EE2022 Electrical Energy Systems

Solar Energy

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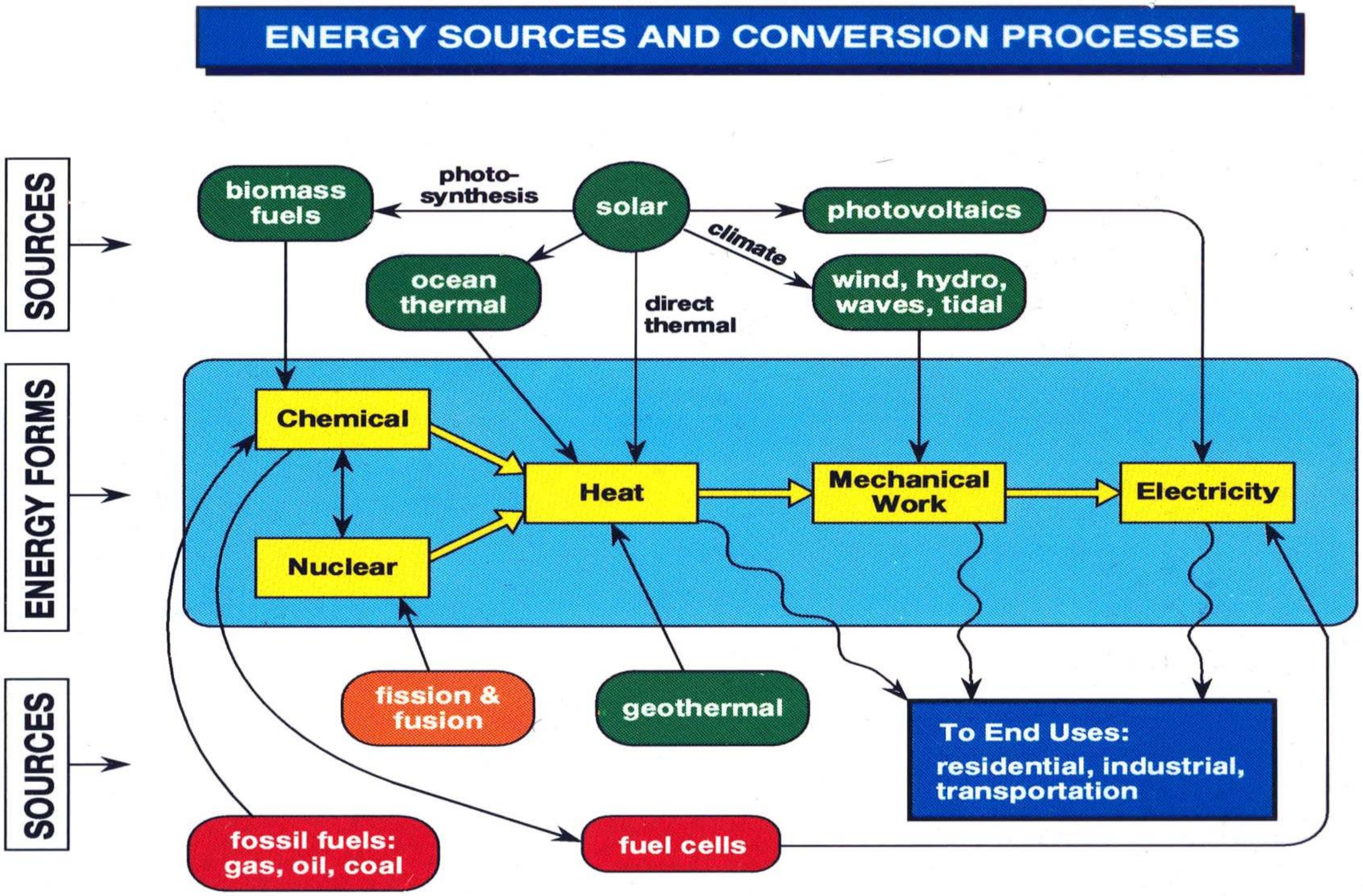
Detailed Syllabus

Topic 1	**Transformer**: Principle of transformer. Ideal transformer. Reflected load. Impedance matching. Practical transformer. Examples
Topic 2	**Renewable Energy Sources:** Sustainable and clean energy sources; Solar Photovoltaic, Wind Energy; Examples
Topic 3	**Per unit analysis**: Single-phase per unit analysis. Three-phase transformer, Three-phase per unit analysis. Examples.
Topic 4	**Generator**: Simple generator concept. Equivalent circuit of synchronous generators. Operating consideration of synchronous generators, i.e. excitation voltage control, real power control, and loading capability. Principle of asynchronous generators. Examples.
Topic 5	Electric energy market operation; Cost of Electricity
Topic 6	**Distributed Generation:** Concept of distributed energy generation and utility interfacing; Energy Storage

Outline

- History of Solar Energy
- Solar Photovoltaic (PV) Systems

Solar Energy- History



PV Technology- History

- Nearly every satellite and spacecraft since 1958 has relied on a PV system for power generation

DOE/NREL, NASA/Smithsonian Institution/ Lockheed Corp.

