# EE2022 Electrical Energy Systems

## Solar Energy

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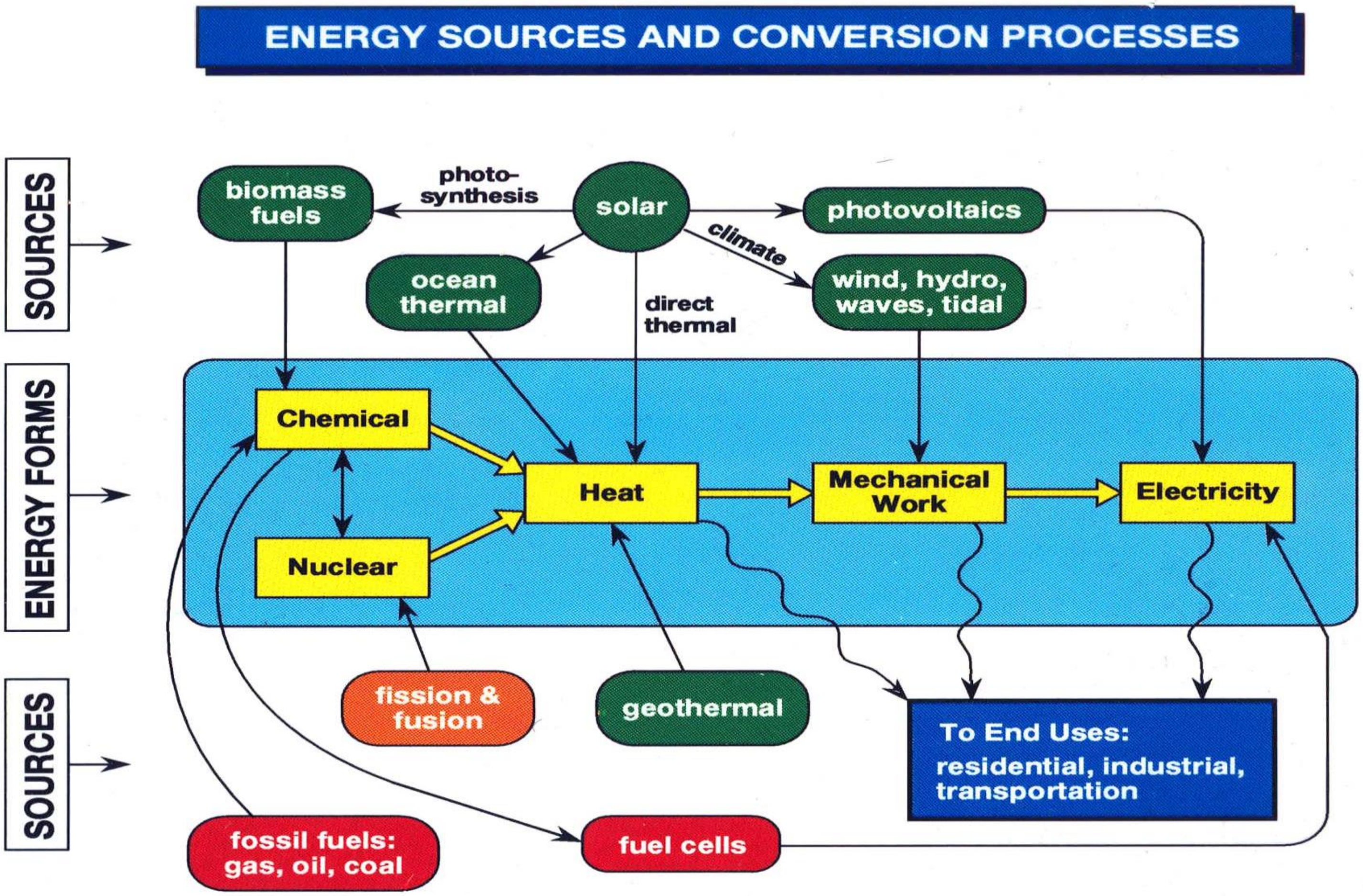
# Detailed Syllabus

