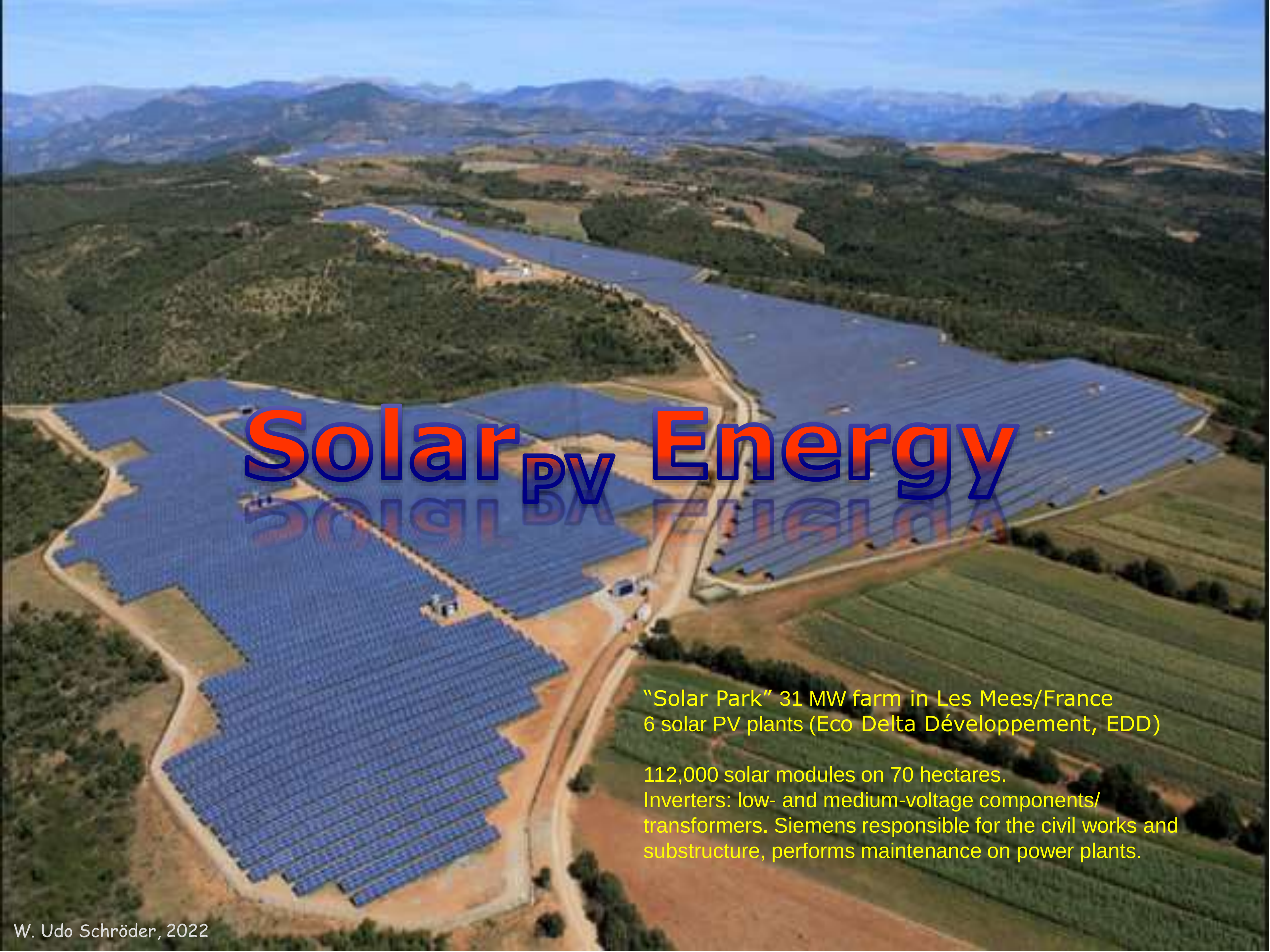

Solar$_{PV}$ Energy

“Solar Park” 31 MW farm in Les Mees/France
6 solar PV plants (Eco Delta Développement, EDD)

112,000 solar modules on 70 hectares.
Inverters: low- and medium-voltage components/ transformers. Siemens responsible for the civil works and substructure, performs maintenance on power plants.

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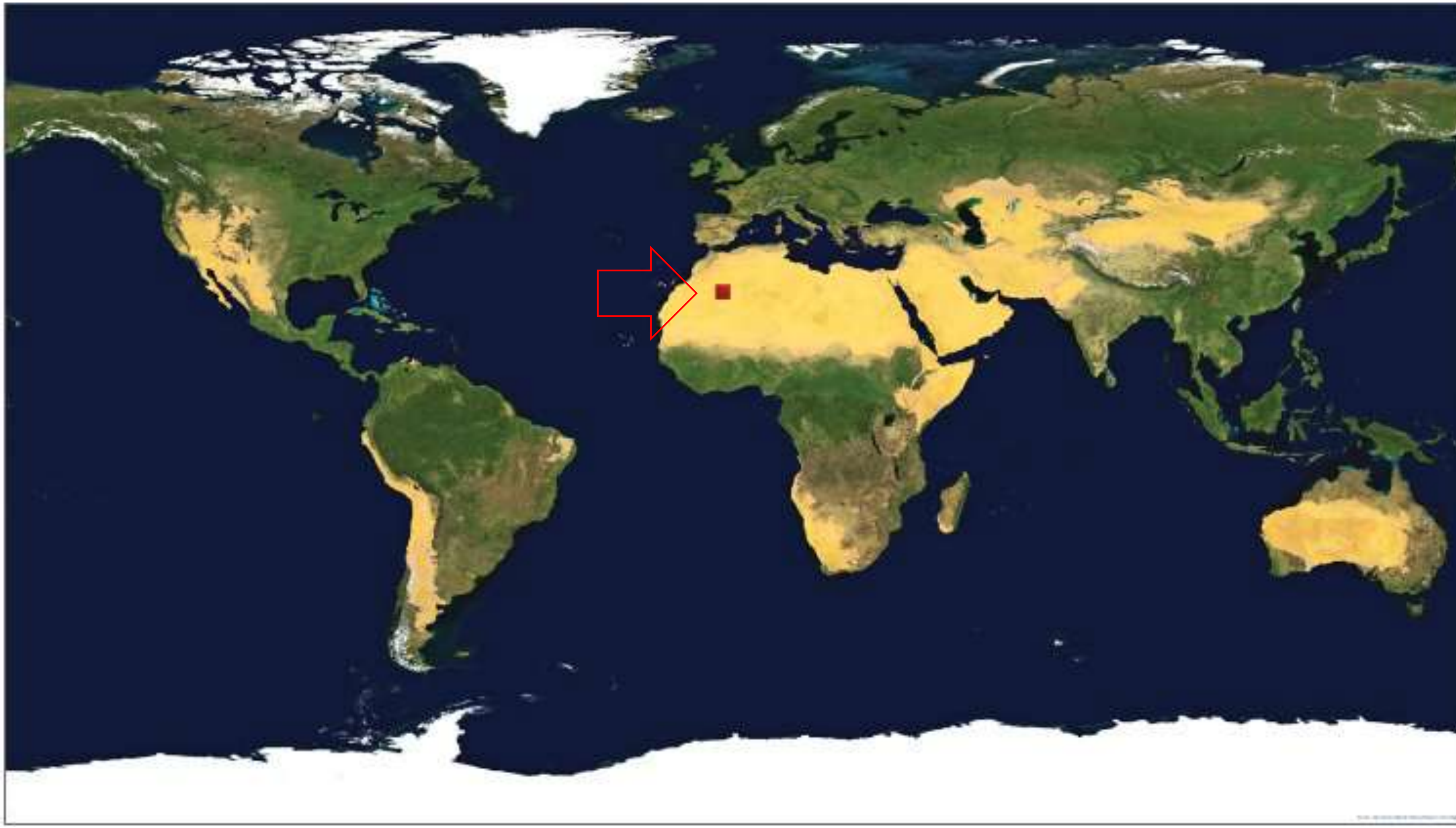
Partially Sunny World



Demand 20 TW worldwide → harvest sunlight (total insolation 10^5 TW). Methods:
→Direct (photon → e^-,h exciton) conversion to el. :photo-voltaic (PV), amorphous Si, single crystal Si, thin-film, organic solar cells
→Indirect (thermal) conversion to electricity: concentrated solar power plant (CSP)

