EELE408 Photovoltaics

Lecture 18 Photovoltaic Arrays & Modules

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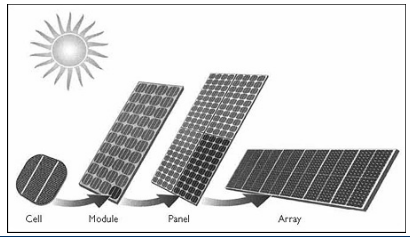
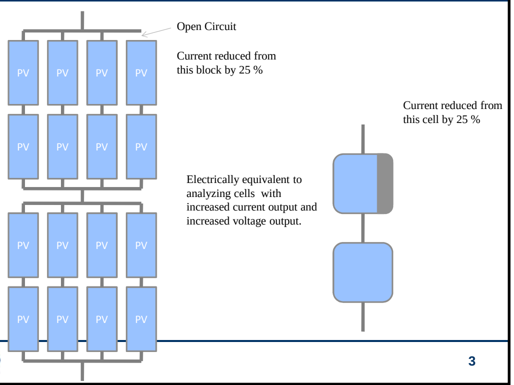
Photovoltaic Arrays

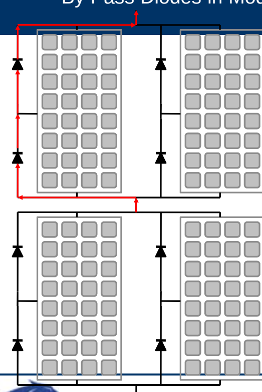
- In large PV systems Modules are connected in series and parallel
  - Series connected modules are called "strings"
  - Parallel connected strings are called "blocks"



Mismatch Effects in Arrays

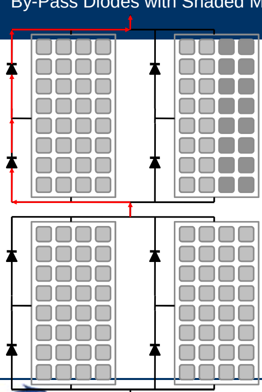


By-Pass Diodes in Modules



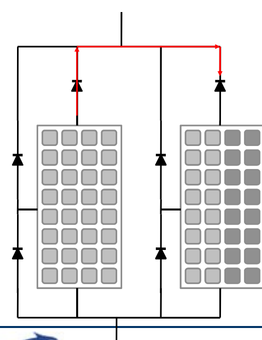
- Typically 2 diodes in each 36 cell module
- Diodes must be matched
  - Lower resistance diodes will have higher current value. Heating the diodes
  - Can create thermal run away and diode failure and damage the PV module

By-Pass Diodes with Shaded Modules



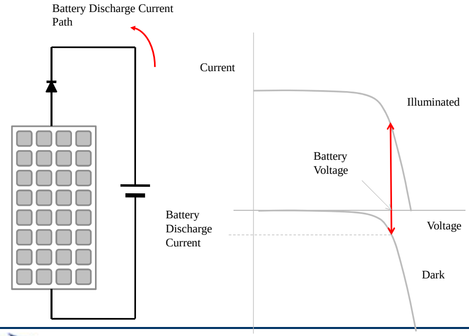
- Shaded Module
- Problems can occur if the by-pass diode is not rated to handle the current for the entire parallel connected array
- A shaded module will force the current of rest of array through the diodes

Blocking Diodes with Shaded Modules



- Blocking diodes reduce the impact of mismatch losses from modules connected in series
- Prevents current flow from parallel connected module into shaded module
- Prevent battery discharging through panel

Operation of Blocking Diode

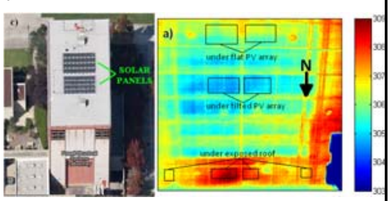


Module Temperature

- A side effect of encapsulation is an increase of operating temperature by altering the heat flow in and out of the solar cells
- Degrades performance
- Can shorten lifetime by increasing failure mechanisms (thermal cycling)