| | |
|---|---|
| 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

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

Space PV Applications

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

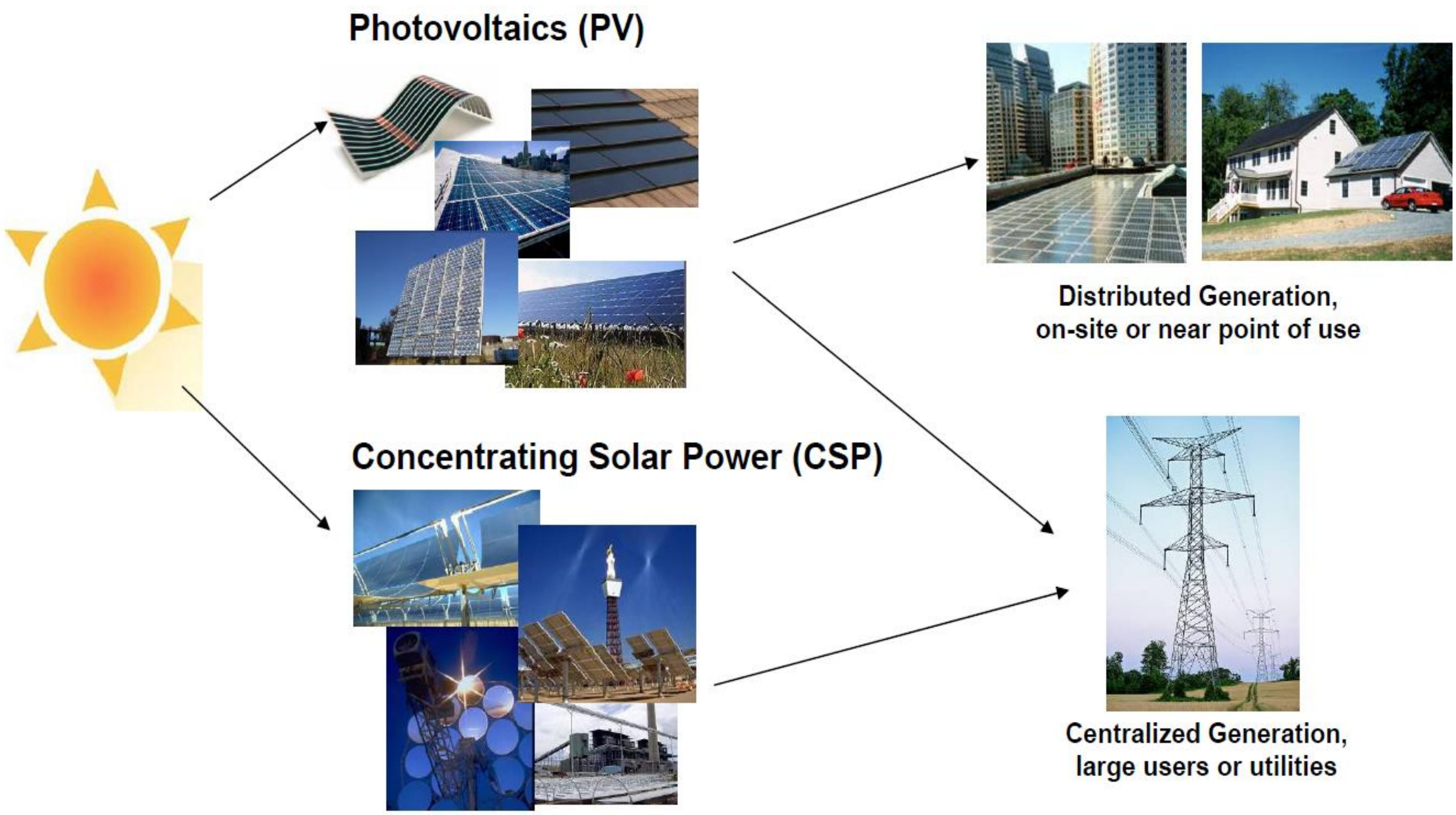
Early PV Applications

*Lucent Technologies Inc./Bell Labs*

# How Much Solar Energy Strikes Earth?

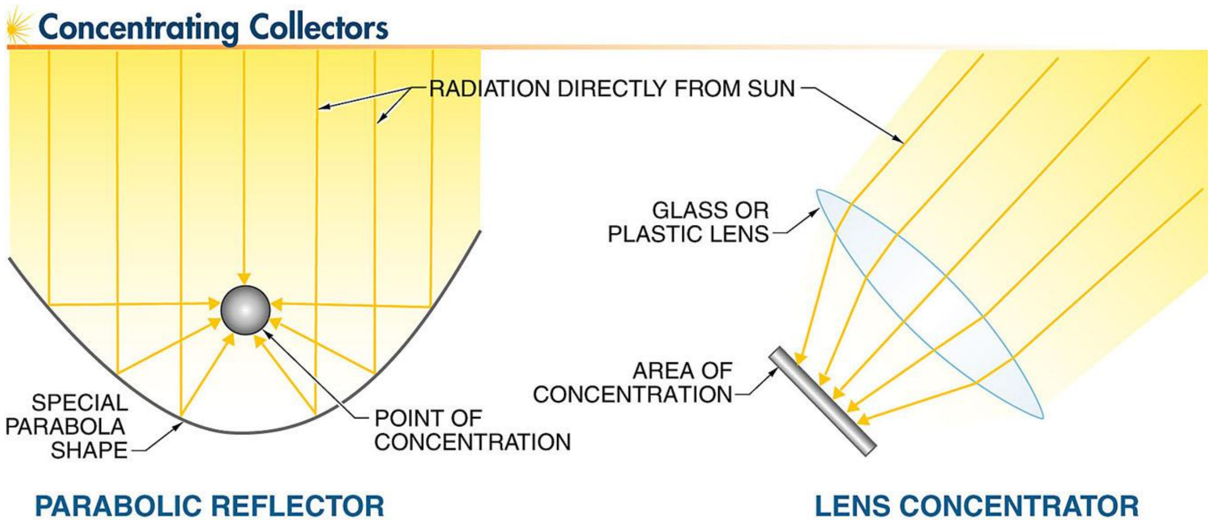
- The sun gives off $3.90 \times 10^{26}$ Watts
- The earth intercepts energy equal to a disk equal to the earth's diameter
- Earth’s radius is 3,393,000 meters
- Earth’s solar interception area is $\Pi * (3,393,000)^2$
- This equals $3.62 \times 10^{13}$ $m^2$
- The amount of power crossing earth's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