Free Power: Solar Radiation

Stefan-Boltzmann Law $S = \sigma \cdot T_S^4 \;(W/area)$

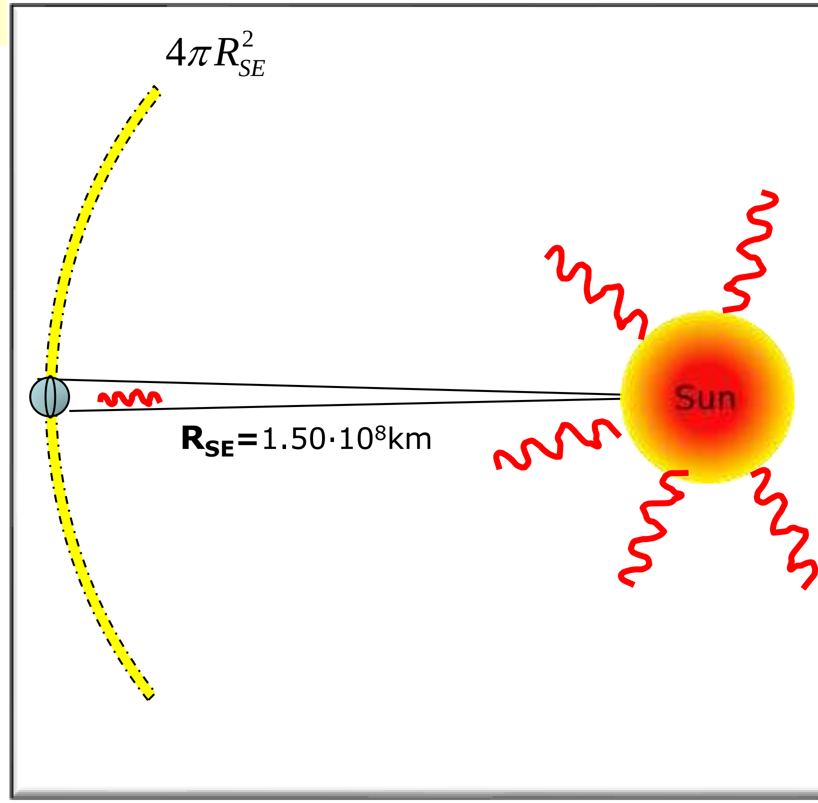
Solar Constant $S = rad\ \ power / area$

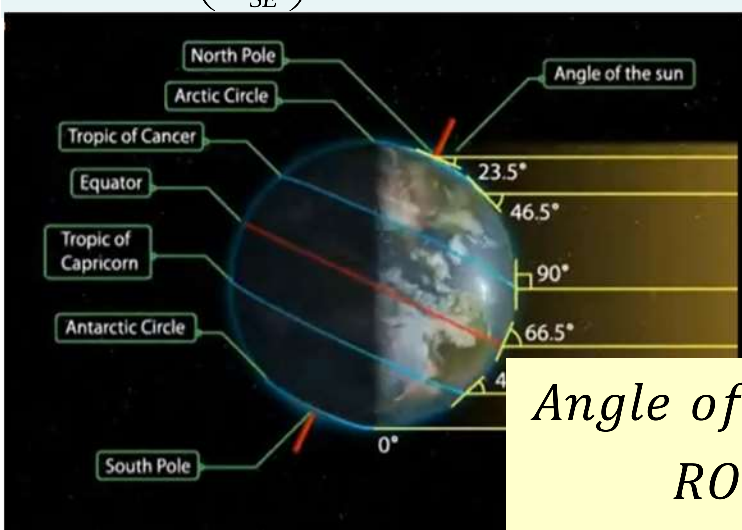
$$Earth\ area\ \ A_E = 5.1 \times 10^8\ \ km^2$$

$$exposed\ to\ Sun = disk\ of\ \ area\ \ A_{R_{SE}} = \pi R_E^2 = \frac{1}{4} A_E$$

$$S \cdot A_{R_{SE}} = \sigma \cdot T_S^4 \cdot \left(4\pi R_S^2\right) \cdot \left(\frac{A_{R_{SE}}}{4\pi R_{SE}^2}\right)$$

$$S = \sigma \cdot T_S^4 \cdot \left(\frac{R_S^2}{R_{SE}^2}\right) \approx 1.370\, kW/m^2$$





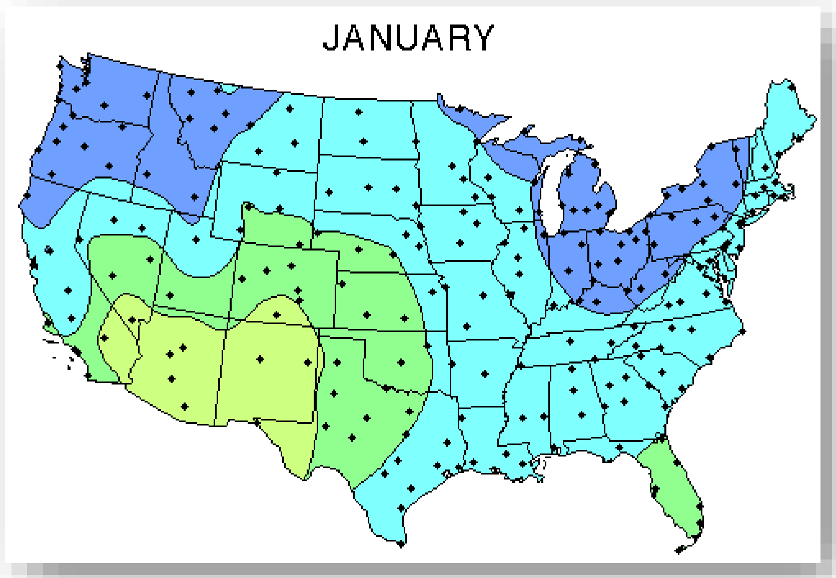
Solar radiation incidence during summer on northern hemisphere

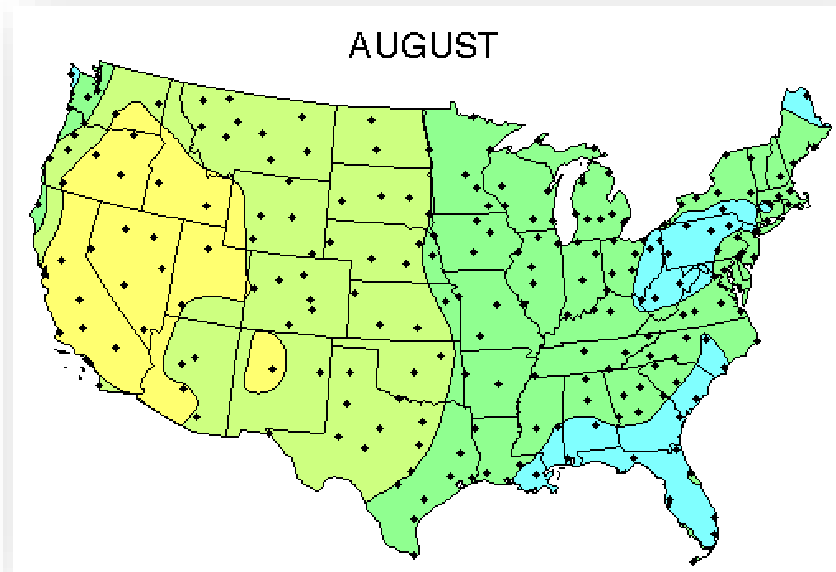
Effect of solar irradiation on Earth surface is non-cumulative → thermal equilibrium

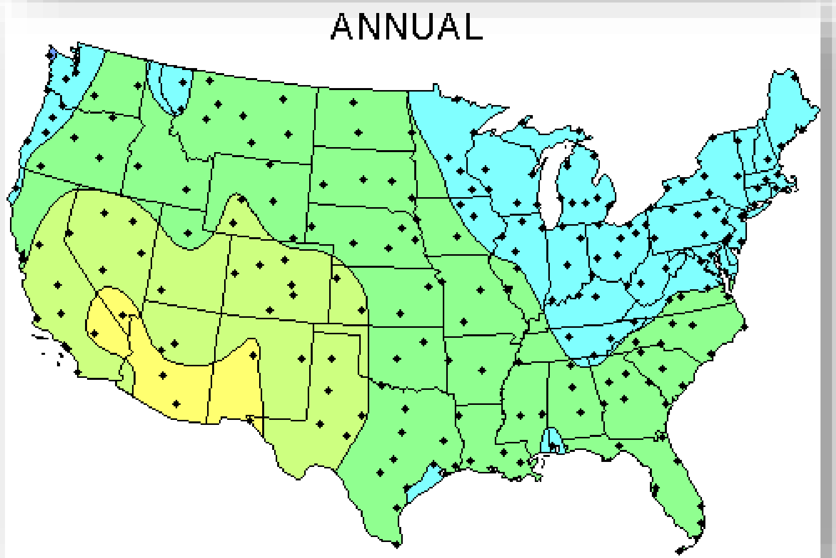
$$Angle\ of\ incidence\ \ \neq 90^0\ reduced\ rad\ density$$

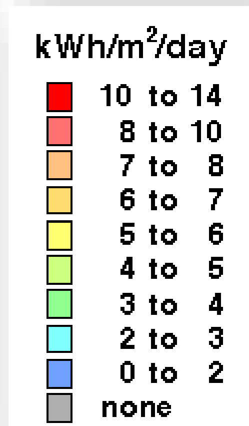
$$ROC@\ 47^0\ latitude \rightarrow \boxed{S_{eff}(t) < S}$$

