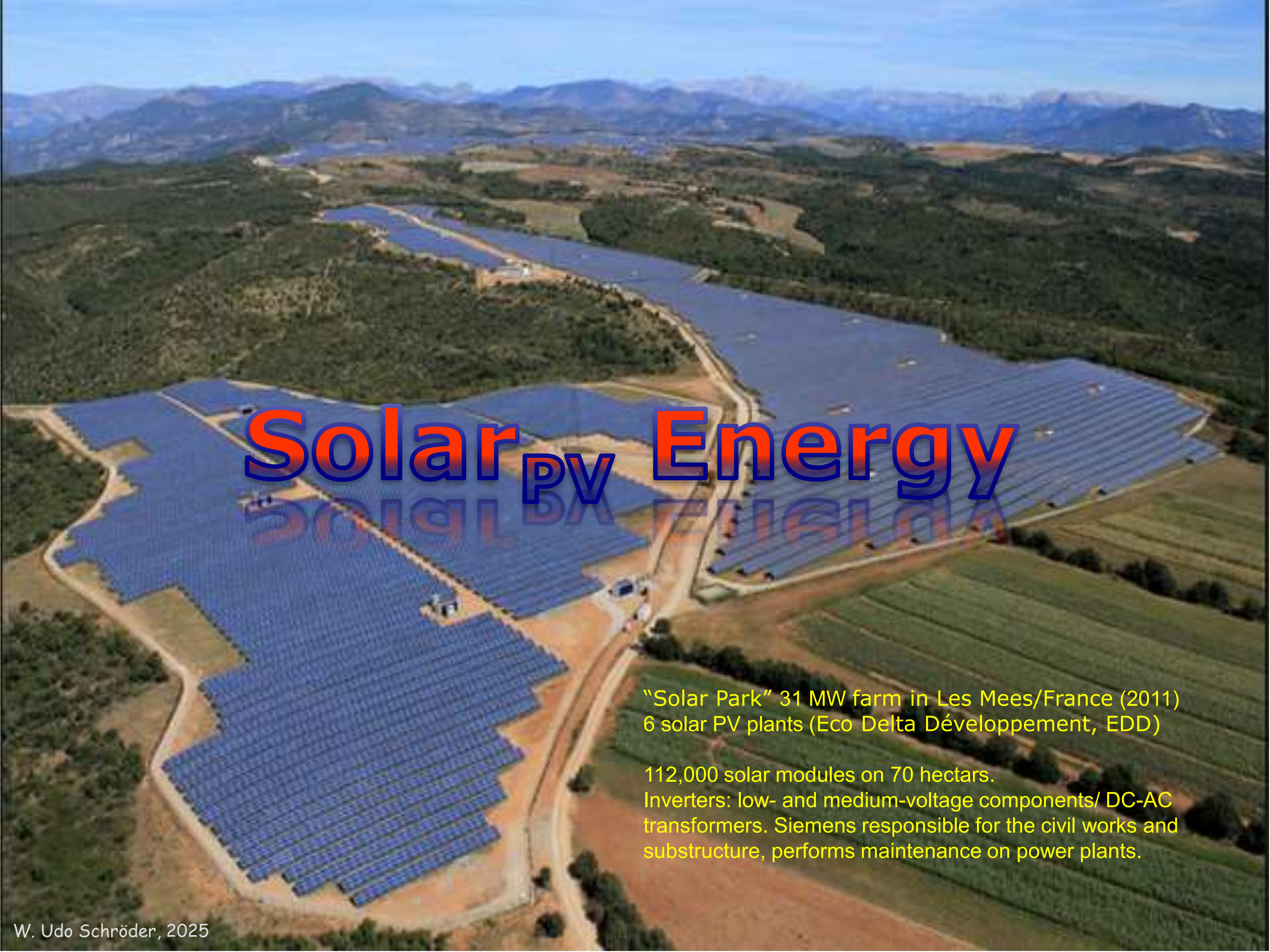

Solar$_{PV}$ Energy
“Solar Park” 31 MW farm in Les Mees/France (2011)
6 solar PV plants (Eco Delta Développement, EDD)
112,000 solar modules on 70 hectars.
Inverters: low- and medium-voltage components/ DC-AC transformers. Siemens responsible for the civil works and substructure, performs maintenance on power plants.
W. Udo Schröder, 2025