# Generating Electricity from the Sun

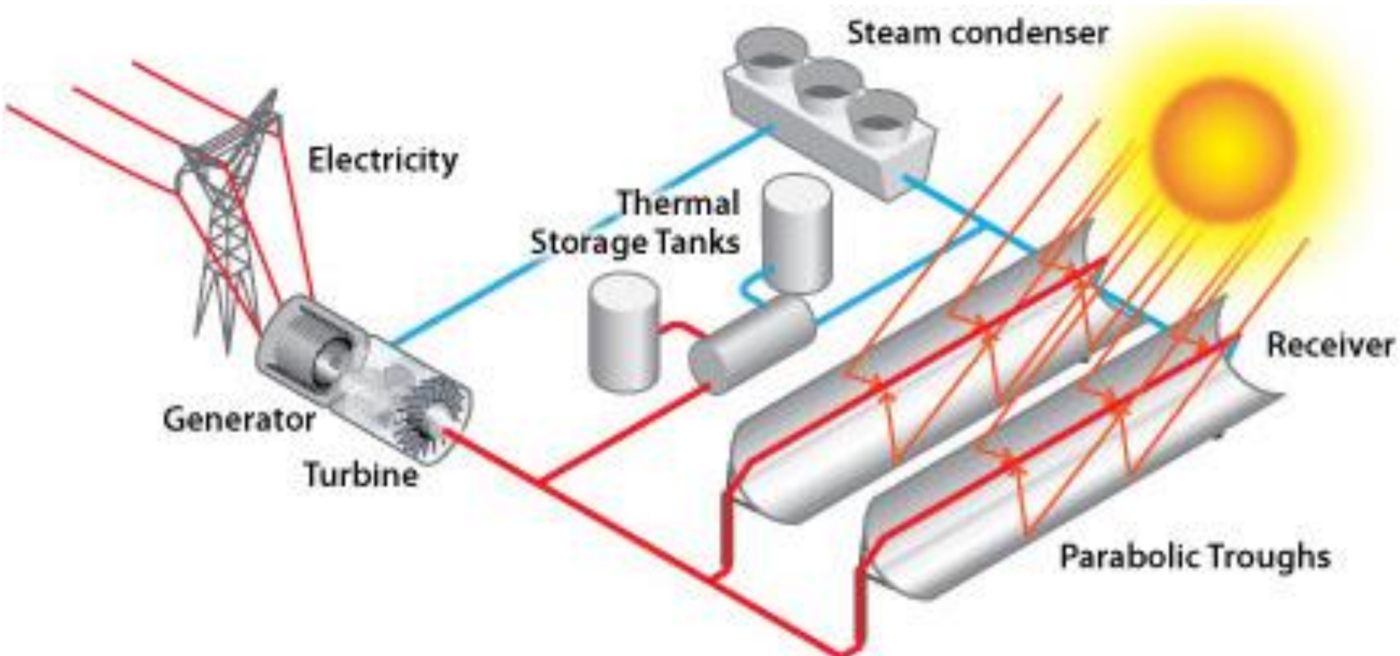


# Solar Energy: Concentrating Solar Power

- 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

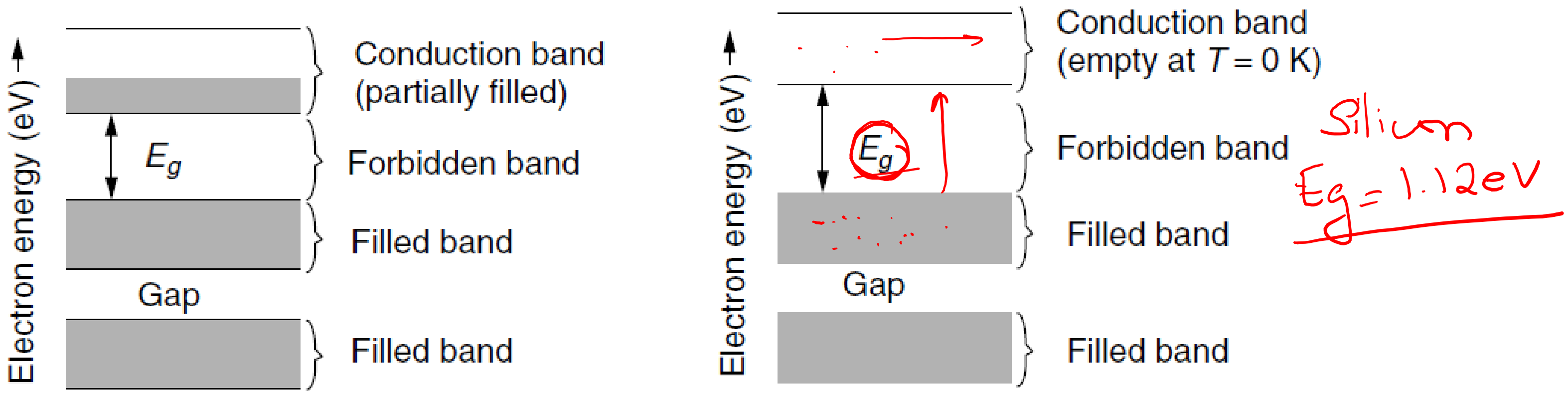
Voltage, Current and Power Curves

PV Modules

# SOLAR PHOTOVOLTAIC (PV) SYSTEMS

# Photovoltaics

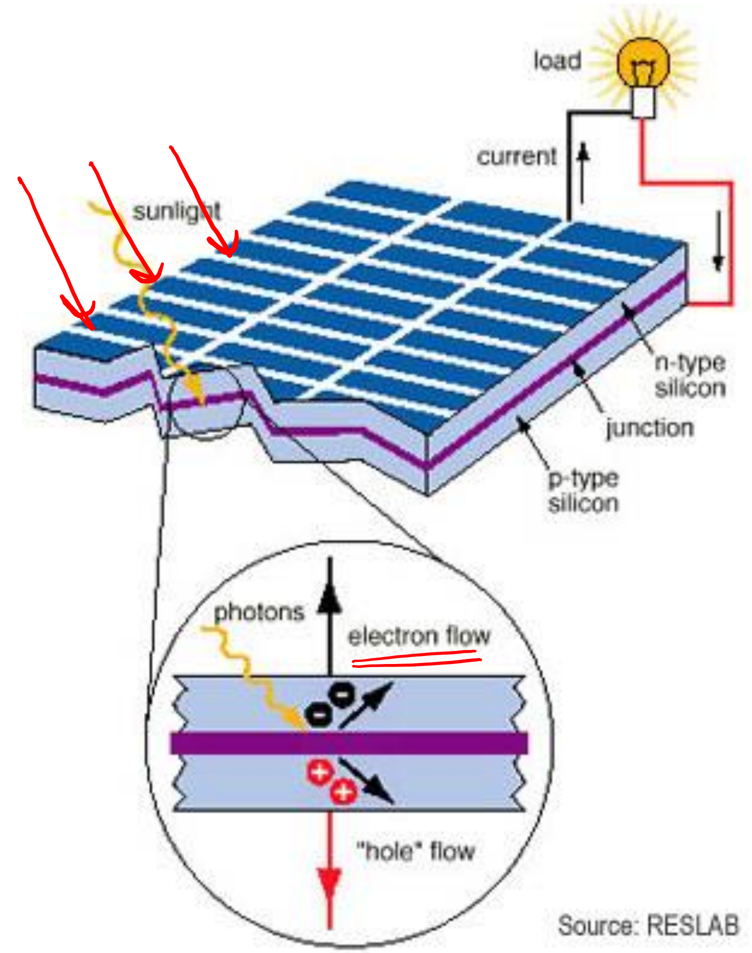
- A material that can convert the energy in photons of light into an electrical voltage and current is a ***photovoltaic***
- Photovoltaics use semiconductor material, typically Silicon




(a) Metals (b) Semiconductors

# Solar PV Cell

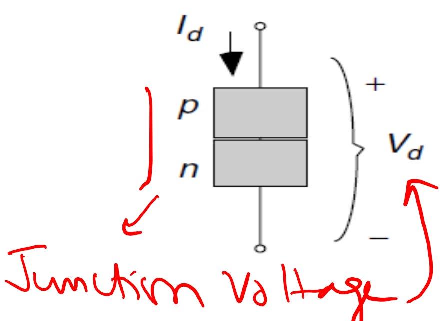
- Photons in sunlight hit the solar panel and are absorbed by semiconducting materials, such as silicon
- Electrons (negatively charged) are knocked loose from their atoms, allowing them to flow through the material to produce electricity. Due to the special composition of solar cells, the electrons 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