Average Daily Insolation









National Renewable Energy Laboratory
Resource Assessment Program

August in NY:
(2-4)kWh/d·m²

Compare to

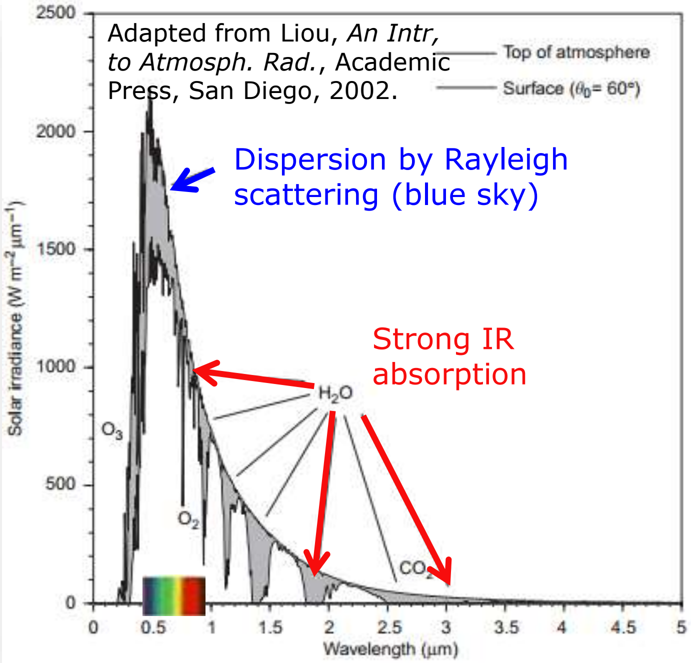
$$I = S \cdot \frac{12h}{d} \approx 17\, kWh/\left(d \cdot m^2\right)$$

Energy use US-NE:
(20-30) kWh/d·pers,

twice that in US-SW

http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/redbook/atlas/

Selective Filter Effect of Atmosphere

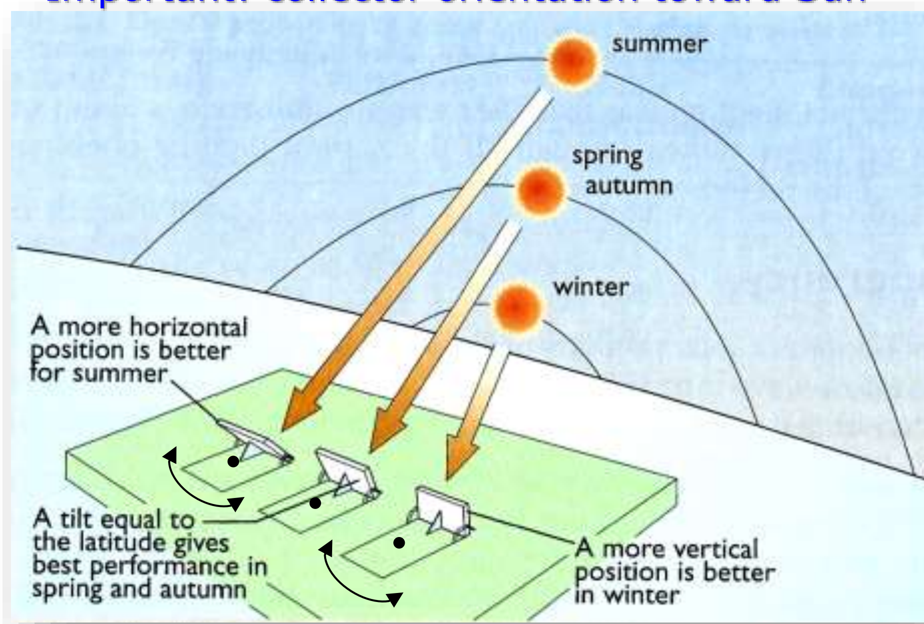


Intense solar radiation available at wave lengths from the UV, over visible to IR. Spectral gaps due to atmospheric absorption.

Utilization for electricity production:

Photo-voltaic (PV)→ direct electrical conversion.
Concentrated Solar (CSP)= thermal conversion

Important: collector orientation toward Sun



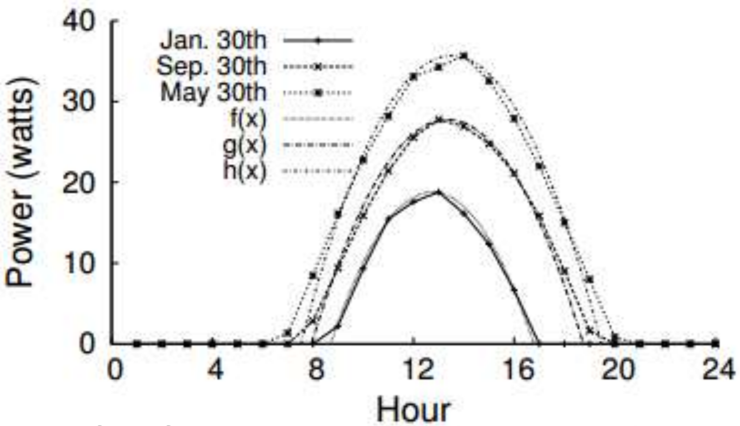
Adapted from G. Boyle et al., Renewable energy, OUP

Apparent orbits of Sun on sky require different tilt of sensors for best efficiency ε. Can vary by $\Delta\varepsilon = \pm 15\%$.

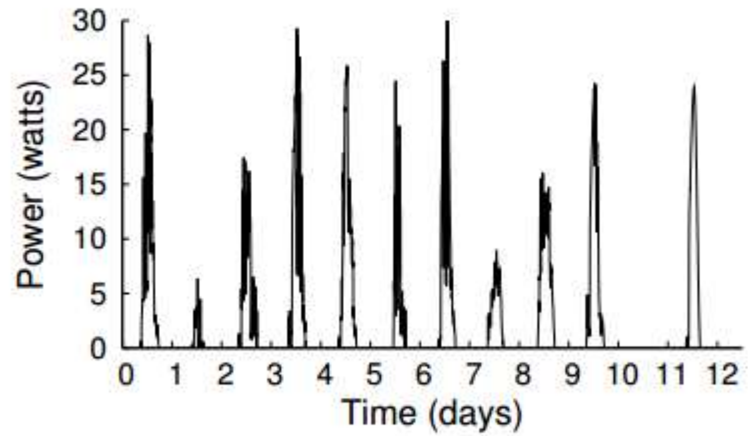
Concentrated Solar Power= CSP
"Receivers" collect and focus sunlight,
Tracking for (θ, ϕ) best efficiency.

Task: Transform solar radiation ($\hbar\varpi$ photons) to electricity (free electrons)

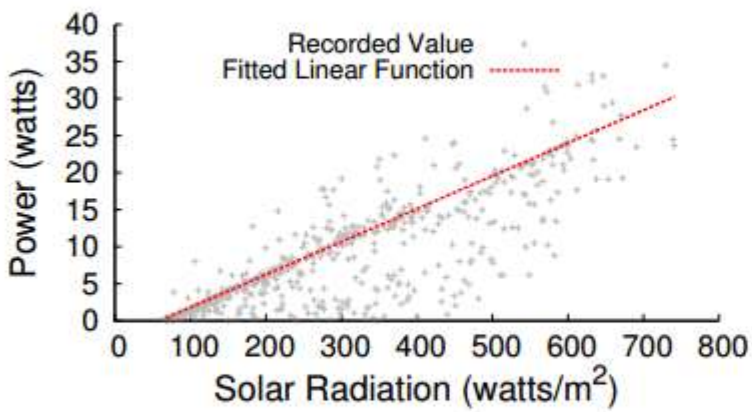
Actual Cell Field Performance (Expt. MIT)



Profile for solar power harvested on clear and sunny days in January, May, and September, and the quadratic fit functions



Power generated during a 12-day period in October 2009 from Kyocera solar panel, maximum power output 65 watts at 17.4 volts under full sunlight.



Relationship between the solar radiation nearby weather station observes and the power generated by solar panel.