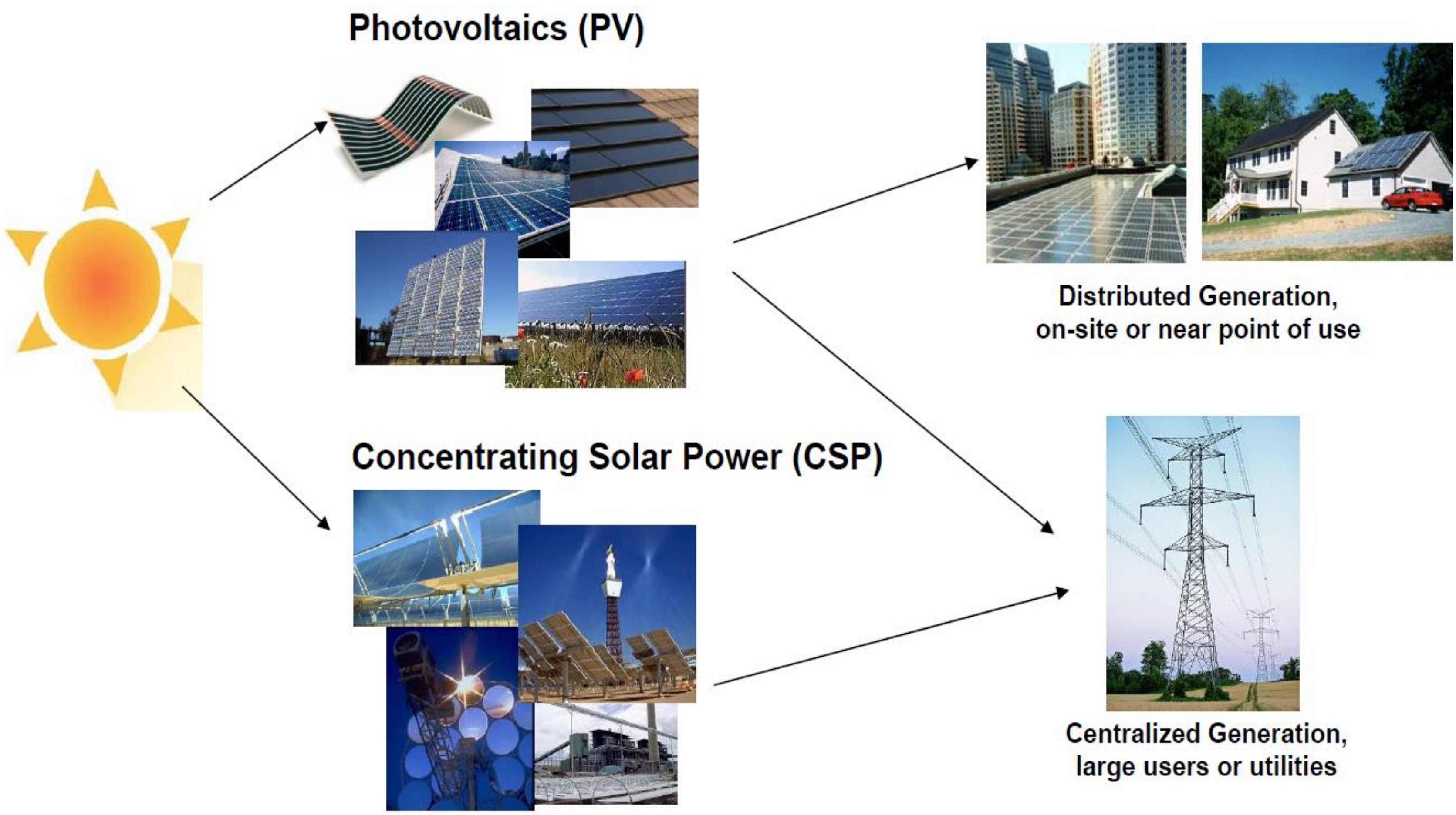
- Rural communications systems in the 1950s were the first terrestrial applications of PV technology

Lucent Technologies Inc./Bell Labs

How Much Solar Energy Strikes Earth?

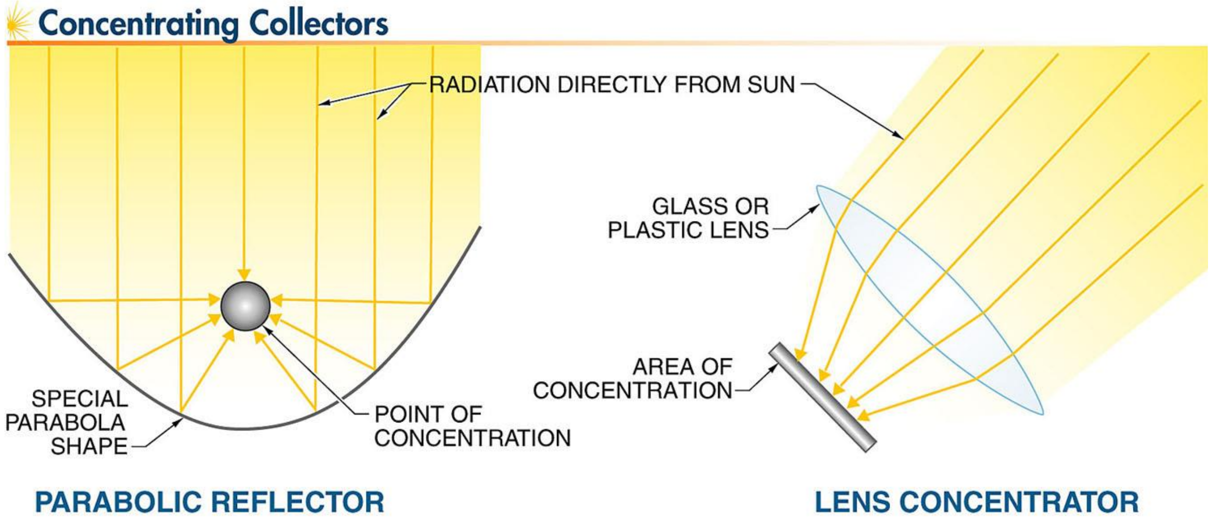
- The sun gives off 3.90×10^{26} Watts
- The earth intercepts energy equal to a disk equal to the earth's diameter
- Earth's radius is 3,393,000 meters
- Earth's solar interception area is $\Pi * (3{,}393{,}000)^2$
- This equals 3.62×10^{13} m^2
- The amount of power crossing earth's orbit is 1388 watts / m^2
- Earth intercepts 5.02×10^{16} watts