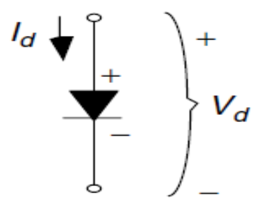
# P-N junction diode

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

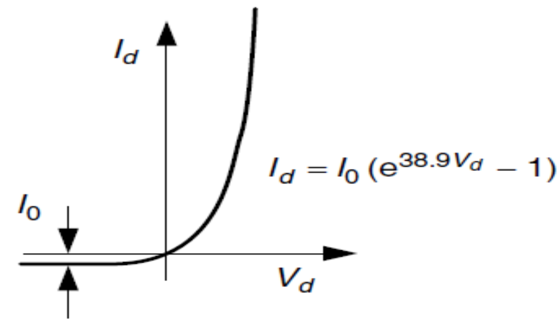
$$I_d = I_0(e^{qV_d/kT} - 1)$$




(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

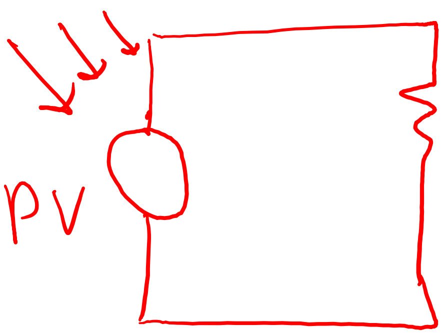
$q$ - Electron Charge ($1.602 \times 10^{-19}$ C)

$k$ – Boltzmann's Constant ($1.381 \times 10^{-23}$ J/K)

$T$- Junction Temperature

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

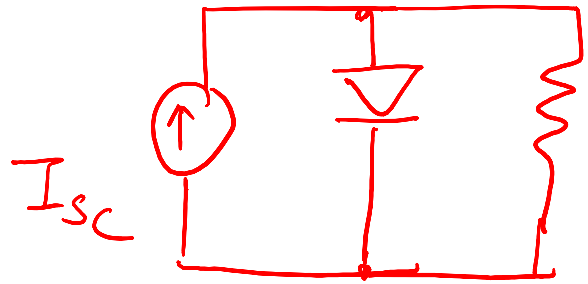
# Equivalent Circuit for a Photovoltaic Cell




pn-junction diode

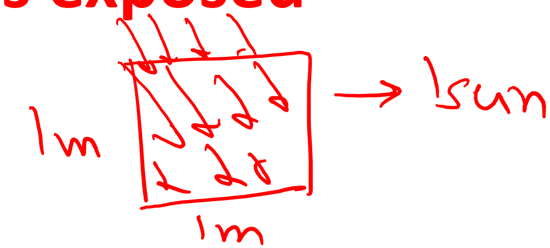
Sun light → current

$I_{sc}$

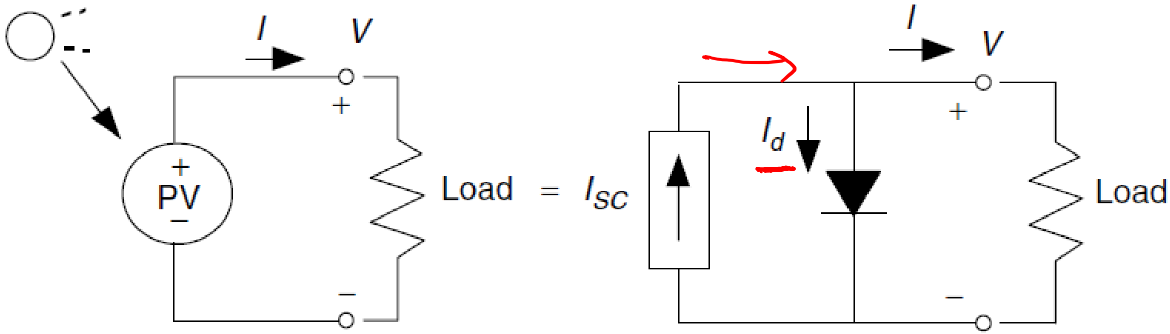



**$I_{SC}$ is directly proportional to the amount of solar flux (also called insolation) to which the solar cell is exposed**

1 sun ⟶ 1000 Watts/m$^2$



# Voltage and Current equations for the PV cell




$$I_d = I_0\left(e^{qV/kT} - 1\right)$$

$$\underline{I_{sc}} = \underline{I_d} + I$$

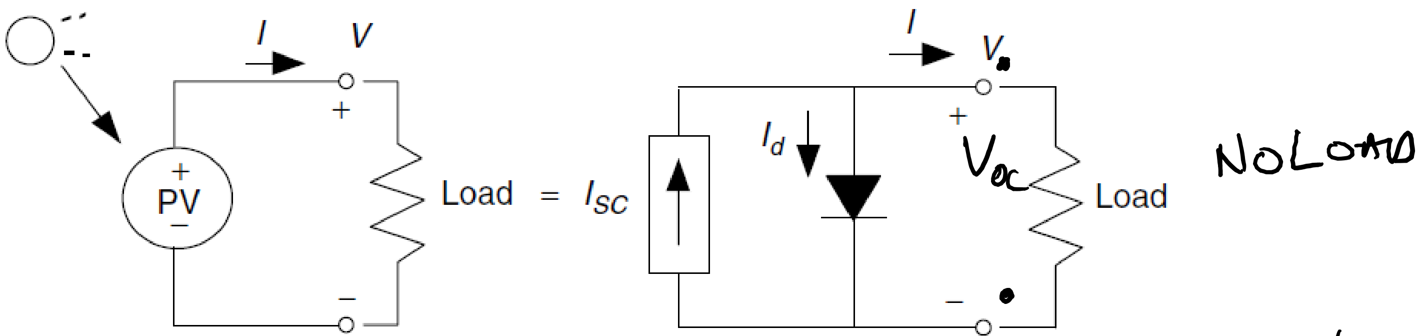
LOAD CURRENT

$$I = I_{sc} - I_d = I_{sc} - I_0\left(e^{qV/kT} - 1\right)$$

At 25°C

$$\boxed{I = I_{sc} - I_0\left(e^{38.9V} - 1\right)}$$

# Voltage and Current equations for the PV cell




$$I = 0 \Rightarrow I_{sc} = I_d \rightarrow I_d = I_0\left(e^{\frac{qV_{oc}}{KT}} - 1\right)$$

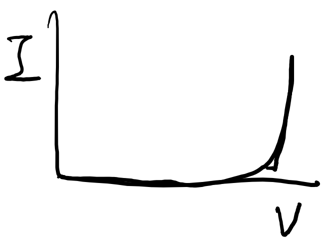
$$\left(e^{\frac{qV_{oc}}{KT}} - 1\right) = \frac{I_{sc}}{I_0} \Rightarrow e^{\frac{qV_{oc}}{KT}} = \frac{I_{sc}}{I_0} + 1$$