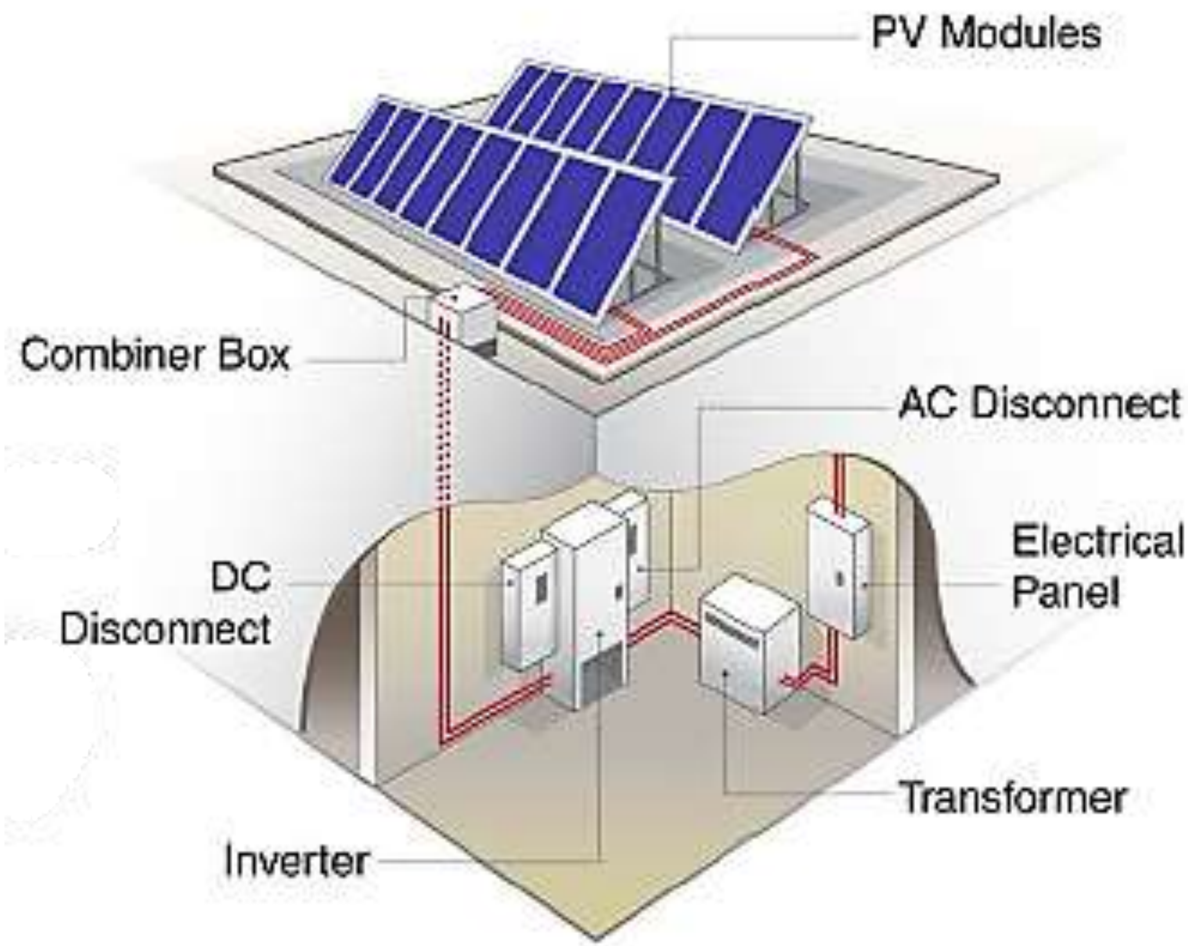
Navin Sharma, Jeremy Gummeson, David Irwin, and Prashant Shenoy
University of Massachusetts, Amherst

Residential/Commercial Installations

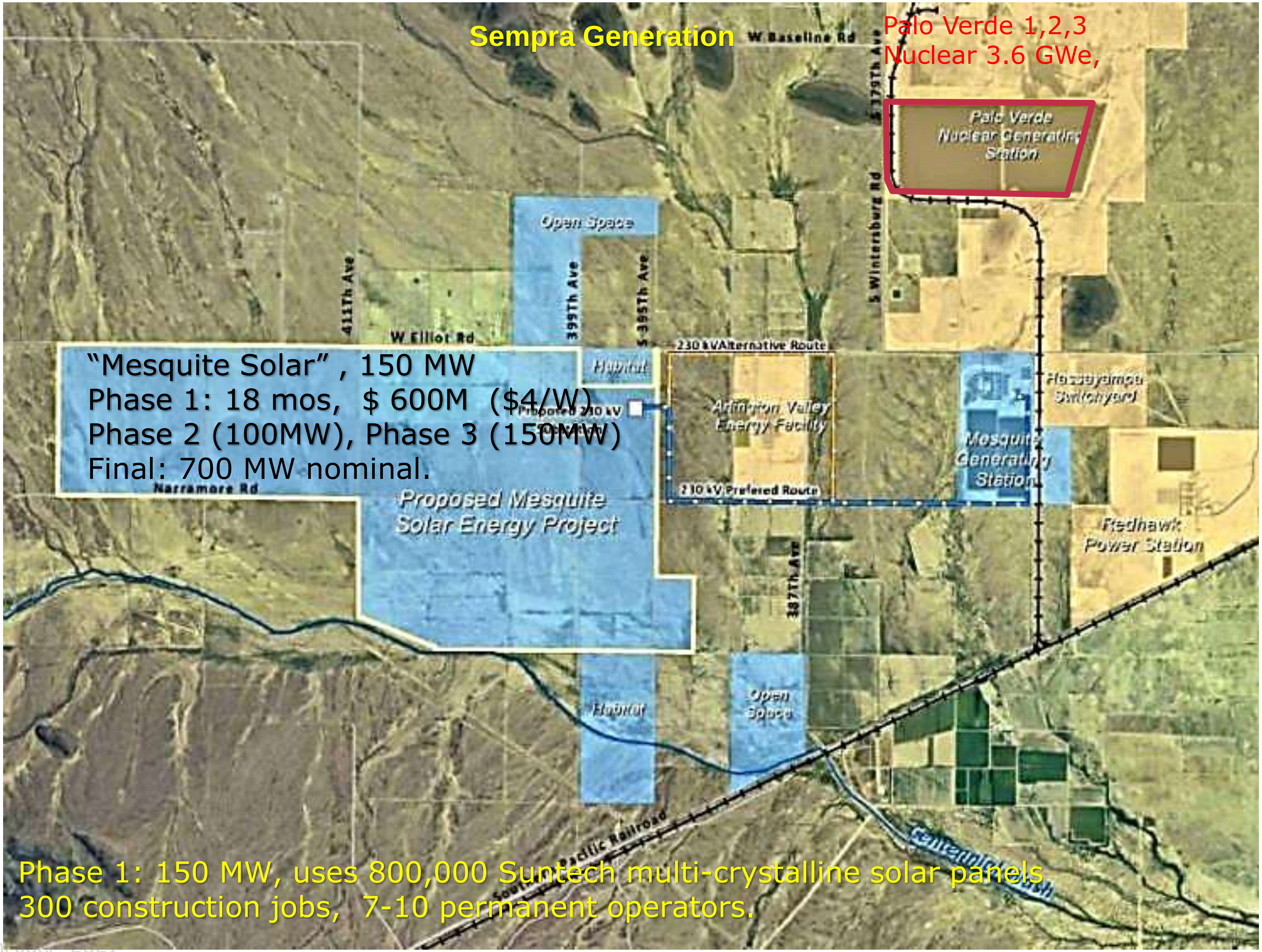
Solar thermal installation at the Allison Inn, Oregon

2022: 5.9 GW_{dc} = nearly 700,000 systems installed (1,687 MW_{dc} in Q4), up 40% from 2021.
Supply chain problems: China, tariffs

