ways
  - Strings – where cells are connected in **series**
  - Blocks 2 or more strings connected together in **parallel**
  - Joining 2 or more blocks together

Solar Cell Panels



Module Structure

- Typically 36 cells wired in series
- Encapsulated in a single long-lasting stable unit
- Purpose to protect solar cells and interconnecting wires
- Prevent mechanical and water damage

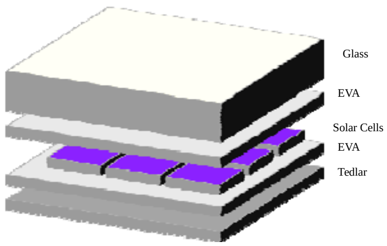
Encapsulation

- Solar cells are thin & brittle and need to be exposed to outdoor conditions for 25-30 years
- A physical casing (encapsulation) protects the PV cells and provide structural strength
- Accomplishes
  - Electrically isolate cells and make contacts
  - Protect from water and oxygen ingress
  - Withstand heavy winds, hail & installation
  - Maintain protection for decades
  - Allow modules to attach to each other

Module Materials

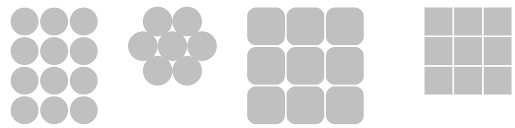
- Tempered Glass(low Iron):
  - Used for the transparent top surface.
    - AR coatings are cost prohibited and can not with stand environment
  - Needs to be highly transparent, scratch-resistant & rain, wind, hail, human… proof.
- Tedlar
  - Typical back layer because it is strong material
  - Gives structural support
  - Removes excess heat that reduces efficiency
- Ethylene Vinyl Acetate (EVA)
  - Transparent encapsulant that is UV resistant
  - Fills all the spaces between the front, rear edges and between layers
- Frame
  - Typically aluminum, strong and light weight

Module Structure



Packing Density

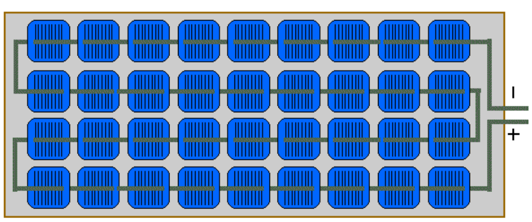
- Ratio of area of module that is covered with solar cells to total area of module face
- Multi-crystalline are usually square and have a higher packing density



Edges of circular cells removed to increase packing density

Module Design

A typical module has 36 cells in series



Sufficient to charge a 12 volt battery

Module Open Circuit Voltage

- Typically 0.6 Volts per cell at 25ºC and AM1.5
- Gives about 21 volts per module
- Allows for reductions due to temperature effects and other non-ideal conditions
- Allows for voltage drops across other PV system components
- Requires 15 V to charge a 12 V battery

Module Current

- Depends primarily on size of solar cell and efficiency
- At AM1.5 commercial cells produce 30-36 mA/cm^2
- Typical cells produce 3-4 A per cell
- Not temperature dependent
- But depends heavily on tilt angle

Identical Cells

$$I_{total} = MI_L - MI_0\left[e^{\left(\frac{qV_{total}}{nkTN}\right)} - 1\right]$$

N : number of cells in series

M : number of cells in parallel

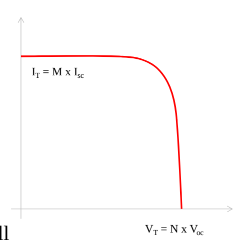
I_{total} : total current from the circuit

V_{total} : total voltage from the circuit

I_0 : saturation current from a single cell

I_L : short-circuit current from a single cell

n : ideality factor for a single cell

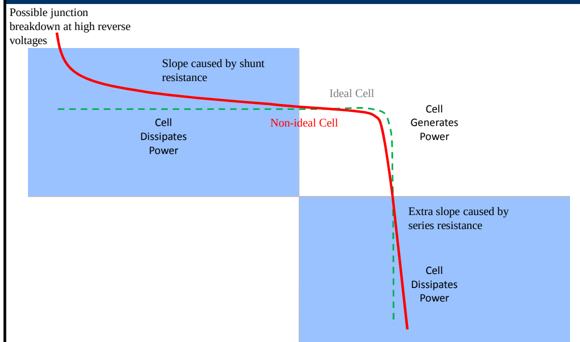


Mismatch Effects

- Interconnecting of cells or modules not having identical properties
- Module Output determined by the cell with the lowest output
- Cells usually matched to each other
- Shaded cell acts like poor cell
  - Significantly reduces output power
  - Localized power dissipation and localized heating
  - Can cause irreversible damage to module