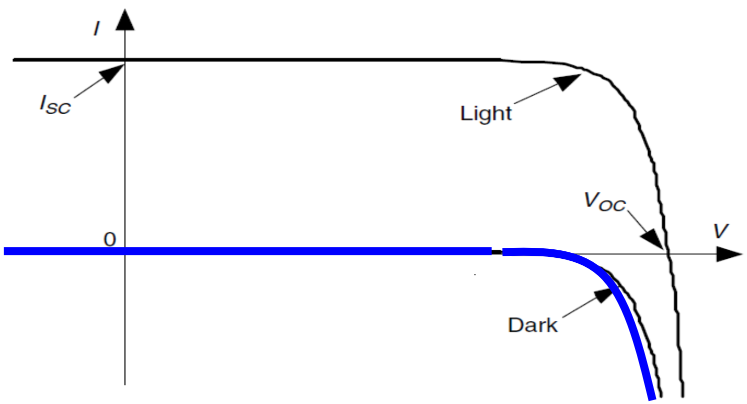
$$V_{oc} = \frac{KT}{q}\left(\ln\left(\frac{I_{sc}}{I_0} + 1\right)\right)$$

At $25^{\circ}C$ we get $\boxed{V_{oc} = 0.0257 \ln\left(\frac{I_{sc}}{I_0} + 1\right)}$

# 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 $I_{SC}$



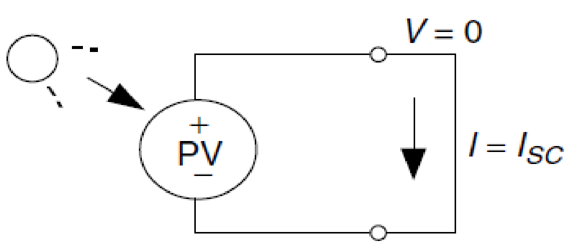




$I = I_{sc} - I_d$

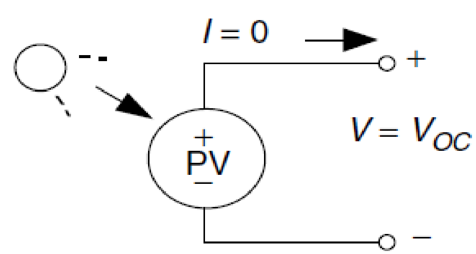
$I_{sc} = 0$

$\Rightarrow I = -I_d$

$I = I_{sc} + (-I_d)$




(a) Short-circuit current




(b) Open-circuit voltage

Example: Consider a 100 cm² PV cell with a reverse saturation current $I_0 = 10^{-12}$ A/cm². In full sun, it produces a short circuit current of 40 mA/cm² at 25°C. Find the open-circuit voltage at full sun and again for 50% sunlight. Plot the results.

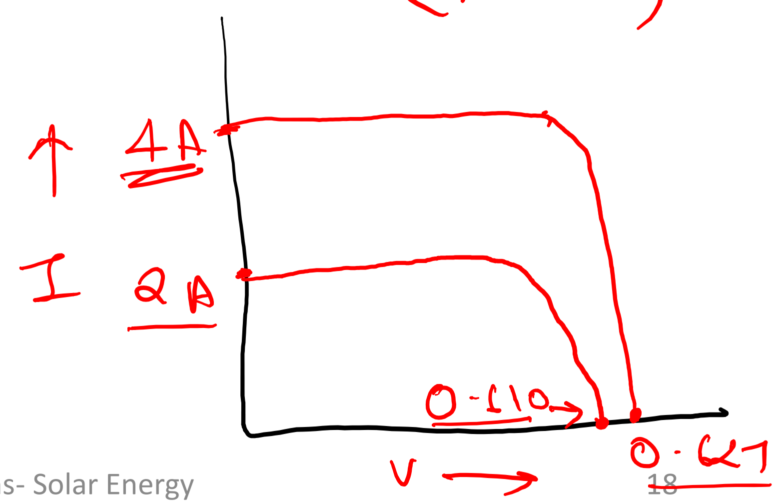
$I_0 = 10^{-12} \times 100 = 10^{-10}$ A

$I_{SC} = 40 mA/cm^2 \times 100 cm^2$
$= 4A$ (Full sun)

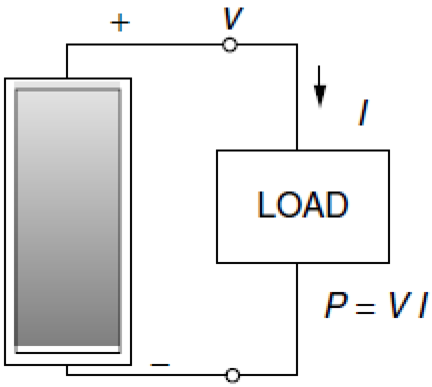
$V_{OC} = 0.0257 \ln\left(\frac{I_{SC}}{I_0}+1\right) = 0.0257 \ln\left(\frac{4}{10^{-10}}+1\right)$
$= 0.627V$