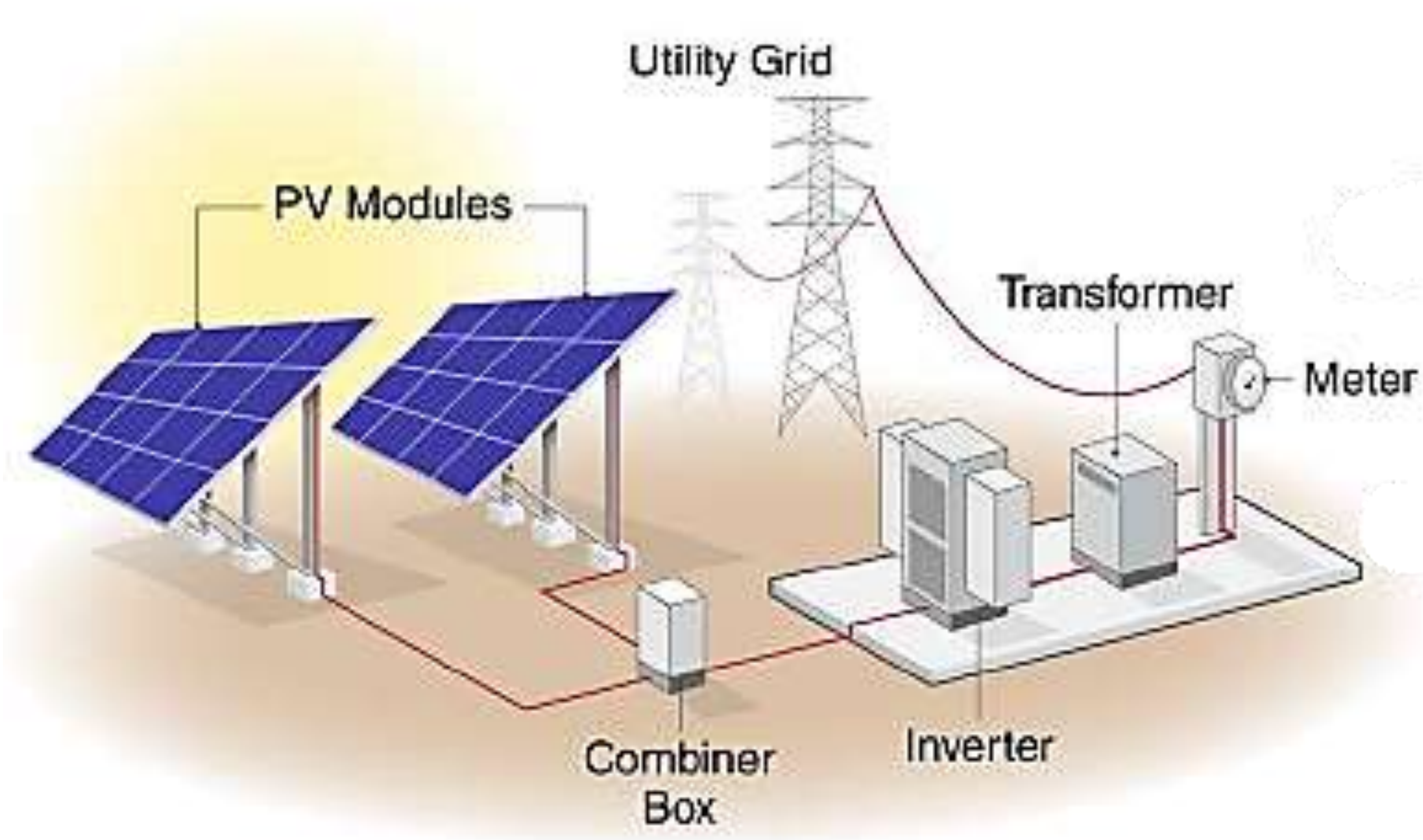
Residential/Commercial PV Installation



Big Commercial US PV Projects: Mesquite Solar



Utility PV Installation



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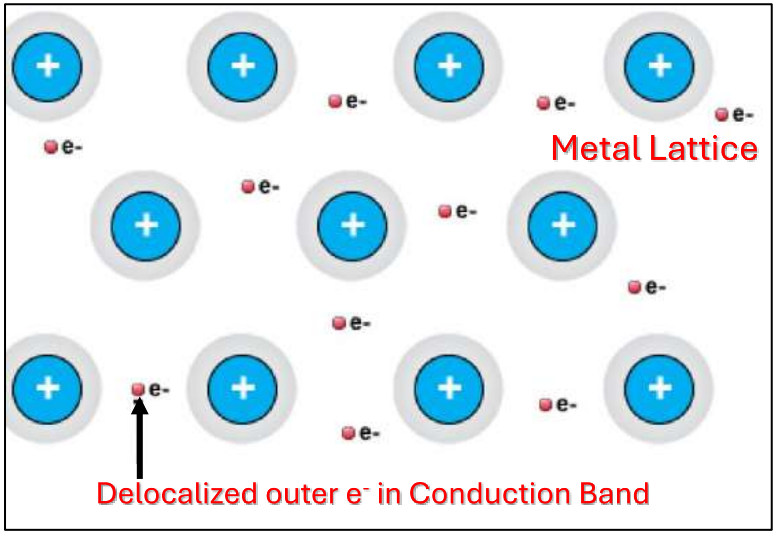
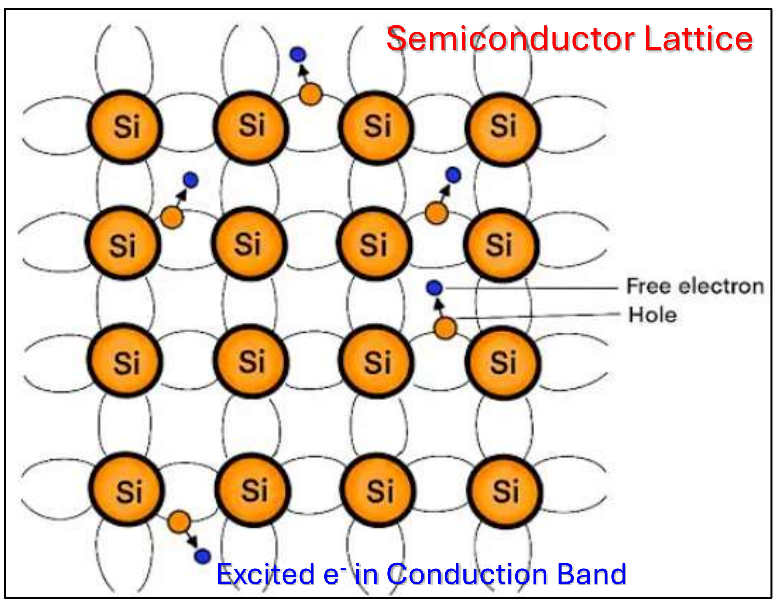
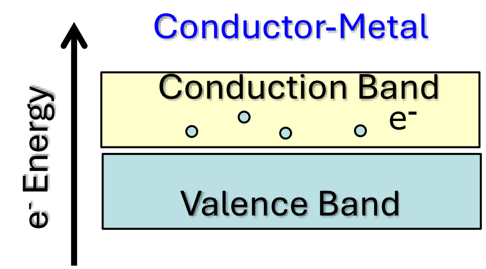
Task: Transform solar radiation ($\hbar\varpi$ photons) to electricity (free electrons).
Find material that is el. neutral in "darkness," and electrically polarized in light

Charge Carriers in Metals and Semiconductors

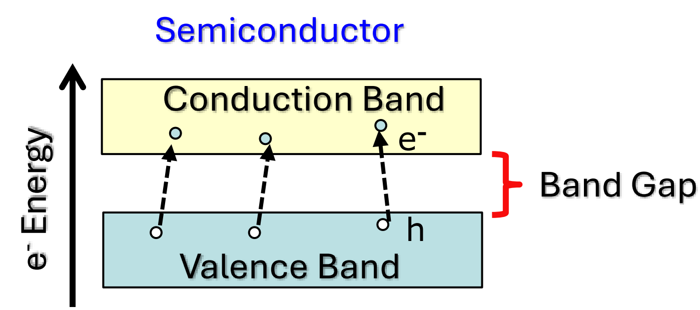




Many body ($\sim 10^{23}$) electrons have overlapping energy states → 2 energy bands: bound valence e^- form valence band. Free electrons move in conduction band.



Ground State: Filled valence band + free electrons in conduction band (=Fermi gas).



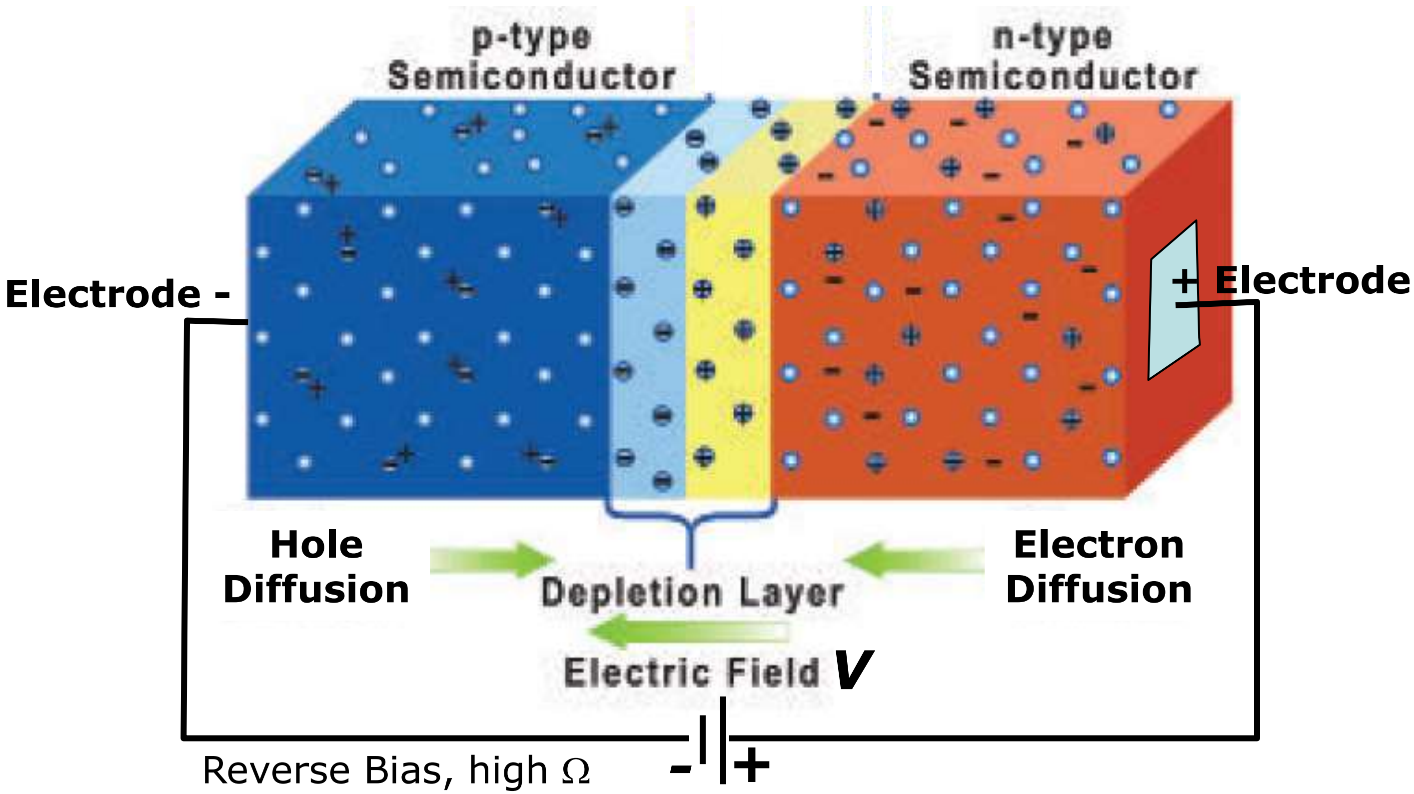
Ground State: No (few) free charge carriers. Excitation produces (quasi-) free e-hole pairs (excitons).