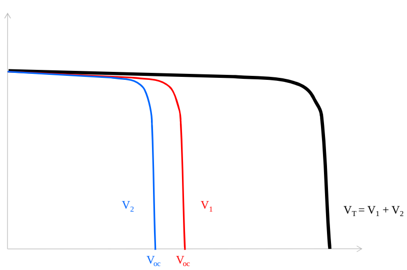
13

Non-ideal cell



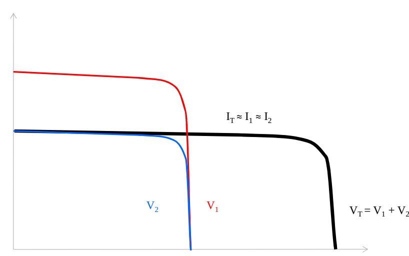
14

Open Circuit Voltage Mismatch connected in series



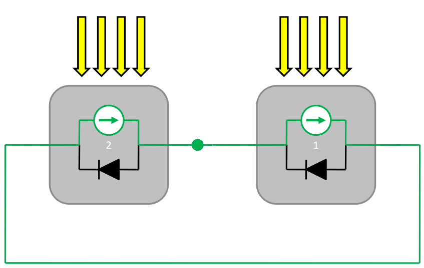
15

Short Circuit Current Mismatch connected in series



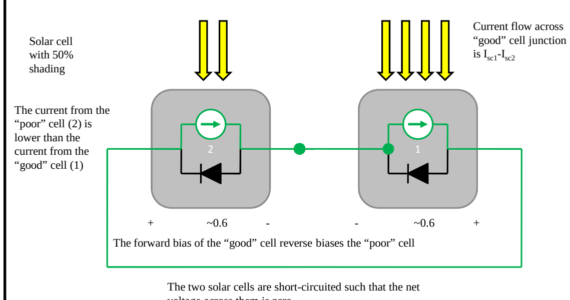
16

Series connected solar cells with identical short circuit currents



17

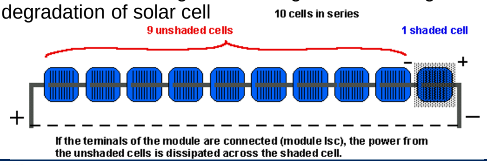
Series connected solar cells with mismatched circuit currents



18

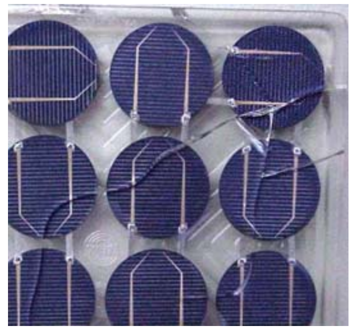
Hot-Spot Heating

- Mismatched cells within a module can result in some cells generating power and others dissipating power.
- Worst case: whole output of 'good' cells can dissipate in the 'bad' cell
- The enormous power dissipated in a small area results in local heating (hot-spot) which in turn results in destructive effects: glass cracking, solder melting or degradation of solar cell



19

Crack module due to heat dissipated from shaded cell



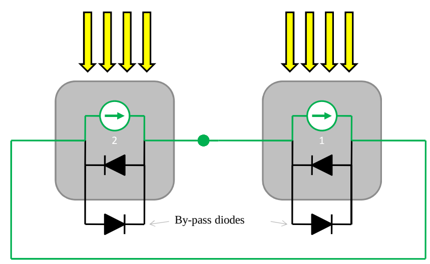
20

By-Pass Diode

- The destructive effects of hot-spot heating can be circumvented through the use of a by-pass diode
- A diode is connected in parallel with the solar cell but with opposite polarity
- The maximum reverse bias across the 'poor' cell is reduced to about the single diode drop