At 50% sunlight $I_{SC} = 2A$

$\Rightarrow V_{OC} = 0.0257 \ln\left(\frac{2}{10^{-10}}+1\right)$
$= 0.610$ V

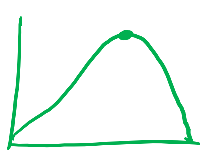


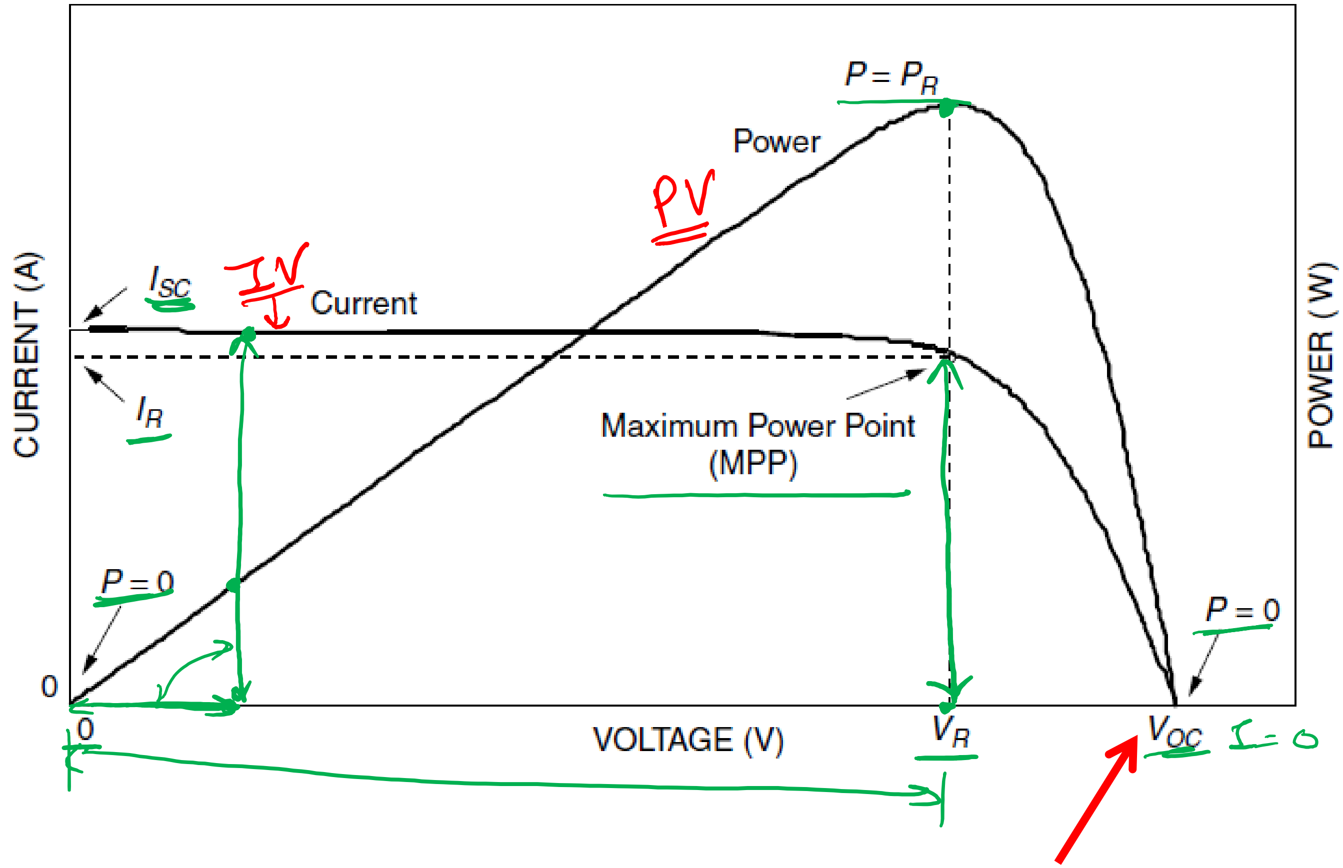
# Voltage, Current and Power Curves




Load connected

P = V I

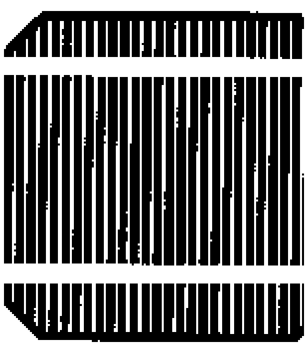




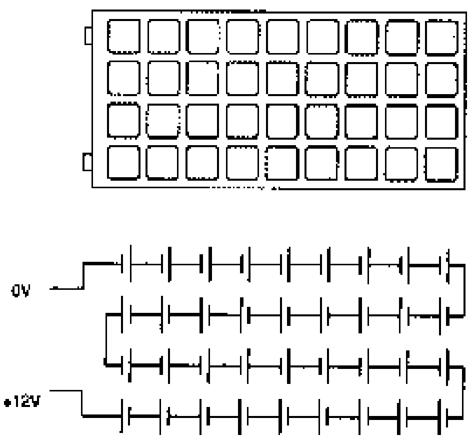

The open circuit voltage Voc is the maximum voltage from a solar cell and occurs when the net current through the device is zero.

# Photovoltaic Cells, Modules and Systems

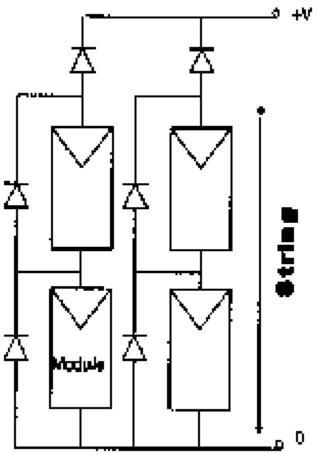
- Solar cell is the basic building blocks of solar PV
- Cells are connected together in series and encapsulated into modules
- Modules can be used singly, or connected in parallel and series into an array with a larger current & voltage output
- PV arrays integrated in systems with components for storage



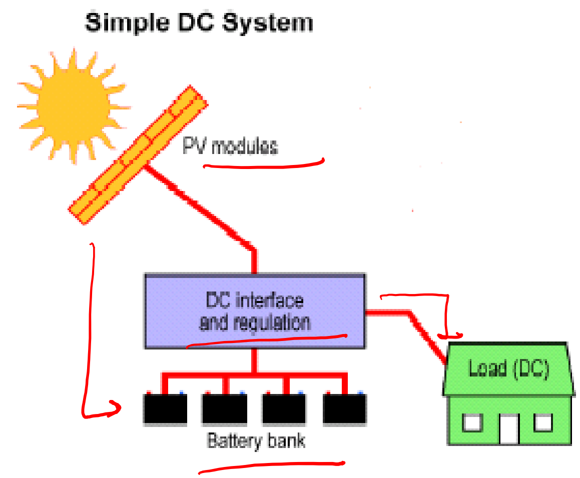
(a)




(b)