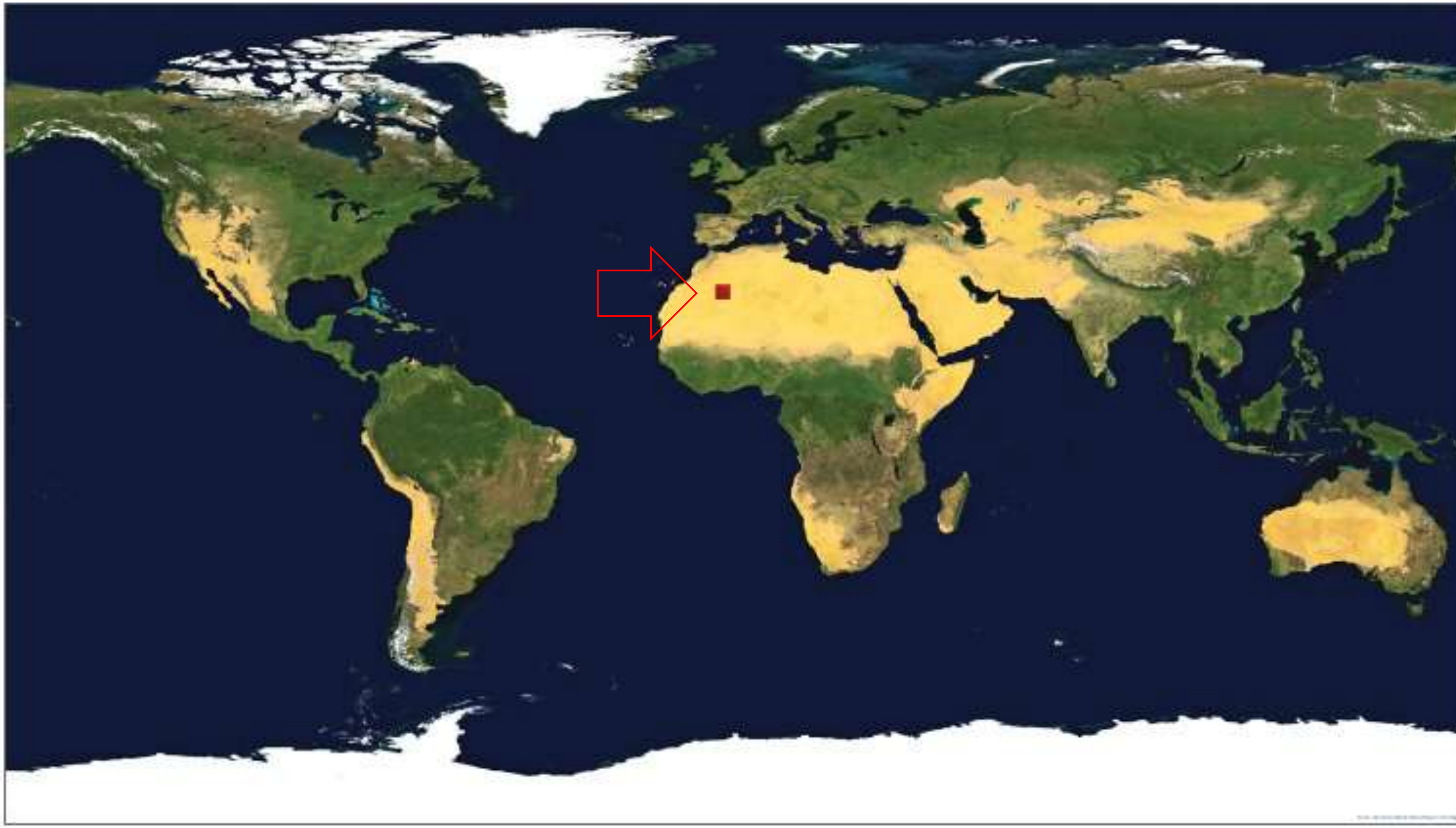
Agenda: RenE Solar PV Energy Conversion

- Intro: Solar insolation, power density, solar emission spectrum
- Utility size(solar farms) & residential PV arrays

- Silicon solar photo-voltaic (PV) technology
  - Semiconductor band structure, gap, junctions
  - Charge carriers in n-type and p-type semiconductors
  - Photocell operation, efficiency
  - Silicon wafer, cell manufacture
  - Materials and emissions in construction

- US and World installations and performance, system cost and incentives
- Solar power strategic issues

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

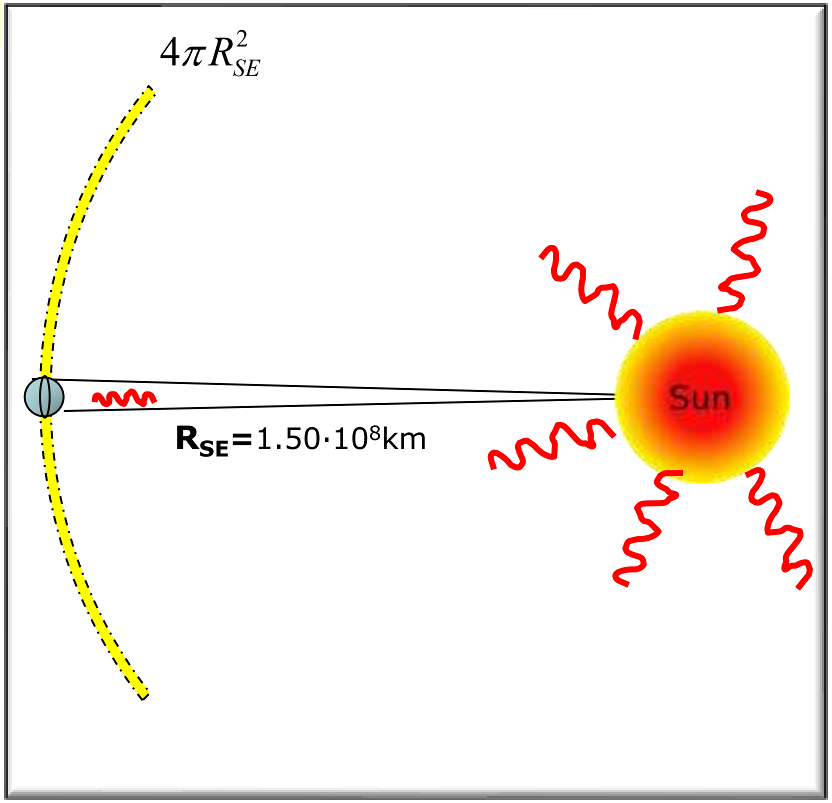
Stefan-Boltzmann Law $S = \sigma \cdot T_S^4 \; (W/area)$