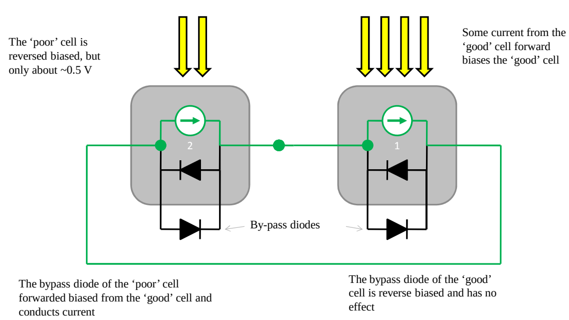
21

Series connected solar cells with by-pass diode (matched) at short circuit



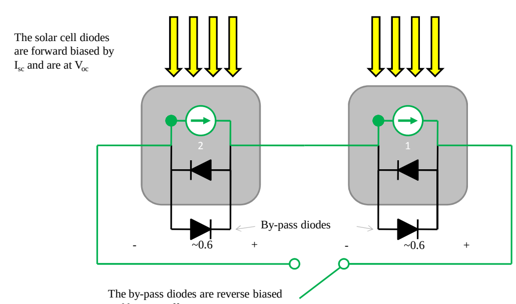
22

Series connected solar cells with by-pass diode (mismatched) at short circuit



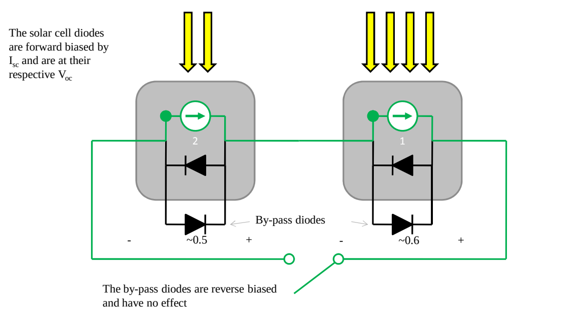
23

Series connected solar cells with by-pass diode (matched) at open circuit



24

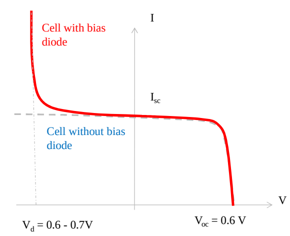
Series connected solar cells with by-pass diode (mismatched) at open circuit



25

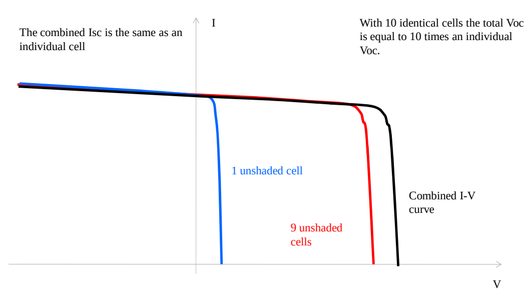
Effect of By-Pass Diode

- The by-pass diode effects the solar cell only in reverse bias
- If the reverse bias is greater than the knee voltage of the solar cell, the diode turns on and conducts current



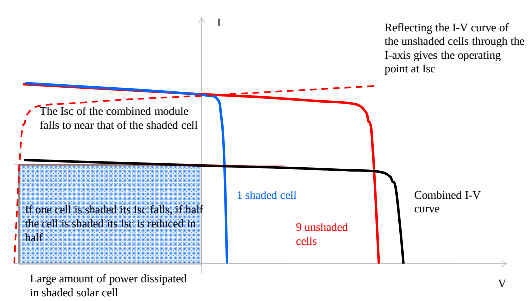
26

By-Pass diode in 10 Cell Module



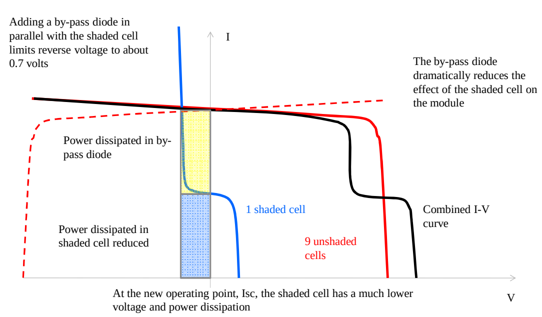
27

By-Pass diode in 10 Cell Module



28

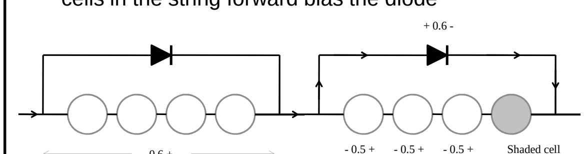
By-Pass diode in 10 Cell Module



29

By-pass diodes used across groups

- Cost prohibitive to use one diode per cell
- By-pass diodes from unshaded cells are reversed bias and have no impact
- Current from string of cells limited by lowest current cell, if some cells are shaded extra current from good cells in the string forward bias the diode