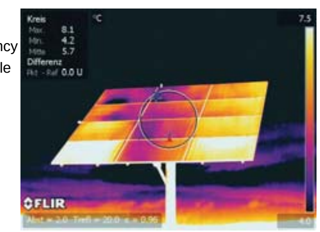
Operating Temperature of Module

- Equilibrium between
  - Heat produced by PV module
    - Function of operating point
    - Optical properties of module
    - Packing density
  - Heat lost to environment
    - Conduction
    - Convection
    - Radiation
  - Ambient Temperature



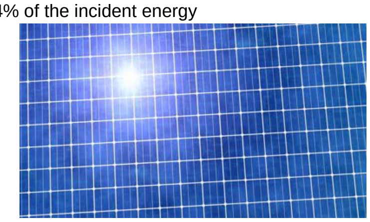
Heat Generation in PV Module

- Typically only 10-15% of the incident light is converted into electricity
- Most of the remaining is converted into heat
- Factors
  - Front Surface Reflection
  - Operating point and Efficiency
  - Absorption of light by module
  - Absorption of IR by module
  - Packing Factor



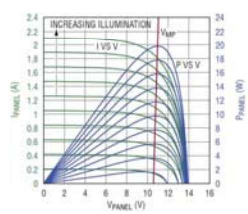
Front Surface Reflection

- Reflected light does not produce electricity or create heat
- The maximum temperature rise of module is calculated from the incident power multiplied by the reflection
- For a typical glass topped module the reflected light contains 4% of the incident energy



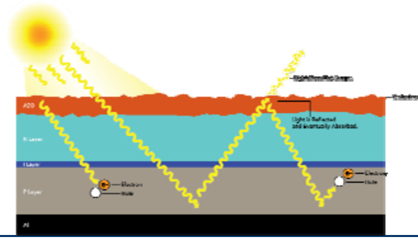
Operating Point & Efficiency

- Determines the fraction of the light absorbed by the solar cell and converted into electricity
- For example if the solar cell is operating at short circuit current or open circuit voltage, no electricity is generated and all the power absorbed by the solar cell is converted into heat



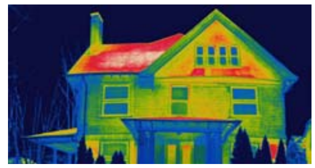
Absorption of Light

- The parts of the module that are not solar cells will absorb light and contribute to heating the module
- How much is dependent on the material and color of the rear backing material layer of the module



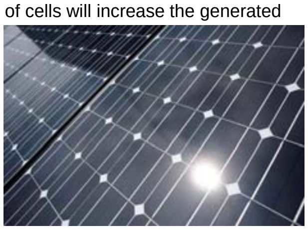
Absorption of Infrared

- Light below the band gap energy of the solar cell cannot contribute to electrical power
- If it is absorbed by the module it will contribute to heating
- The aluminum frame will also absorb infrared and contribute to heating the module
- Most modules are designed to allow the IR to pass through the material exit the module

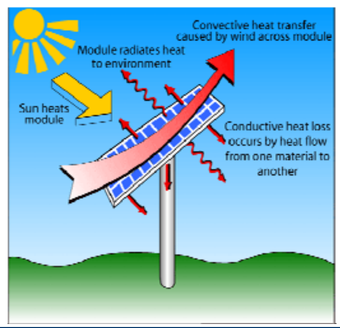


Packing Factor of Solar Cells

- Solar cells are designed to be efficient absorbers of solar radiation. Each cell will generate significant amounts of heat that needs to be dispersed, usually greater the rest of the system
- A higher packing factor of cells will increase the generated heat per unit area



Heat Losses



- Heat in must equal heat out in equilibrium
- Losses
  - Conduction
  - Convection
  - Radiation

Heat Conductive Losses

- Due to thermal gradient across material
- Ability to transfer heat is characterized by the thermal resistance and configuration of the module and its materials
- Conductive heat flow is analogous to Conductive current flow
  - Driven by temperature difference (potential difference)

$$\Delta T = \Theta \frac{dQ}{dt} \Leftrightarrow V = RI \rightarrow \Delta V = R\frac{dq}{dt}$$