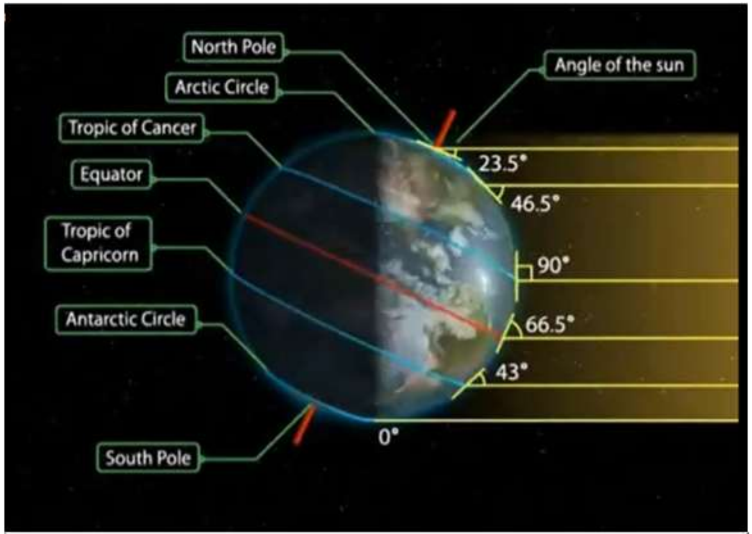
Solar direct S = mean power density

$$A_{R_{SE}} = \pi R_E^2 = \frac{1}{4} A_E; \; A_E = 5.1 \times 10^8 \; km^2$$

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

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



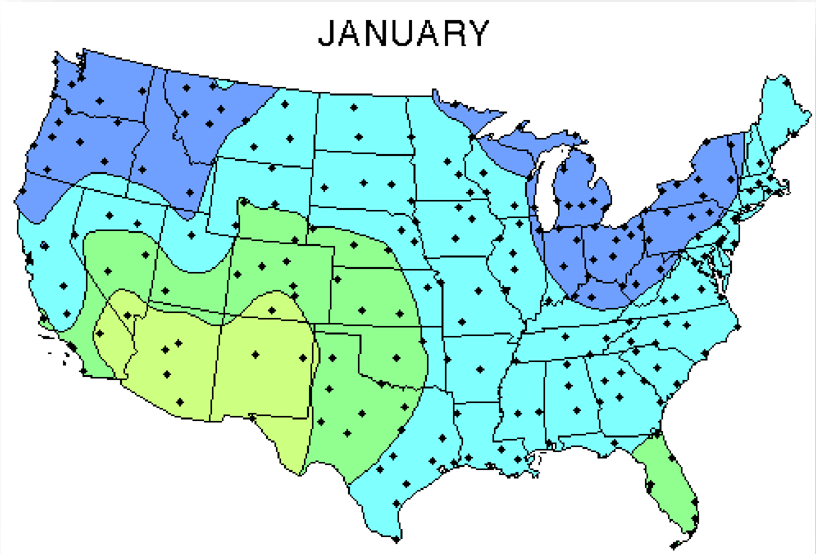


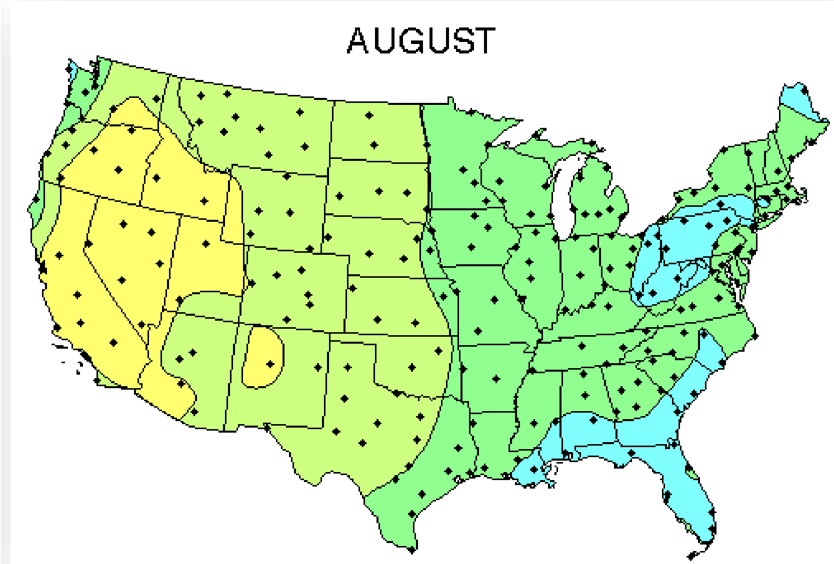
Solar radiation incidence during summer on northern hemisphere