Semiconductor pn Junction (Diode)

N-Type= Si doped with phosphorous emits e^-→ promotes free $\boldsymbol{e^-}$

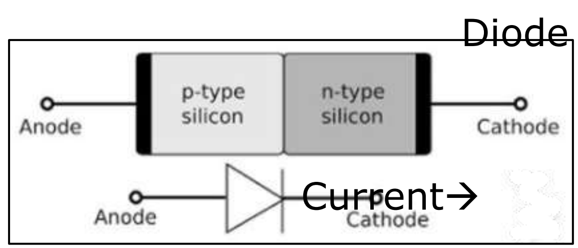
P-Type = Si doped with Boron captures e-, promotes free $\boldsymbol{h^+}$.

→ At normal *T:* both e^- and h^+ diffuse → annihilate in a depletion layer.

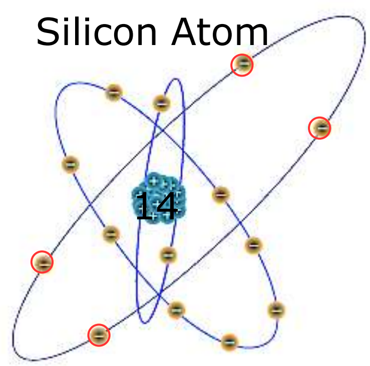


depletion layer has no free charge carriers.

Rad induced free charges move toward electrode of opposite sign = el. current



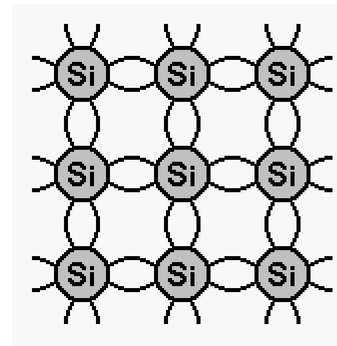
PV Basics: Properties of Semiconductors

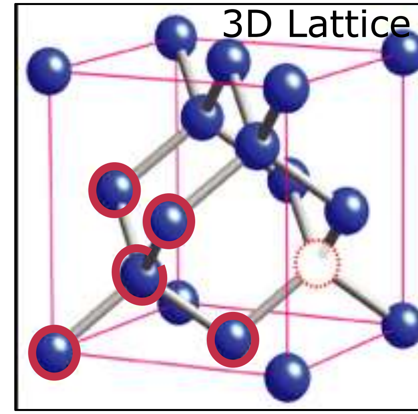


Basic idea of solar cell: Photons polarize non-conductive cell and deliver free e^- from bound states → external electric circuit.

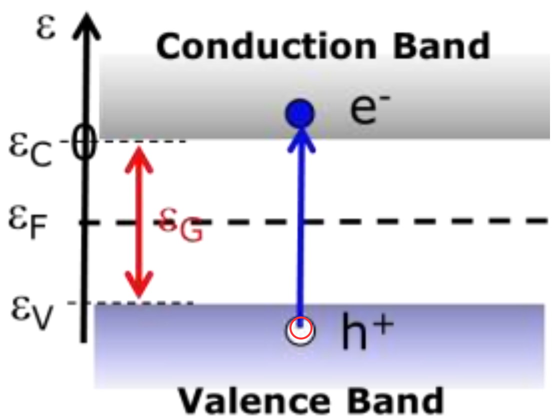
Crystal lattice: Covalent binding of 4 valence e^-.
e^- in "valence" or "conduction" bands of states."

2D Structure





Band Structure of Crystal Lattices Insulators/Semiconductors



Magnitude of band gap ε_G → electrical properties/conductivity.

ε_G: Si: 1.11, Ge: 0.66, InSb: 0.17, InAs: 0.36, InP: 1.27, GaP: 2.25 eV.

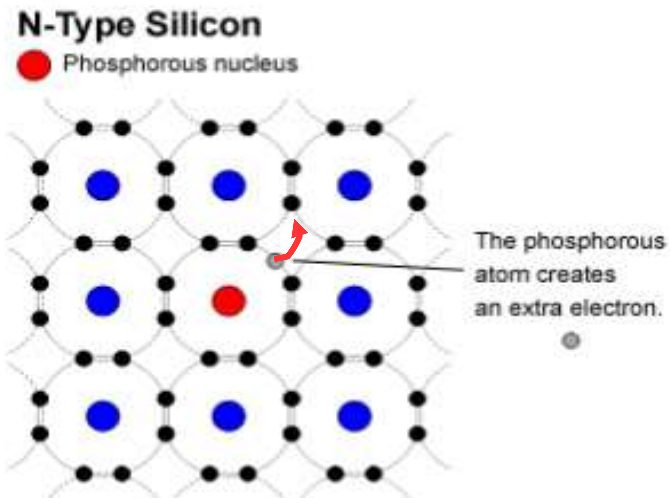
Ideal for solar sensitivity: When irradiated with light, electrically inactive (insulating) material becomes polarized and electrically active →*Power*.

Actual: Always significant "dark" current = residual conductivity.

This is property of all semi-conductors
- → Pure elements of Group IV (Si, Ge,…)
- → Binary compounds (GeAs, InSb, SiC, CdSe,...)
- → ….. oxides
- → Organic compounds (COP)

"Purification:" Silicon Doping

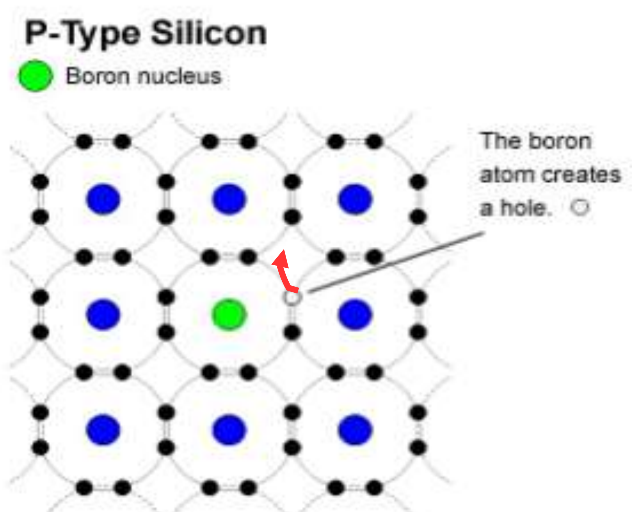
Desired properties → super-pure "intrinsic" semi-conductor materials. Not achievable directly → always slightly conducting! →compensate impurities by "doping" crystal.



P (phosphorus, Group V element) has one valence electron more than Si, which is less bound and moves in the Si-conduction band.

P-doped Si= ***N-type silicon***

P is an electron donor.