Generating Electricity from the Sun

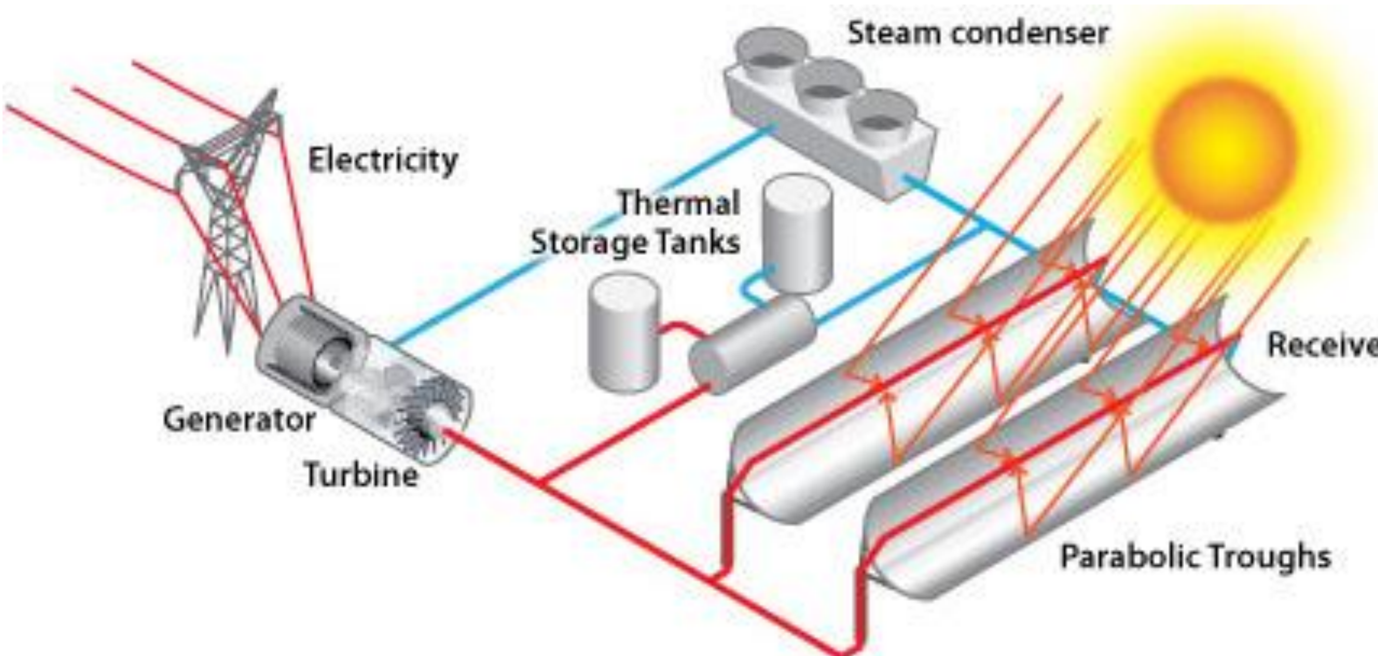


Solar Energy: Concentrating Solar Power

- Concentrating collectors focus a large area of direct solar radiation onto a relatively small area.
- Concentrating collectors have increased efficiency and reduced size because of the ability to channel more solar radiation onto the desired surface