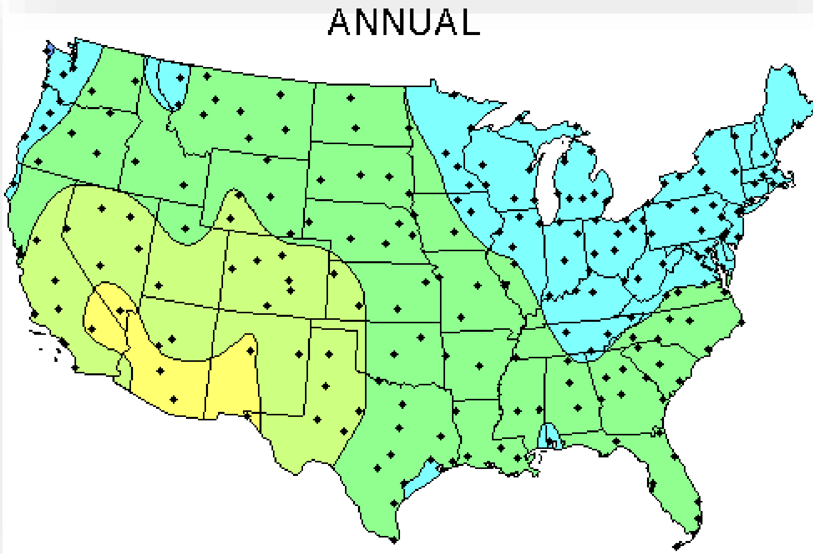
Angle of incidence $\neq 90^0$ *reduced power*

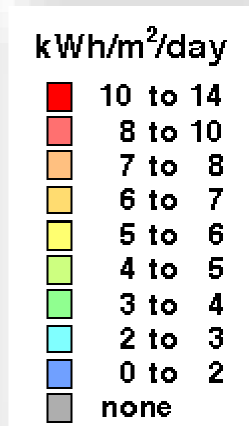
$ROC@\; 47^0 \; latitude \rightarrow \boxed{S_{eff}(\theta) < S}$

Average Daily Insolation









National Renewable Energy Laboratory
Resource Assessment Program

August in NY:
(2-4)kWh/d·m²

Compare to

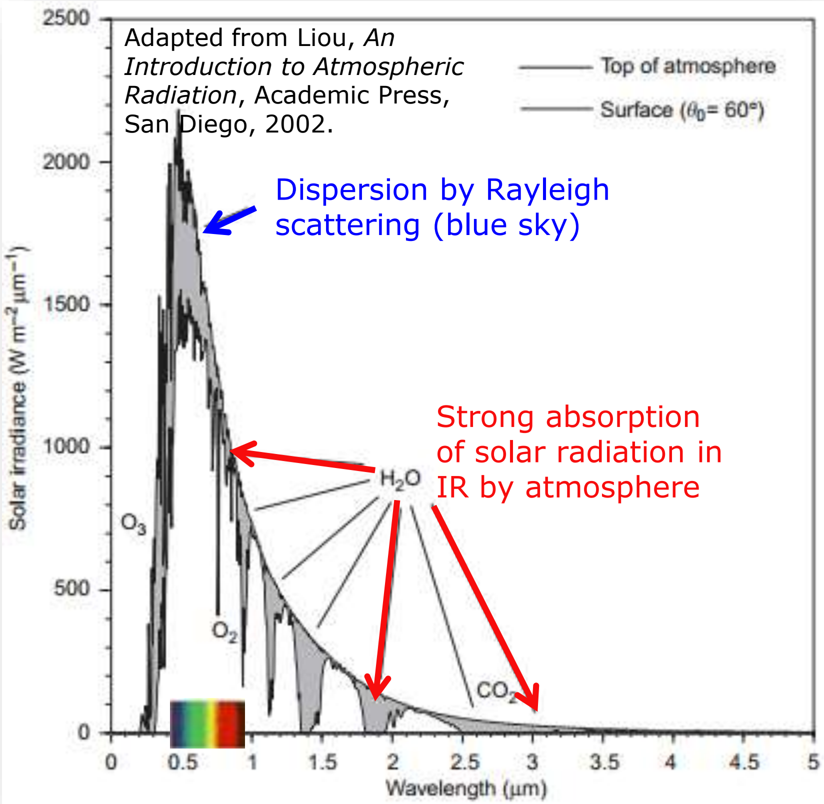
$$I = S \cdot \frac{12h}{d} \approx 17\,kWh/\left(d \cdot m^2\right)$$