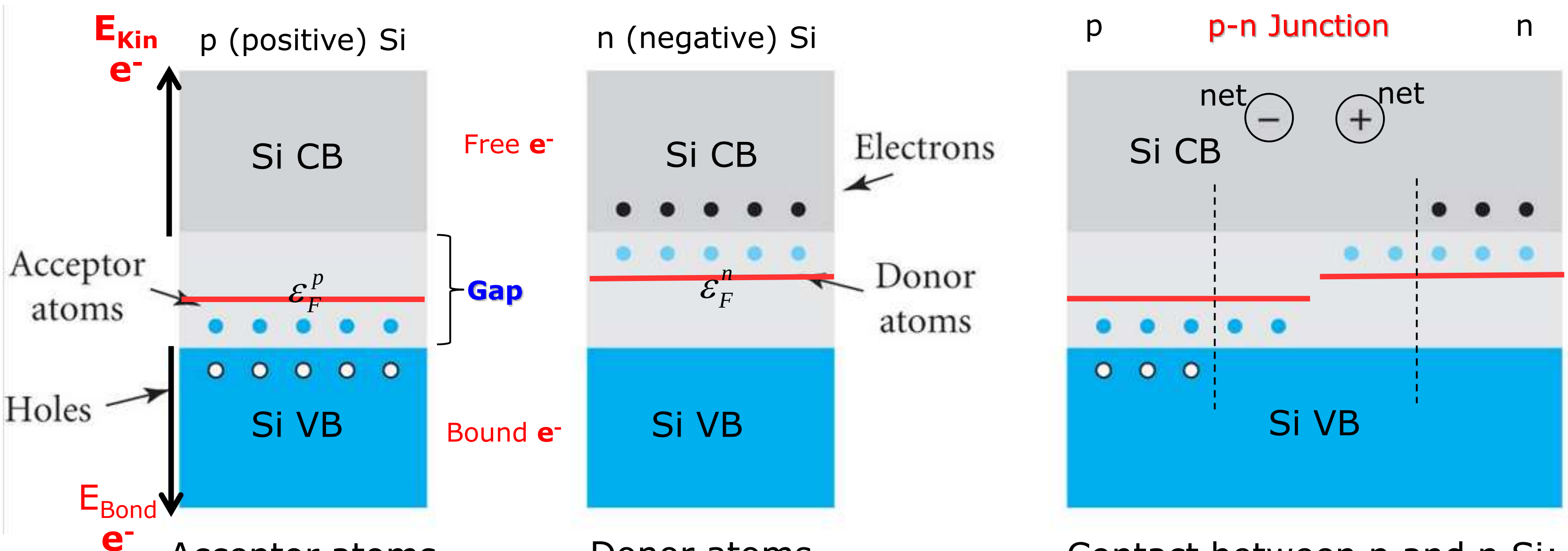
B (boron, Group III element) has one electron less than Si, creates a hole in the Si-valence band, which can move in that band.

B-doped Si = ***P-type silicon***,

B is an electron ***acceptor***.

Doped Semiconductor/Junction

Intrinsic Si: $N_{si} = 5\times10^{22}$ atoms/cm³. Doping concentration $N_{dop} = (10^{13} - 10^{18})\ cm^{-3} \ll N_{si}$. Retains mainly Si band structure (VB & CB). Doping atoms have different electronic levels → influences Fermi Level ε_F (half-way between fully occupied & completely empty)



Acceptor atoms attract electrons from Si → holes in Si valence band= majority charge carriers in p-silicon.

Donor atoms donate electrons to Si → electrons in Si conduction band= majority charge carriers in n-silicon.

Contact between p and n Si: Initial conc. gradient → diffusion of e^- & h^+ to opposite material → n-Si less negative, p-Si less positive. → "Reverse bias" = contact voltage.
Fermi levels equalize, $\varepsilon_F^p = \varepsilon_F^n$

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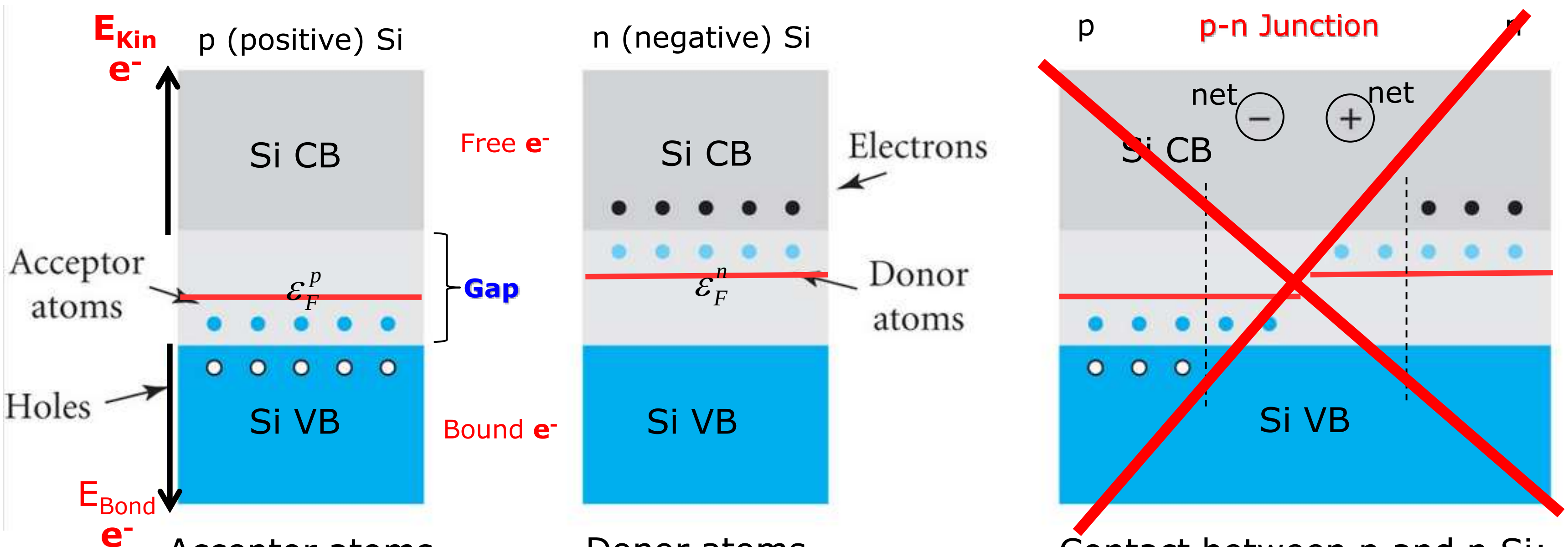

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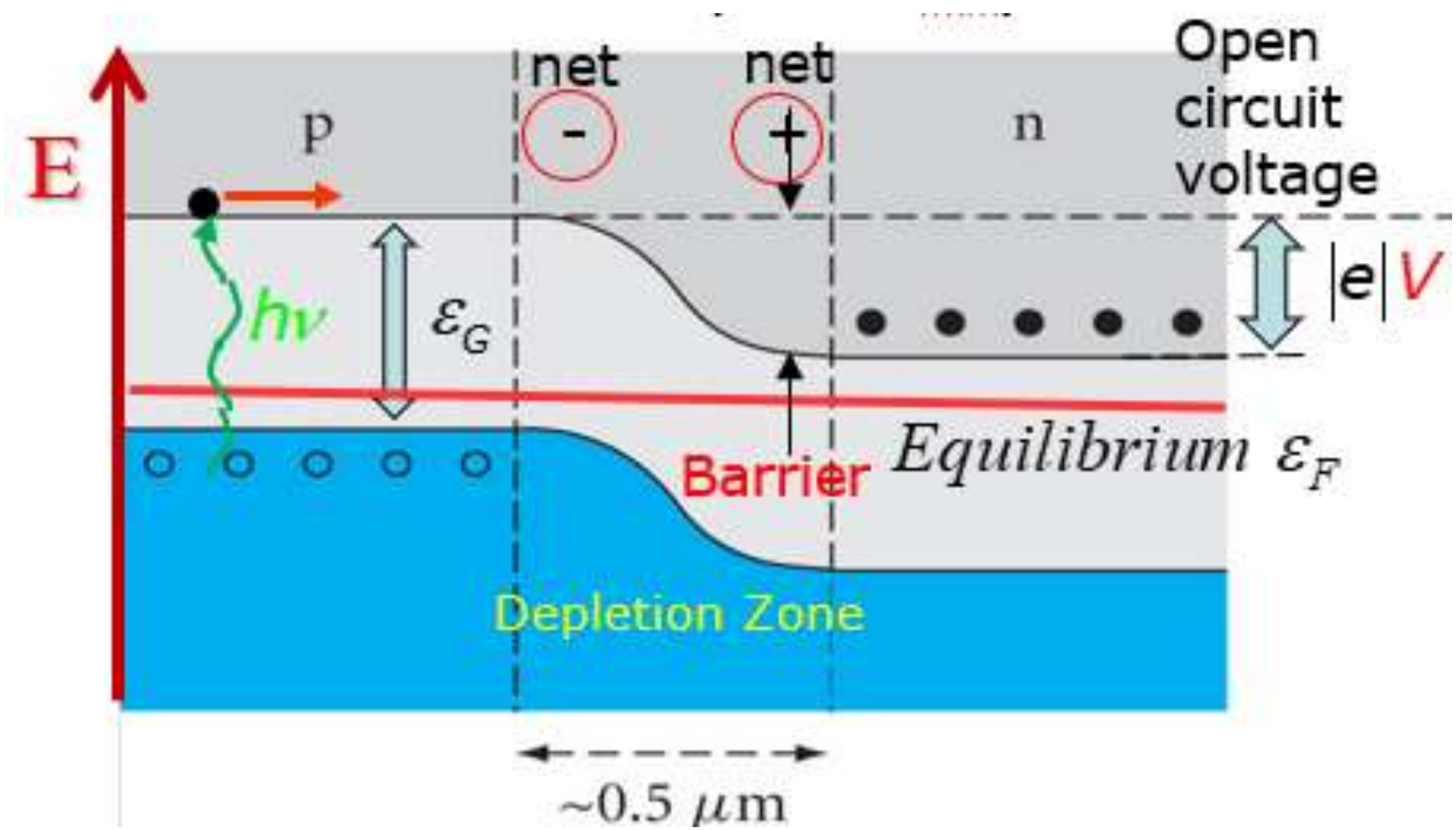
Semiconductor Junction Diodes

In asymmetric junction zone, no free charge carriers (e^- or holes) → Depletion Zone. Extra + charges in n-region
→ e- have lower energy (more strongly bound).
Effective barrier prevents additional migration of charges→ charge-free zone (except thermal excitations & photo ***h*ν**)!