Solar Thermal Energy Generating System



Source: http://www.ecomena.org/csp-desalination-mena/

- US Dept of Energy:
  https://www.youtube.com/watch?v=rO5rUqeCFY4

Photovoltaics

Solar PV Cell

Equivalent Circuit for a Photovoltaic Cell

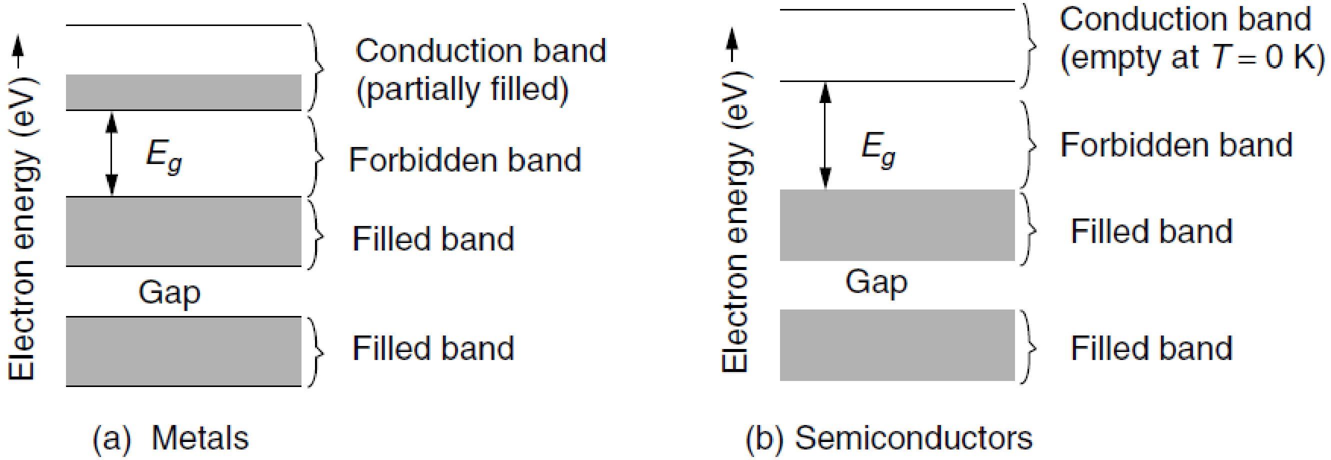
Voltage, Current and Power Curves

PV Modules

SOLAR PHOTOVOLTAIC (PV) SYSTEMS

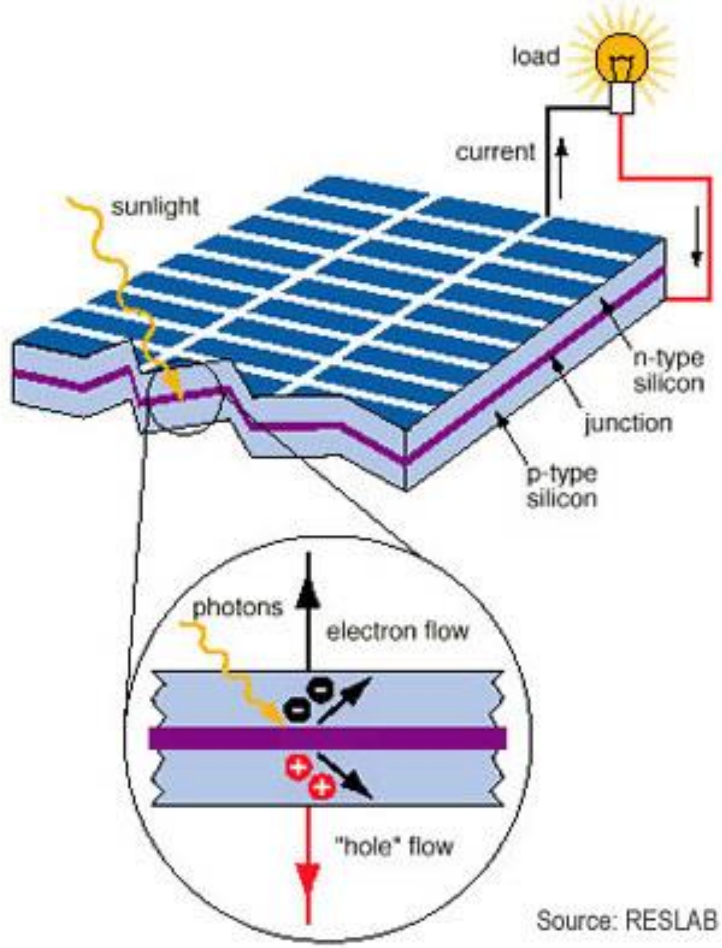
Photovoltaics

- A material that can convert the energy in photons of light into an electrical voltage and current is a ***photovoltaic***
- Photovoltaics use semiconductor material, typically Silicon



Solar PV Cell

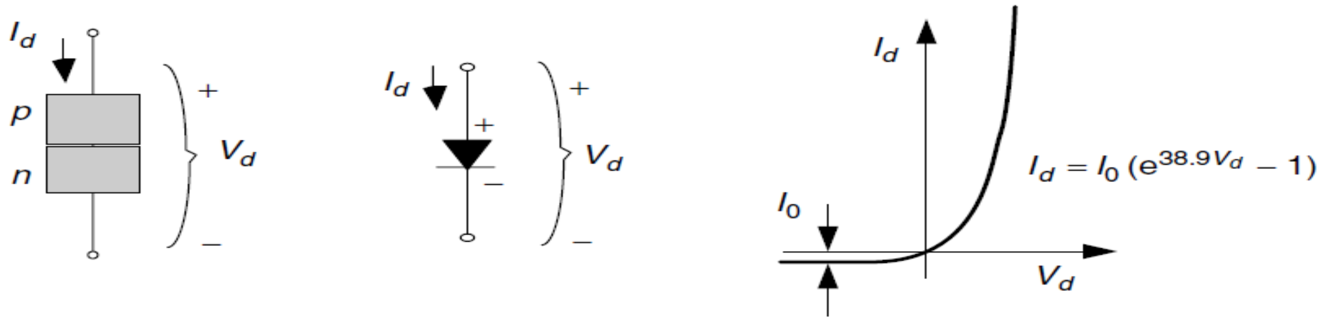
- Photons in sunlight hit the solar panel and are absorbed by semiconducting materials, such as silicon
- Electrons (negatively charged) are knocked loose from their atoms, allowing them to flow through the material to produce electricity. Due to the special composition of solar cells, the electrons are only allowed to move in a single direction
- An array of solar cells converts solar energy into a usable amount of direct current (DC) electricity



P-N junction diode

- Photovoltaics use p-n junction semiconductor to avoid holes recombining with electrons

$$I_d = I_0(e^{qV_d/kT} - 1)$$



(a) p–n junction diode (b) Symbol for real diode (c) Diode characteristic curve

I_d - Diode current
V_d – Voltage across the diode terminals
I_0 – Reverse Saturation Current