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/

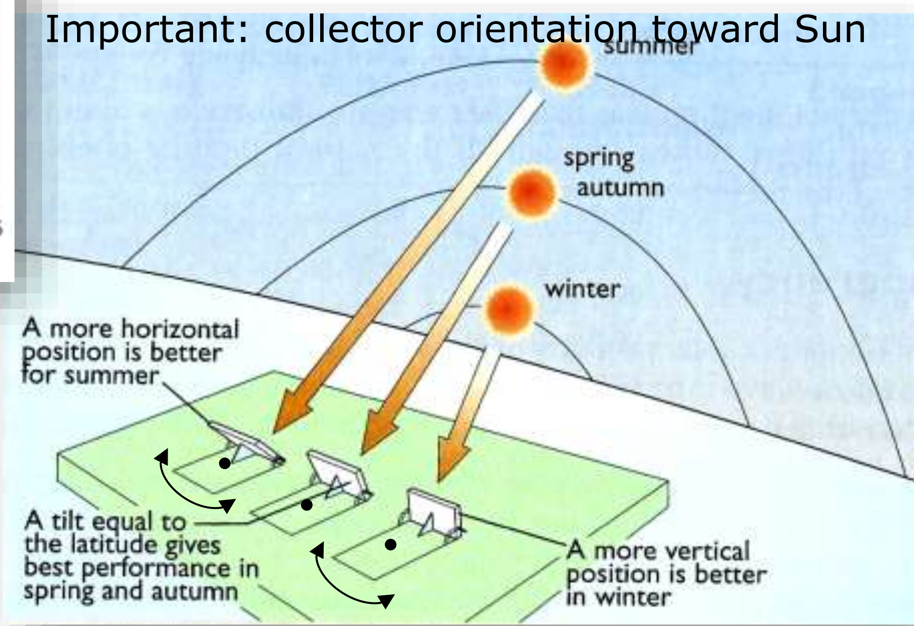
Capturing Sun Rays on Surface



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

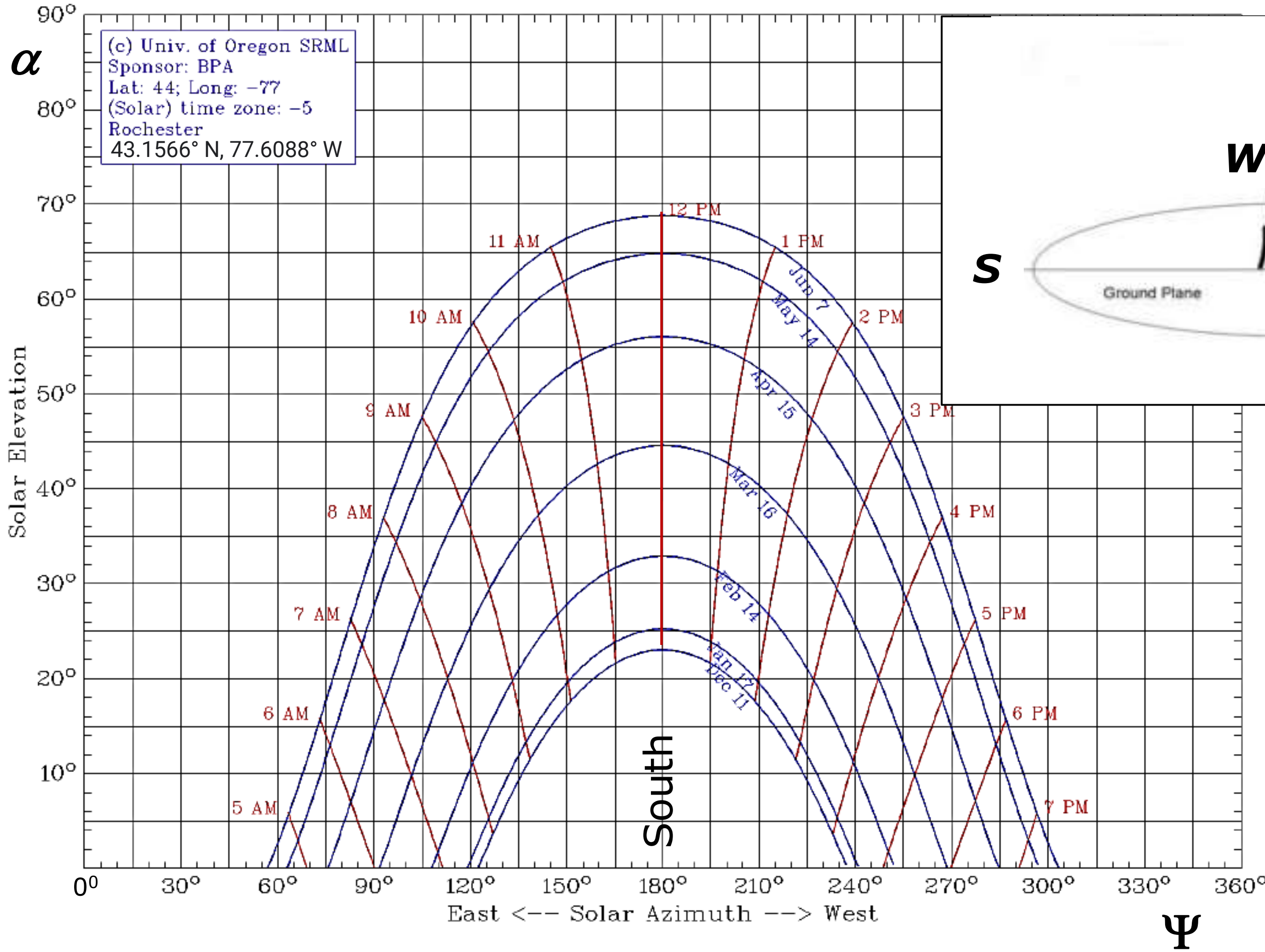


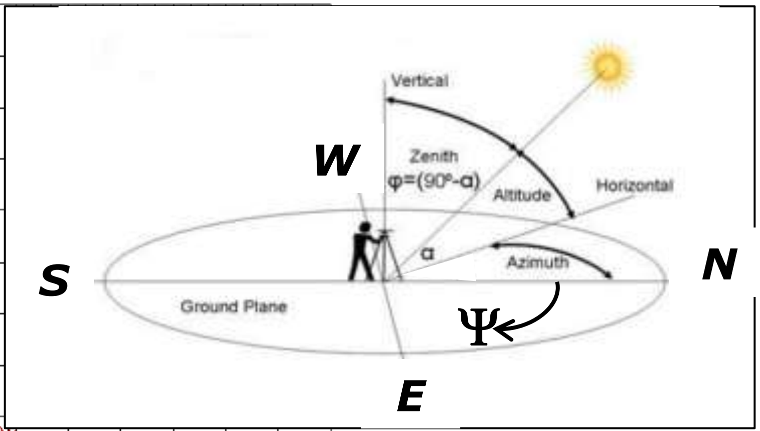