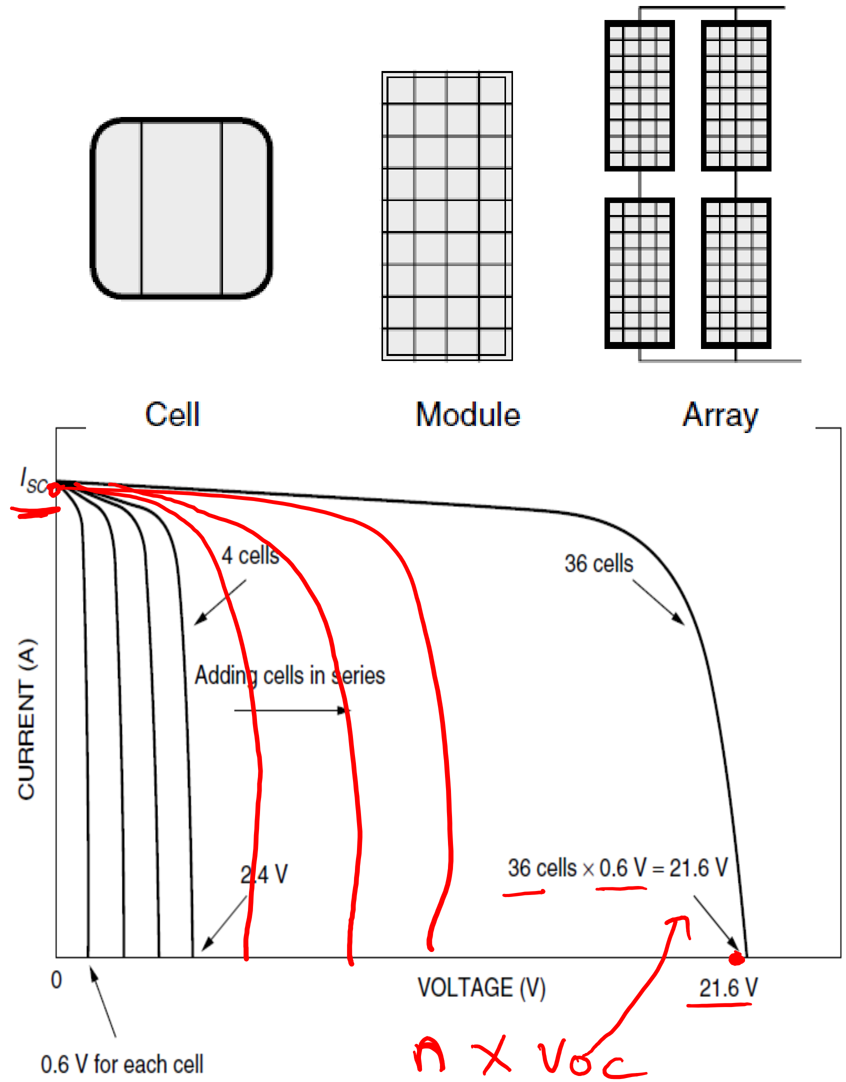

(c)