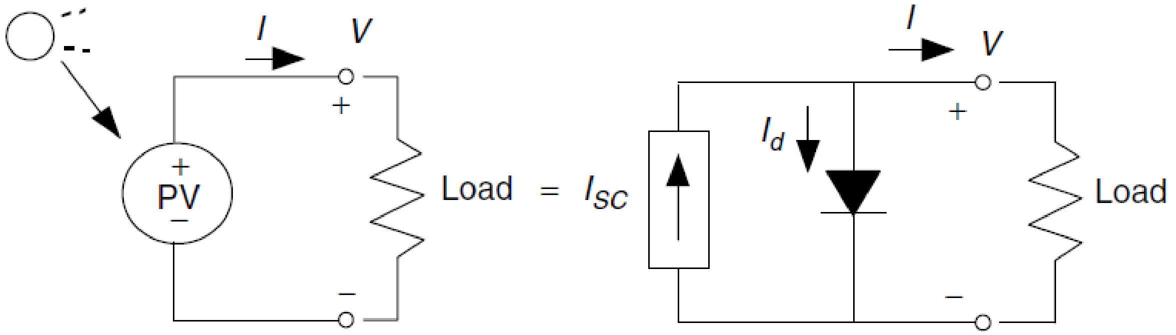
q - Electron Charge (1.602x10-19 C)
k – Boltzmann's Constant (1.381x 10-23 J/K)
T- Junction Temperature

$$I_d = I_0(e^{38.9V_d} - 1) \qquad \text{(at } 25^\circ\text{C)}$$

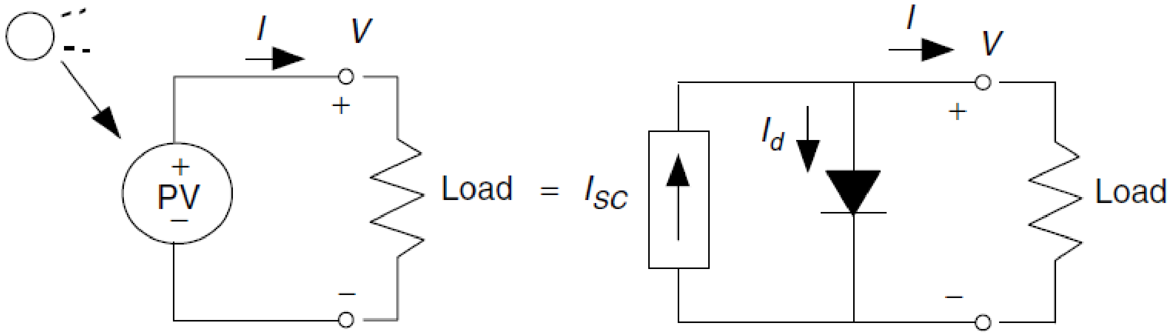
Equivalent Circuit for a Photovoltaic Cell

I_{SC} is directly proportional to the amount of solar flux (also called insolation) to which the solar cell is exposed

Voltage and Current equations for the PV cell

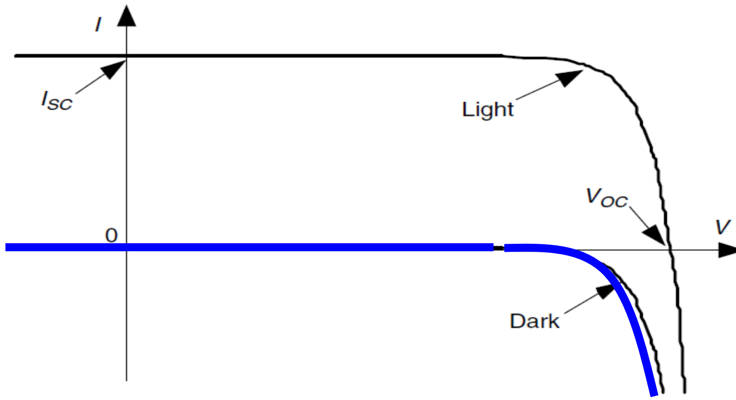


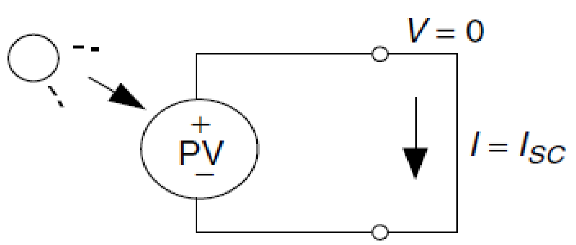
Voltage and Current equations for the PV cell



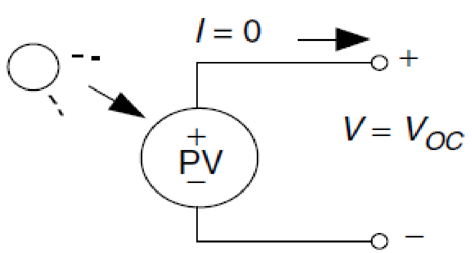
Photovoltaic current–voltage relationship

- In both these equations, short circuit current is directly proportional to solar insolation, hence we can now plot current-voltage curves for varying sunlight.
- The dark (no sunlight) curve is just the diode curve turned upside-down. The light (illuminated cell) curve is the dark curve plus I_{SC}