Thermal Resistance

$$\Theta = \frac{L}{\kappa A}$$

- A Θ: thermal resistance (°C/W)
- L: length of the material the heat must travel
- A: Area of the surface conducting the heat
- k: thermal conductivity (W/m- °C)

Convection

- Transport of heat due to one material moving across the surface of another
- In PV modules typically due to wind blowing air across the module

$$\frac{dQ}{dt} = hA\Delta T$$

  - dQ/dt: Heat
  - h: convection heat transfer coefficient (W/m^2/ ^{0}C)
  - A: area of contact between two materials
  - ΔT: temperature difference between the materials

Radiation

- Any body will radiate based on its temperature
- Blackbody radiation $\frac{dQ}{dt} = \sigma T^4$
- Solar cells are non-ideal blackbodies, scaled by the emissivity of the object $\frac{dQ}{dt} = \varepsilon\sigma T^4$
- Net heat loss is the difference from ambient

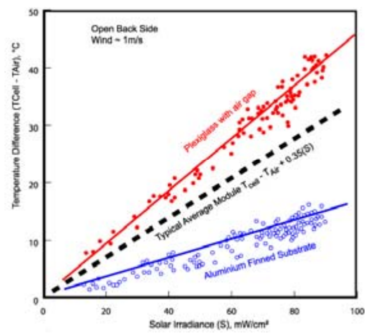
$$\frac{dQ}{dt} = \varepsilon\sigma \left(T_{sc}^{\ 4} - T_{amb}^{4}\right)$$

Nominal Operating Cell Temperature

- (NOCT)
  - Irradiance on cell surface (800 W/m^2)
  - Air Temperature (20ºC)
  - Wind Velocity (1 m/s)
  - Mounting (open rear surface)

Temperature Characteristics	
Nominal Operating Cell Temperature (**NOCT**)	45±2°C
Temperature Coefficient of Pmax	-0.45 %/°C
Temperature Coefficient of Voc	-0.34 %/°C
Temperature Coefficient of Isc	0.050 %/°C

Nominal Operating Cell Temperature



Cell Temperature

$$T_{cell} = T_{air} + \frac{NOCT - 20}{800} \times S \quad \left({}^{\circ}C\right)$$

- S: insolation in W/m^2
- Module temperature will be lower with increase wind velocity and higher under calm conditions

Impact on NOCT

- Cell packing density
  - Lower density → lower temperature
- Mounting Conditions
  - Stand off or surface mounted
    - Roof Integrated systems can raise temperature 10 ^{0}C

Thermal Expansion & Stress

- Cycling of temperature causes materials to shrink and expand
- If the coefficients of thermal expansion are not matched stresses can be created in the modules and solar cells
- Can delaminate the cell from encapsulation
- Or delaminate the module

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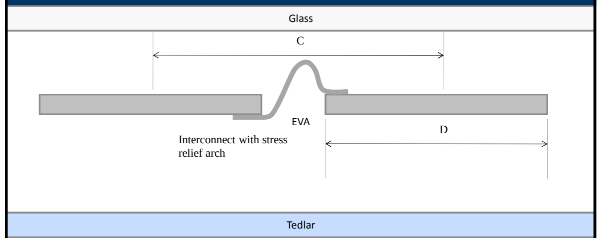
Thermal Expansion



$$\delta = (\alpha_g C - \alpha_c D)\Delta T$$

δ: change in spacing between cells
α_g: coefficient of thermal expansion for glass
α_c: coefficient of thermal expansion for cell
C: Cell center to center distance
D: Cell diameter or width

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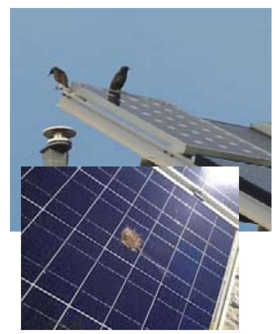
Degradation and Failure Modes

Front Surface Soiling

- Module performance can be reduced by the accumulation of dirt on the top surface
- PV modules generally experience a 10% loss in output due to front surface soiling