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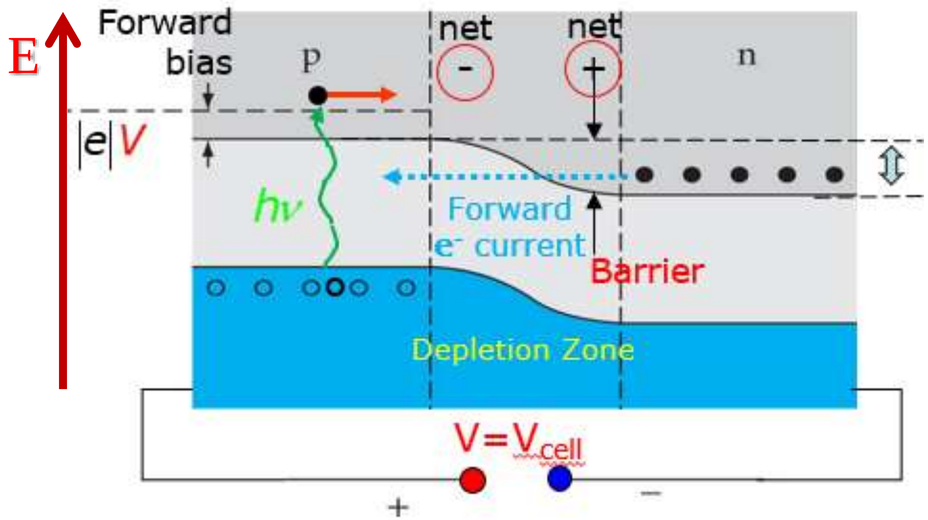
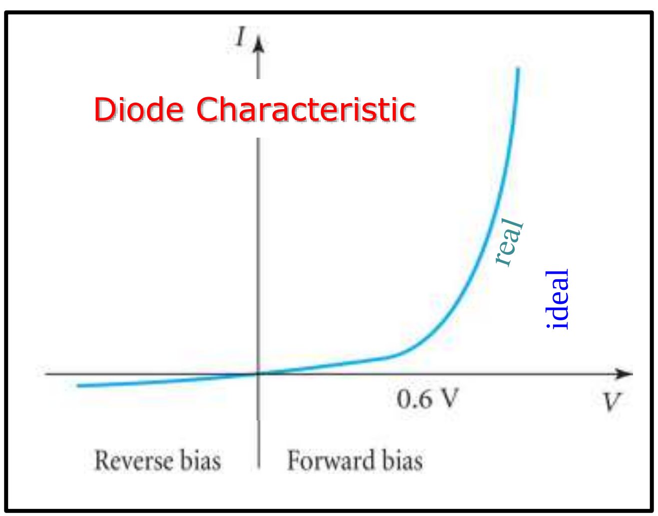


Forward bias lowers barrier

Forward: normal n→p across junction due to thermal→ No Bias applied → $I \approx 0$
Forward bias lowers barrier → $I \neq 0$, *increases.*

Reverse bias: smaller p→n reverse e^- current due to thermal transitions over higher barrier. → *Diode Characteristic*

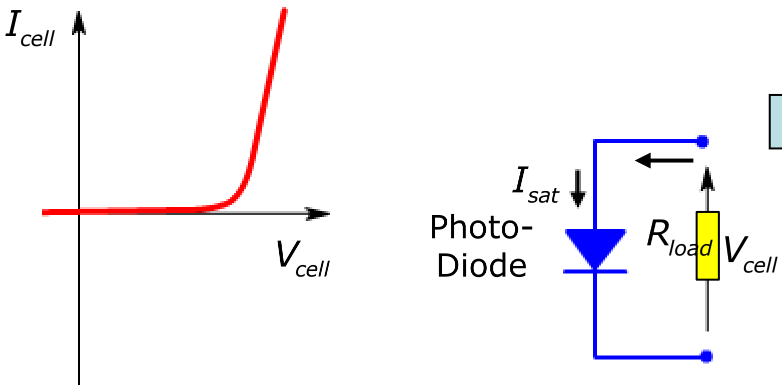


Diff & *Field* *Currents* : $I(V) = I_{sat} \cdot \{e^{+e \cdot V/kT} - 1\}$ *Fermi – Dirac Statistics*

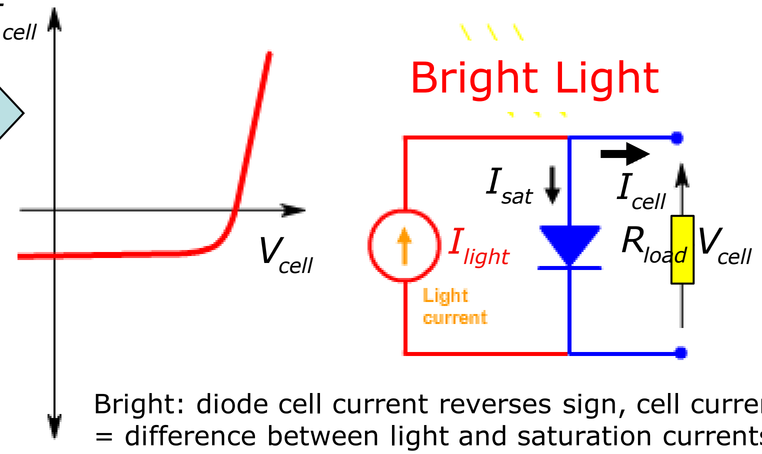
$$\text{Ambient } T: \quad kT = 25\ meV\ @\ T = 293K$$
$$\text{Elementary charge } e,$$
$$\text{"Saturation" ("dark", "field") current } I_{sat}$$

Cell Equivalent Electronic Circuits

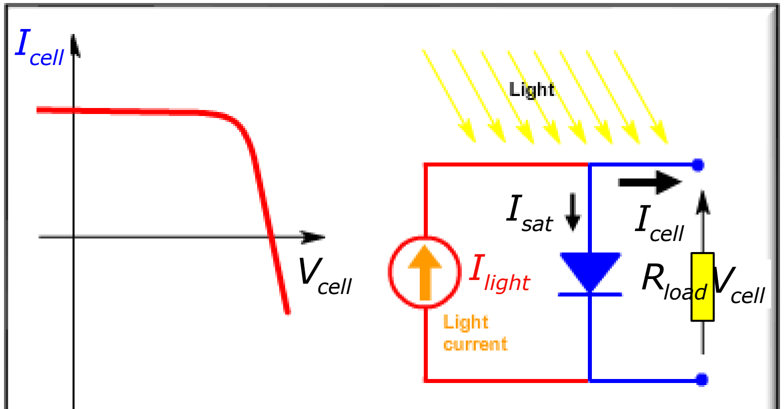
I_{cell} can be measured via R_{Load}



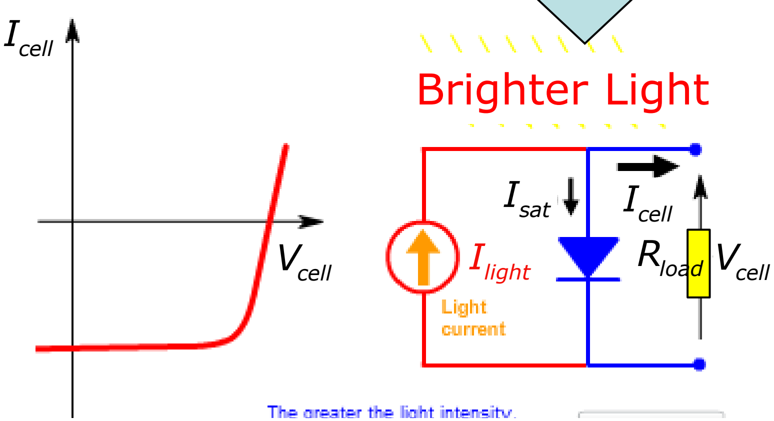
Dark: normal diode functions, saturation dark current



Bright: diode cell current reverses sign, cell current = difference between light and saturation currents



Convention: define cell current as positive.



Brighter: diode current becomes more negative, cell current = difference between light and saturation currents increases.

By Convention