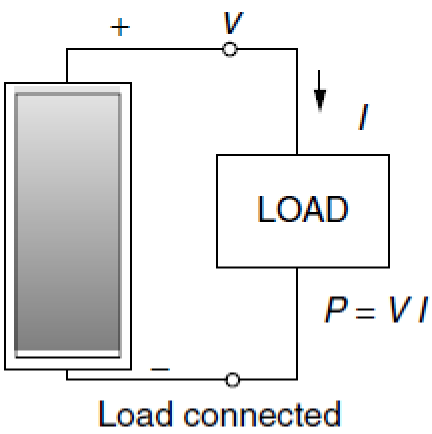
(a) Short-circuit current

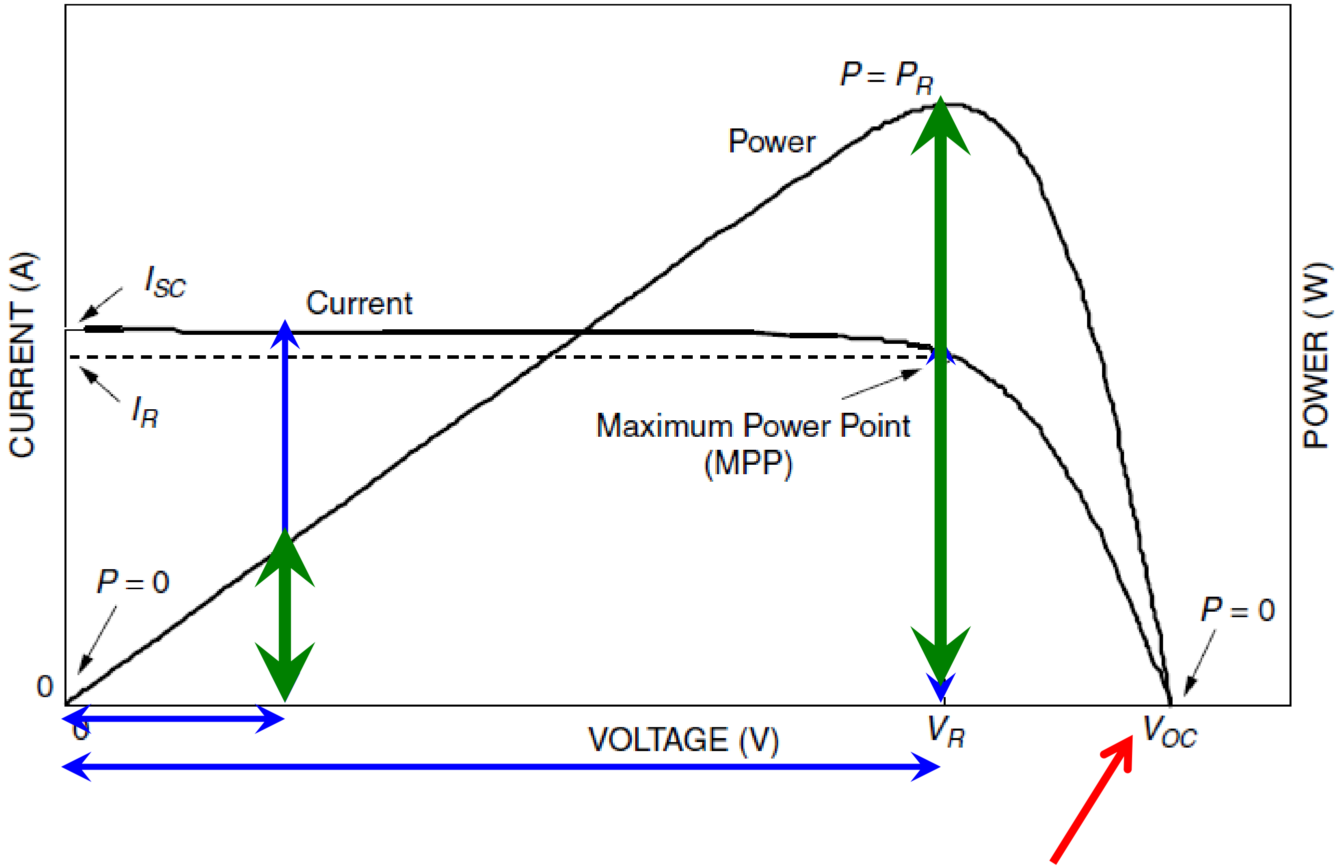


(b) Open-circuit voltage

Example: Consider a 100 cm^2 PV cell with a reverse saturation current $I_0=10^{-12}$ A/cm^2. In full sun, it produces a short circuit current of 40 mA/cm^2 at 25°C. Find the open-circuit voltage at full sun and again for 50% sunlight. Plot the results.

Voltage, Current and Power Curves

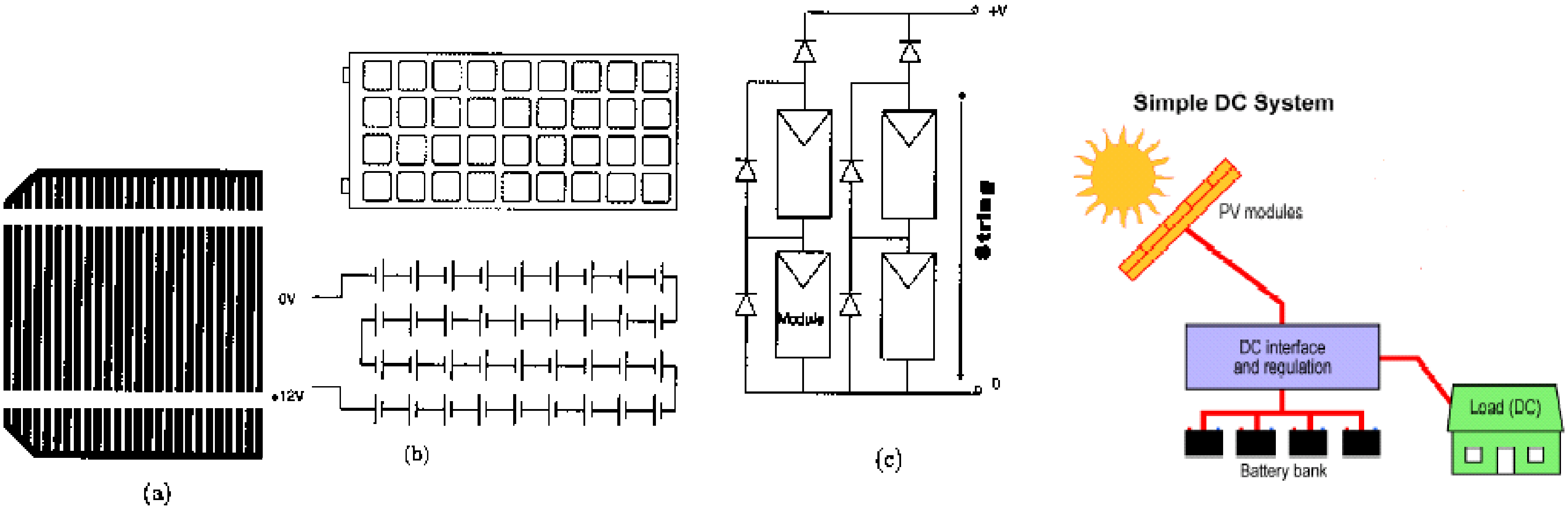




The open circuit voltage Voc is the maximum voltage from a solar cell and occurs when the net current through the device is zero.