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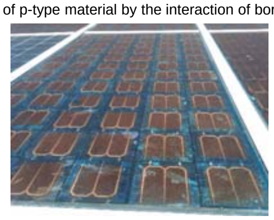
Cell Degradation

- A gradual degradation in module performance
  - Increase in series resistance due to contact corrosion or separation (usually caused by water vapor)
  - Decrease in shunt resistance due to metal migration through pn junction
  - Antireflection coating deterioration
  - Degradation of p-type material by the interaction of boron-oxygen complexes



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Module Optical Degradation

- Discoloration of the encapsulating materials
- Ultraviolet light can yellow polymers
- Diffusion of foreign matter or water from edges

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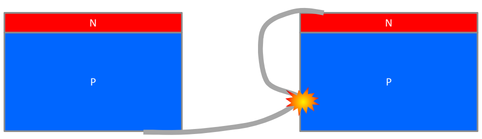
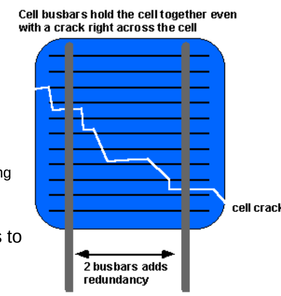
Short Circuit Cells



- Short circuiting at the cell interconnections
- Pin holes, corrosion, or damaged cells are common in thin film cells since top and rear contacts are much closer together

Open Circuit Cells

- Common failure mode
- Cracking of cells
  - Thermal stress
  - Hail
  - Snow load
  - "Latent Cracks" created during processing but undetectable during inspection
- Redundant contact points and interconnect busbar allow cells to continue functioning



Interconnections

- Fatigue due to cyclic thermal stress or wind and snow loading leads to interconnect open circuits failures
- Series resistance can gradually increase with age
- As tin-lead solder ages, the solder separates into grains of tin and lead, becomes brittle and cracks at grain boundaries increasing resistance

Module Open Circuit & Series Resistance

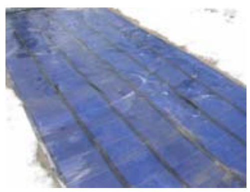
- Open circuit failures and aging effects can also occur in the module, typically in the bus wiring and junction box

Module Short Circuit

- Although each module is tested before sale, module short circuits are often the results of manufacturing defects
- They occur due to insulation degradation with weathering, resulting in delamination, cracking or electrochemical corrosion

Module Glass Breakage

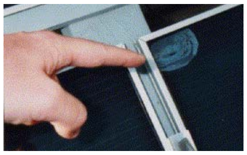
- Shattering of the top glass surface can occur because of hail, wind, handling, thermal stress, or vandalism
- Roofing gravel has been found to cause fractures in relatively low wind speeds by blowing up the tilted modules then falling back down on the next row of modules



Blew off roof

Module Delamination

- Common failure mode in early generation of modules, but now less of a problem
- Caused by reduction of bond strength
  - Environmentally induced moisture
  - Photothermal aging
  - Stress aging due to thermal and humidity expansion
- More frequent in hot and humid climates

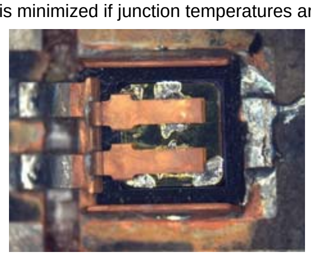


Hot-Spot Failures

- Mismatched, cracked or shaded cells can lead to hot-spots failure

Bypass Diode Failure

- Bypass diodes used to overcome cell mismatching problems can themselves fail, usually due to overheating and often due to undersizing
- The problem is minimized if junction temperatures are kept below 128ºC



Encapsulant Failure

- Ultraviolet absorbers and other encapsulant stabilizers have been added to ensure a long life for module encapsulating materials
- Slow depletion by leaching and diffusion occurs, once concentrations fall below a critical level, rapid degradation of the encapsulant materials occurs
- Browning of the EVA layer with a build-up of acetic acid has degraded some arrays