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

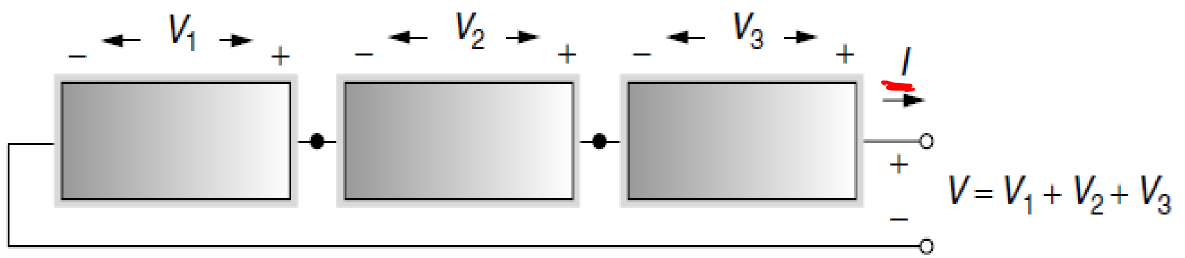


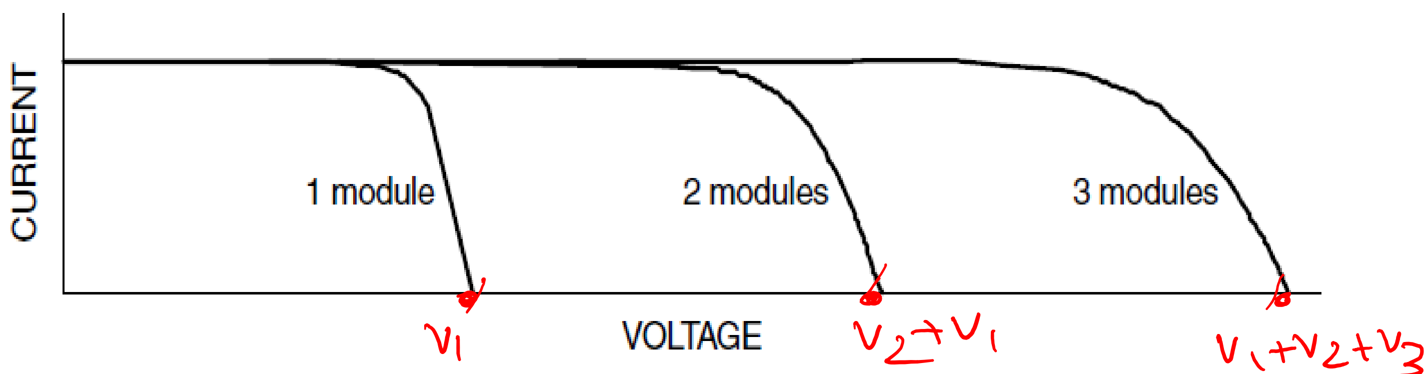
# Modules connected in series

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

$I \rightarrow$ same

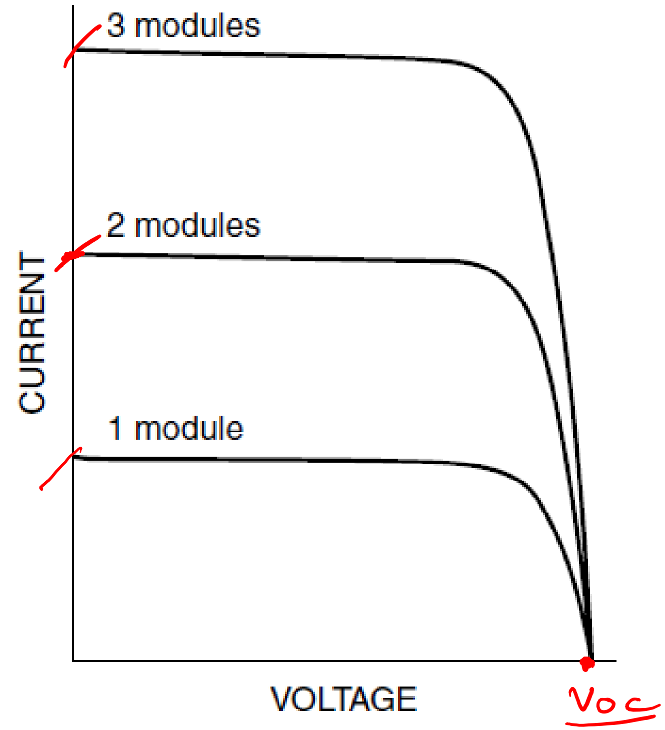
$V \rightarrow \Sigma V_{module}$

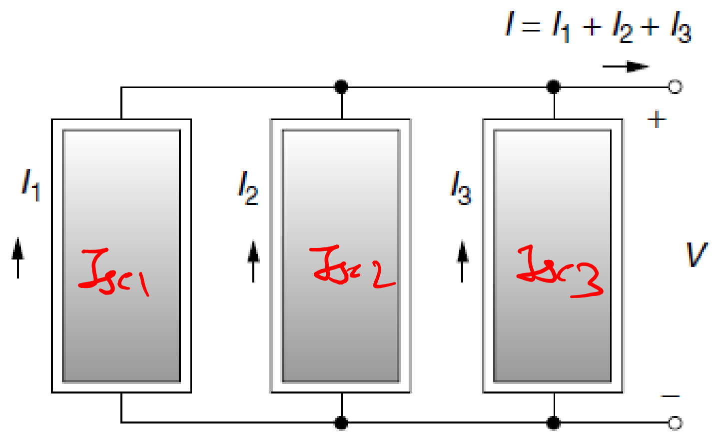


# Modules connected in parallel

- Currents add, while voltage remains the same

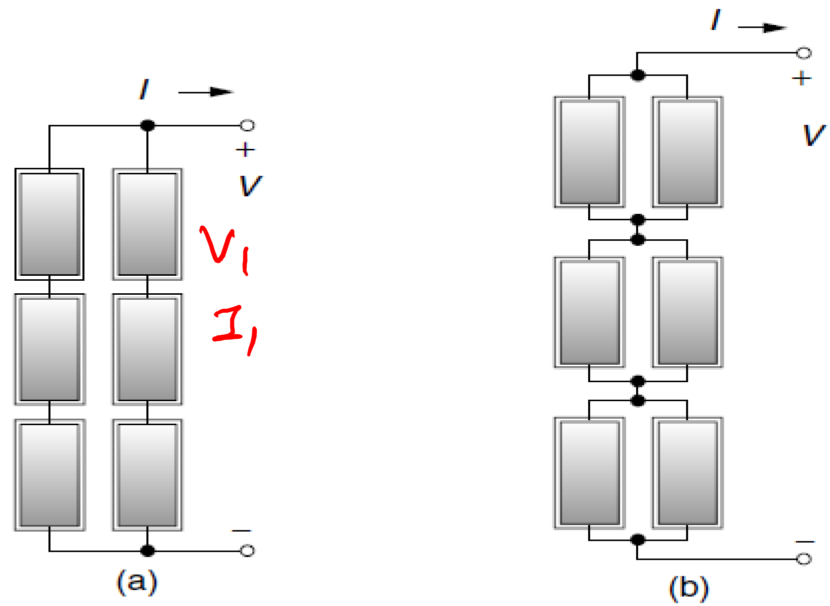


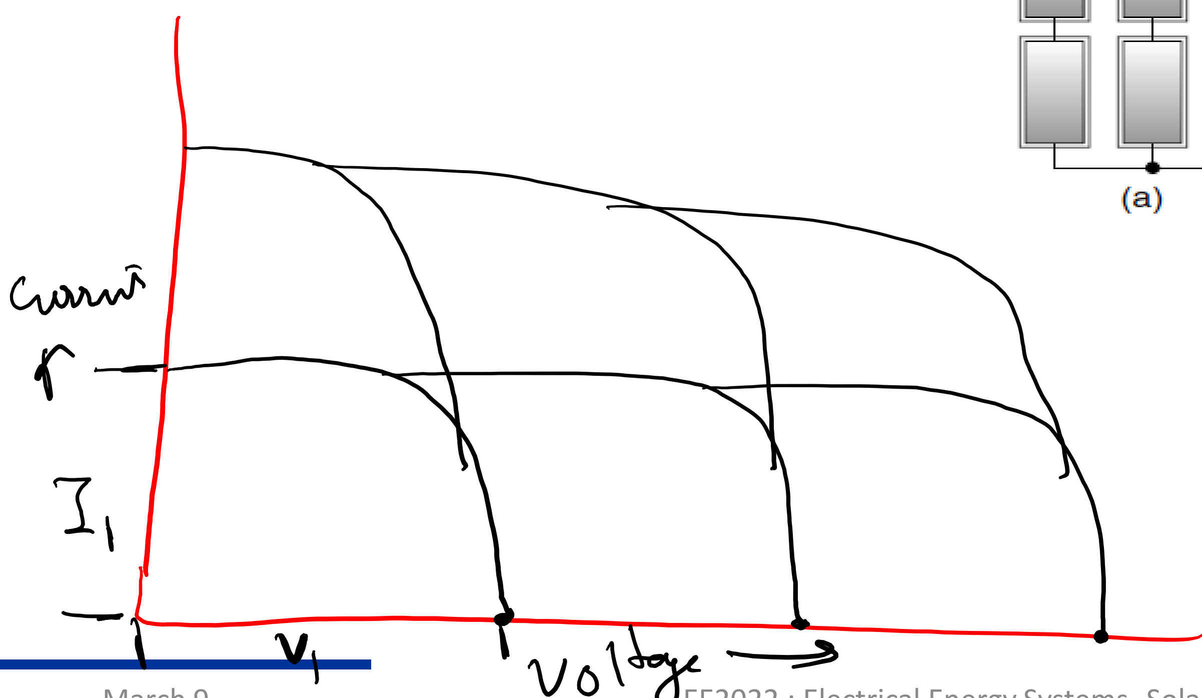




$I_{sc} = I_{sc1} + I_{sc2} + I_{sc3}$

# Modules in series-parallel configuration

- Example: Three modules in series, two in parallel

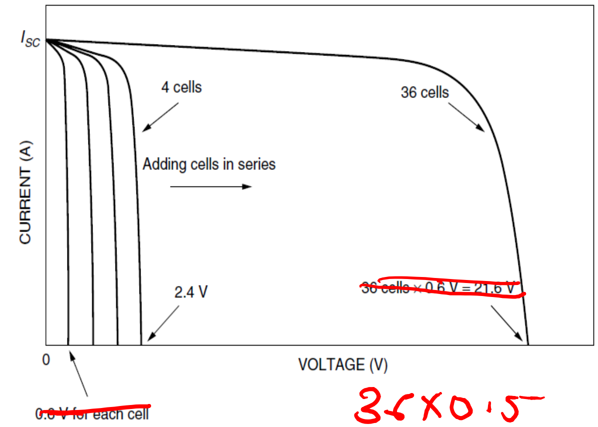



$$V = 3 \times V_1$$

$$I = 2 \times I_1$$

**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* $25^\circ C$ *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




0.5

36×0.5

$I_{sc} = 3.4A \qquad I_o = 6\times10^{-10}A$

$V_{oc} = V_d = 0.5\ V$

$I = I_{sc} - I_d = I_{sc} - I_o(e^{38.9\times V_d} - 1)$

$= 3.4A - 6\times10^{-10}(e^{38.9\times0.5} - 1)$

$\boxed{I = 3.236A}$

$\boxed{V_{module} = 0.5\times36 = 18V}$

$P = V_{module} \times I$

$= 18 \times 3.236$

$\boxed{P = 58.248W}$