Photovoltaic Cells, Modules and Systems

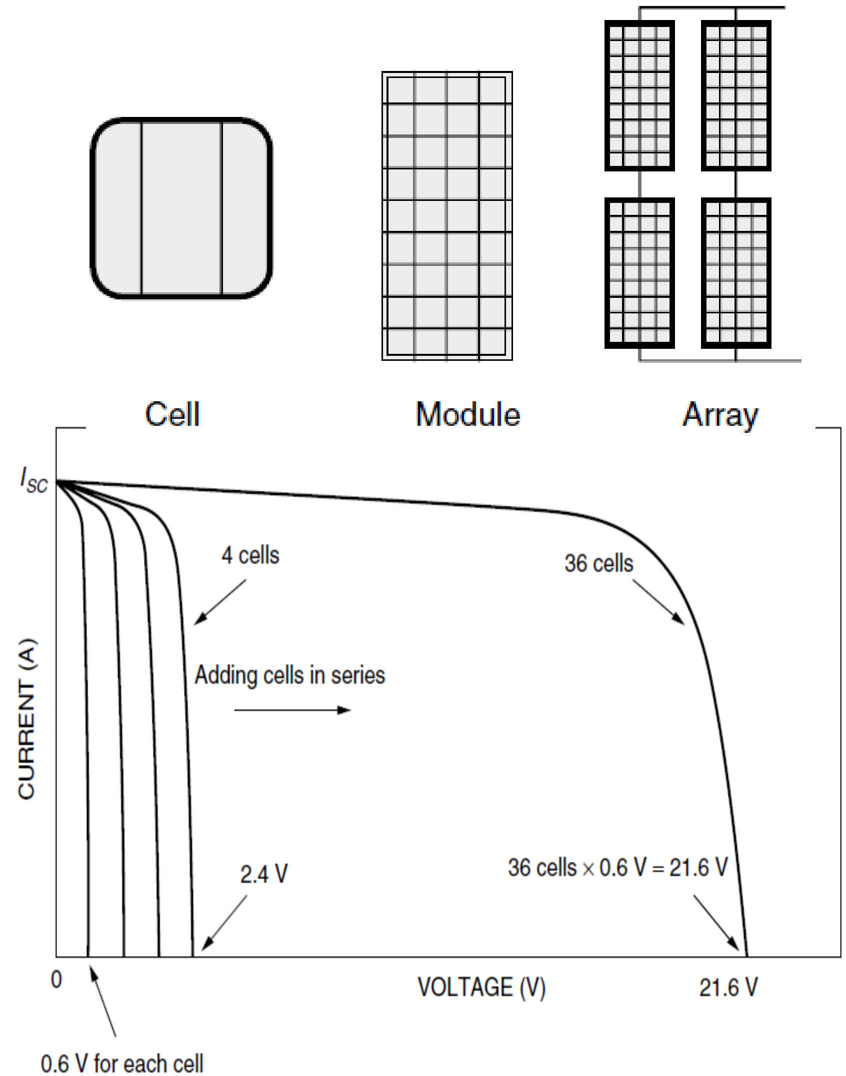
- Solar cell is the basic building blocks of solar PV
- Cells are connected together in series and encapsulated into models
- Modules can be used singly, or connected in parallel and series into an array with a larger current & voltage output
- PV arrays integrated in systems with components for storage