Adapted from G. Boyle et al., Renewable energy, OUP

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

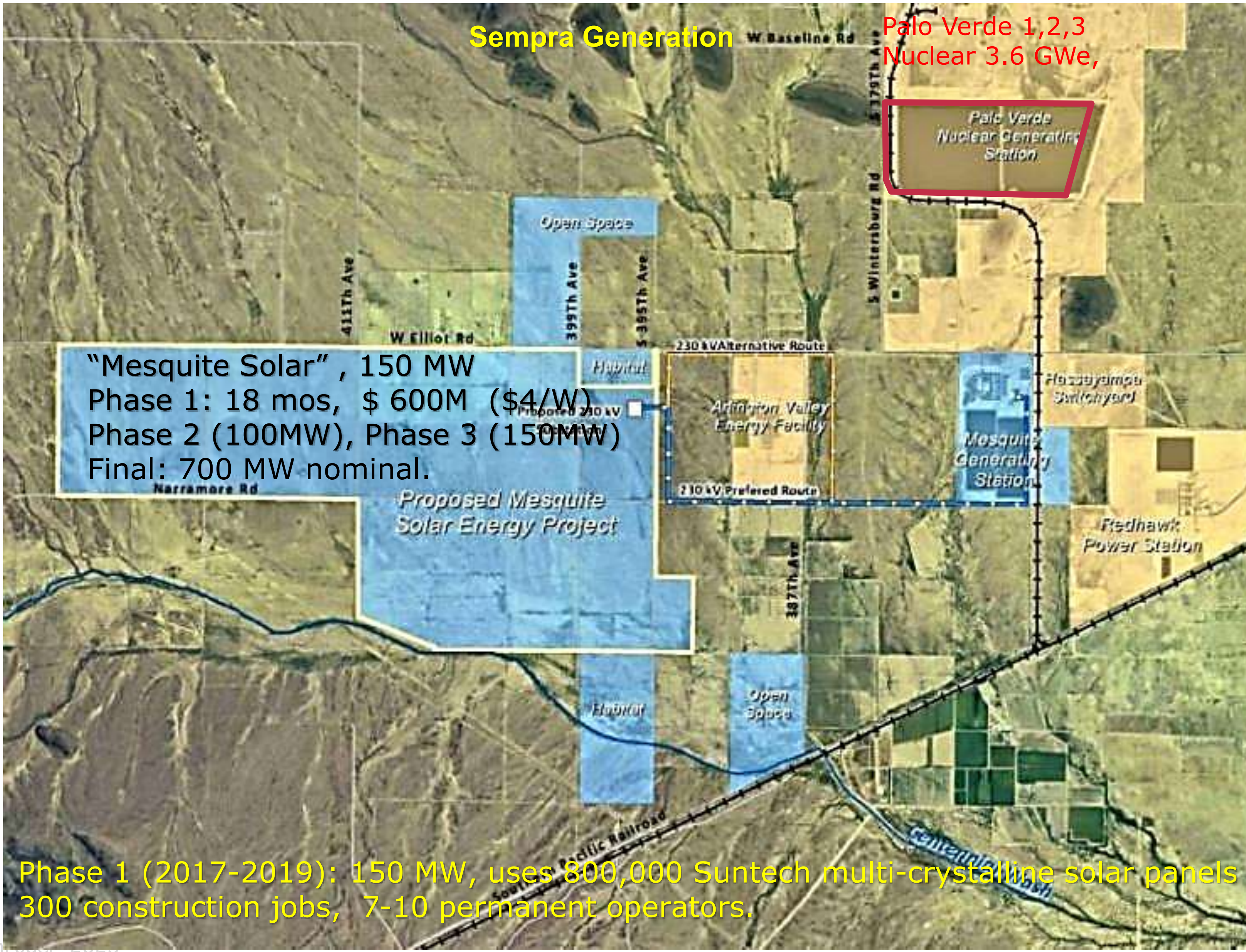
Concentrated Solar Power= CSP
"Receivers" collect and focus sunlight,
Tracking for (θ, ϕ) best efficiency.