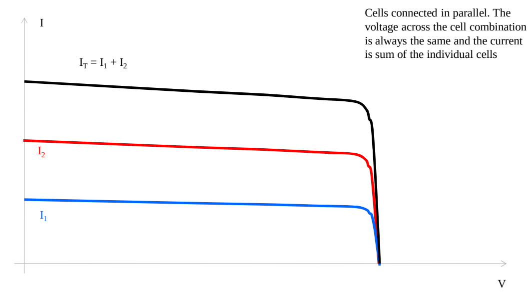
30

Mismatch for Modules connected in Parallel

- In small modules the cells are usually placed in series so parallel mismatch is not an issue
- Modules are placed in parallel in large arrays

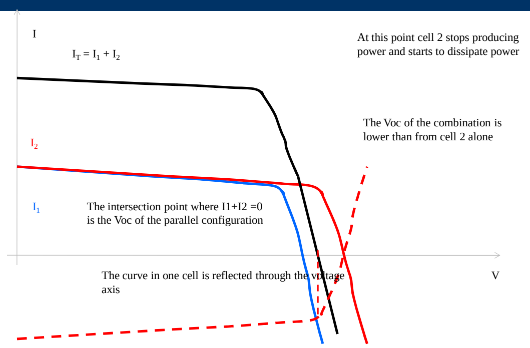
31

Cells in Parallel with Current Mismatch



32

Cells in Parallel with Voltage Mismatch



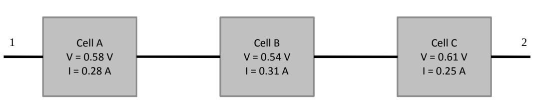
33

Calculating Voltage and Current

- **Series** connections are made by connecting one cell's n-type contact to the p-type of the next cell
- **Parallel** connections are made by joining each cells n-type contacts together and p-type contacts together
- **Series** connections the voltages add
- **Parallel** connections the current add
- **Series** connections the current flow is equal to the current from the cell generating the smallest current (limited by poorest cell)
- **Parallel** connections the voltage is the average of the cells or string in parallel

34

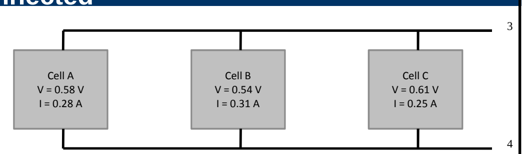
Example: Cells Series Connected



- The voltage across terminals 12 is the sum of the voltages
- $V_{12} = V_A + V_B + V_C = 0.58 + 0.54 + 0.61 = 1.73(V)$
- The current through the cells is restricted by the smallest current produce by any of the cells
- $I_{12} = 0.25$ (A)

35

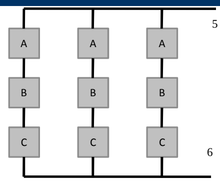
Example: Cells Parallel Connected



- The voltage across terminals 34 is the average of the voltages
- $V_{34} = (V_A + V_B + V_C)/3 = (0.58 + 0.54 + 0.61)/3 = 0.58(V)$
- The current at the terminals 34 is the sum of the currents in each cell
- $I_{34} = (I_A + I_B + I_C) = (0.28 + 0.31 + 0.25) = 0.84(A)$

36

Example: Block Connected



- The voltage across terminals 56 given by the series voltage already calculated:
- $V_{56} = V_A + V_B + V_C = 0.58 + 0.54 + 0.61 = 1.73(V)$
- The current at the terminals 56 is the sum of the currents in each string already calculated
- $I_{56} = 3(I_{string}) = 3(0.25) = 0.75(A)$

Summary Linking Cells

- Linking modules or batteries is similar to connecting PV cells
  - Series Connections
    - Voltages are added in series connections
    - The current is restricted to the smallest current
  - Parallel connections
    - The currents are added in parallel connections
    - The voltages are averaged from each string
- Solar Cells and Modules are Matched to improve the power generated