Cell module array system

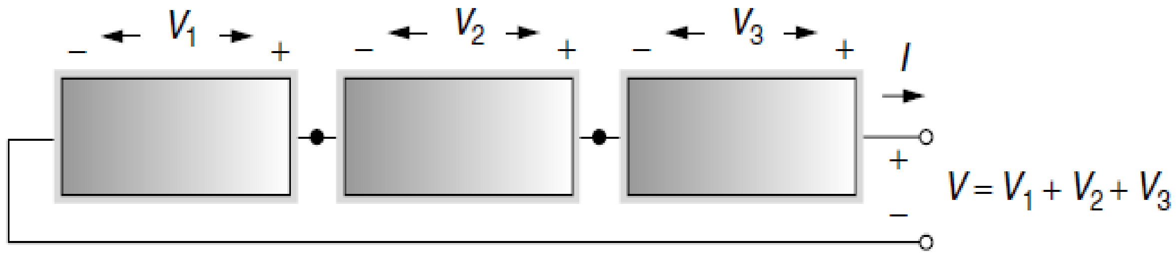
From cells to a module

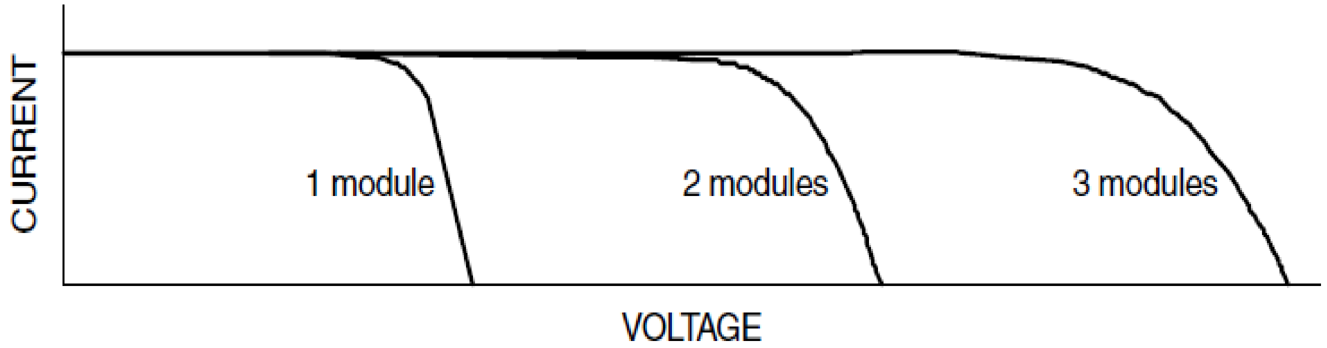
- A typical module has 36 cells
- Often designated as 12-V module
- When wired in series, they carry the same current, but voltages add
- Modules can be connected in parallel to increase current
- Series and parallel connection increases power



Modules connected in series

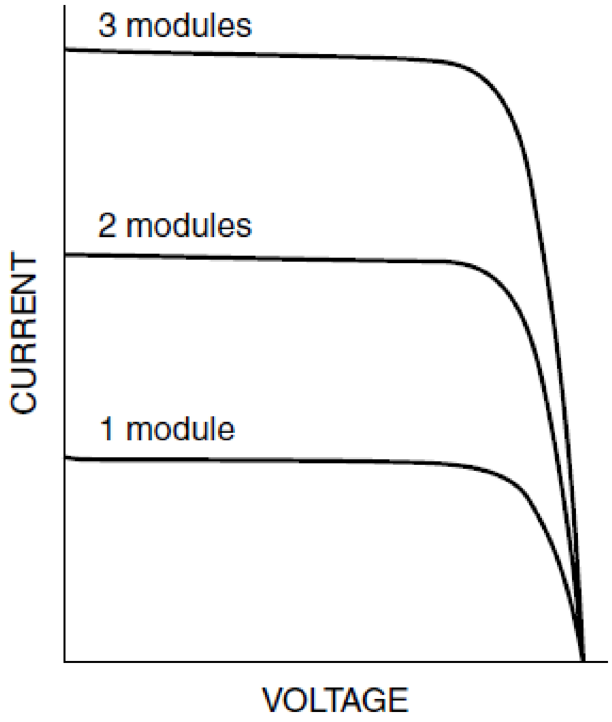
- The voltages produced are added
- Same current flows through all

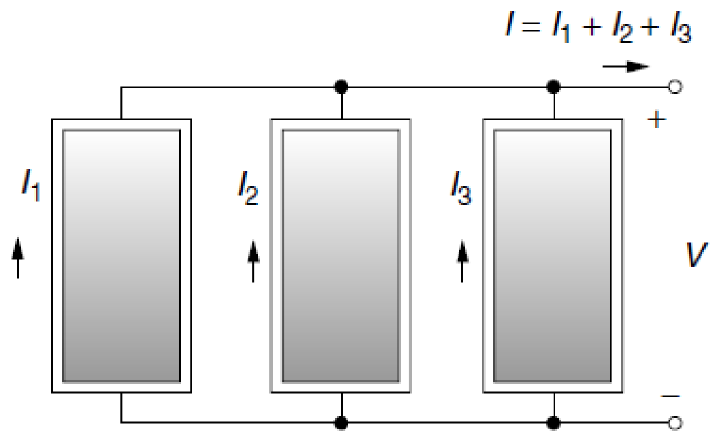




Modules connected in parallel

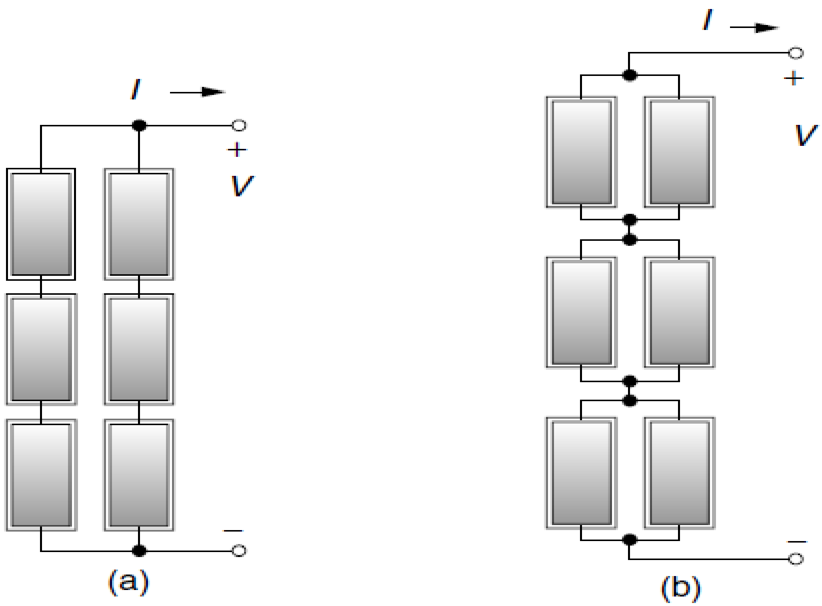
- Currents add, while voltage remains the same





Modules in series-parallel configuration

- Example: Three modules in series, two in parallel



Example: 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.* Find the voltage, current, and power delivered when the junction voltage of each cell is 0.50 V