Rochester Solar Elevation α (app.)vs. Azimuth





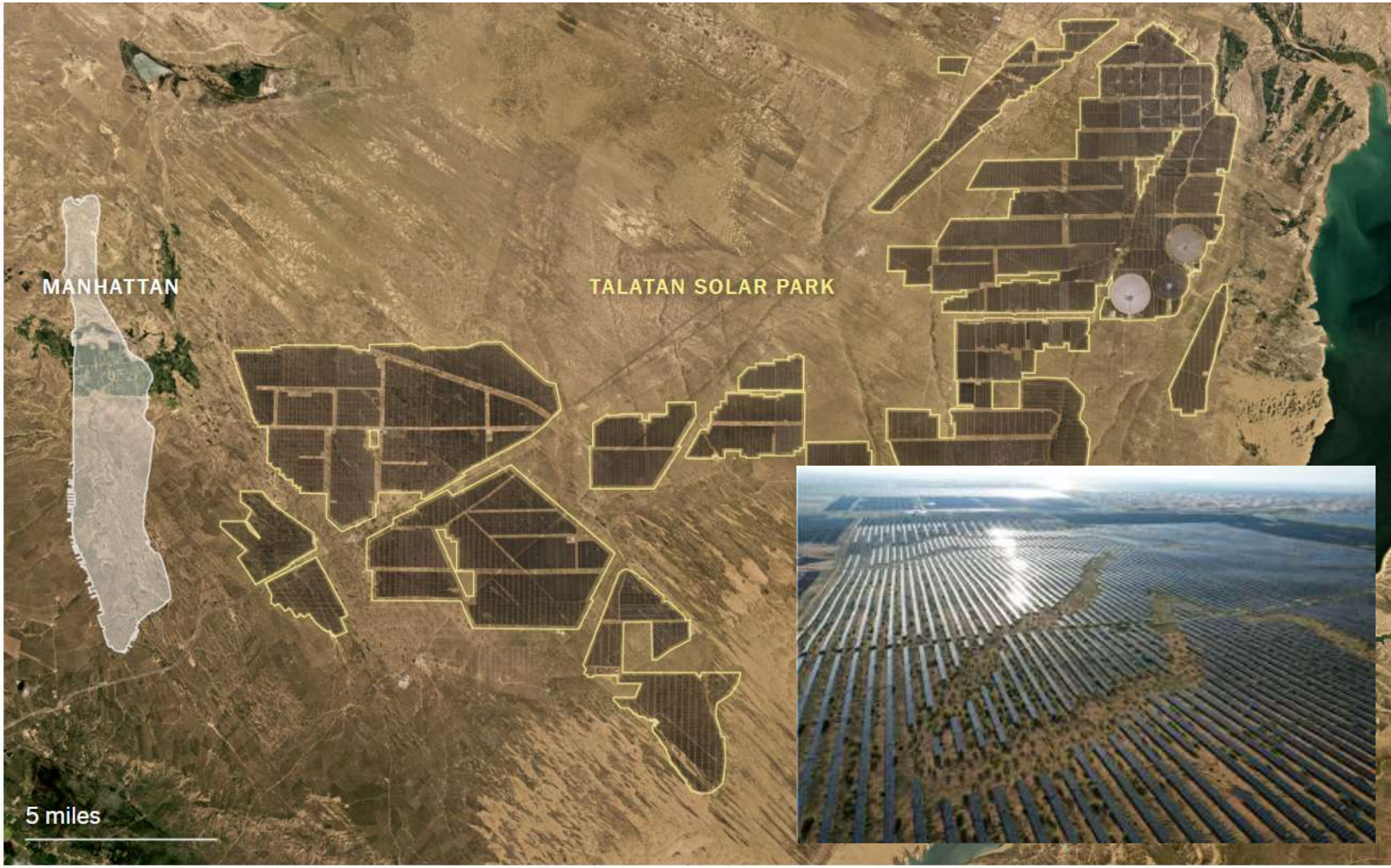
Big US PV Projects: Mesquite Solar



"Mesquite Solar" , 150 MW
Phase 1: 18 mos, $ 600M ($4/W)
Phase 2 (100MW), Phase 3 (150MW)
Final: 700 MW nominal.

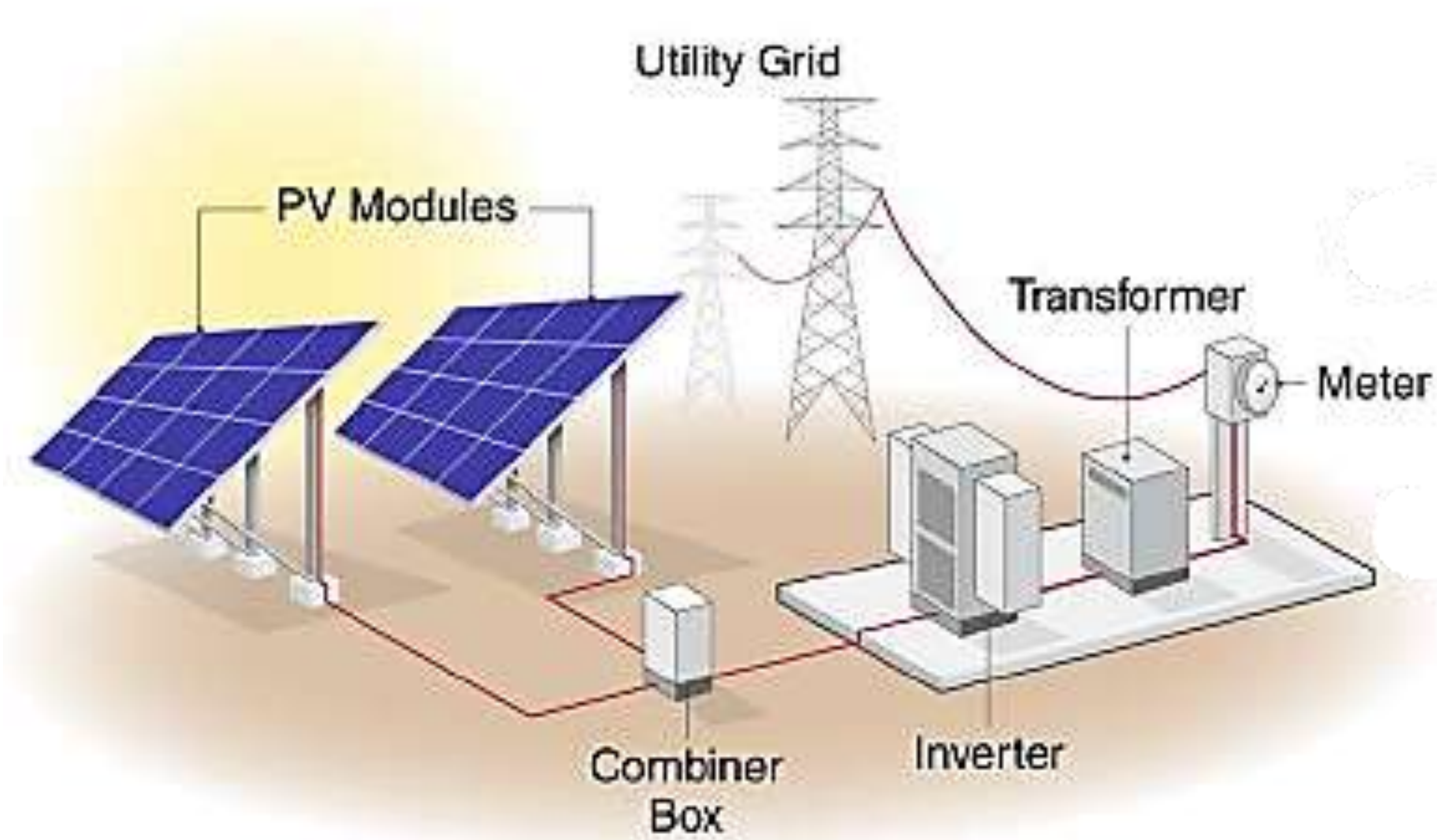
Phase 1 (2017-2019): 150 MW, uses 800,000 Suntech multi-crystalline solar panels
300 construction jobs, 7-10 permanent operators.

Large Solar PV Arrays: China



Talatan solar project (Qinghai) 16,930 megawatts, 10x Manhattan area →2030: 100GW PV “Great Wall”.

Utility PV Installation



Residential/Commercial Installations

European installations: Balcony Power, 1.8 kWp. Bifacial cells, battery storage 1.6 kWh incl. 800W inverter.

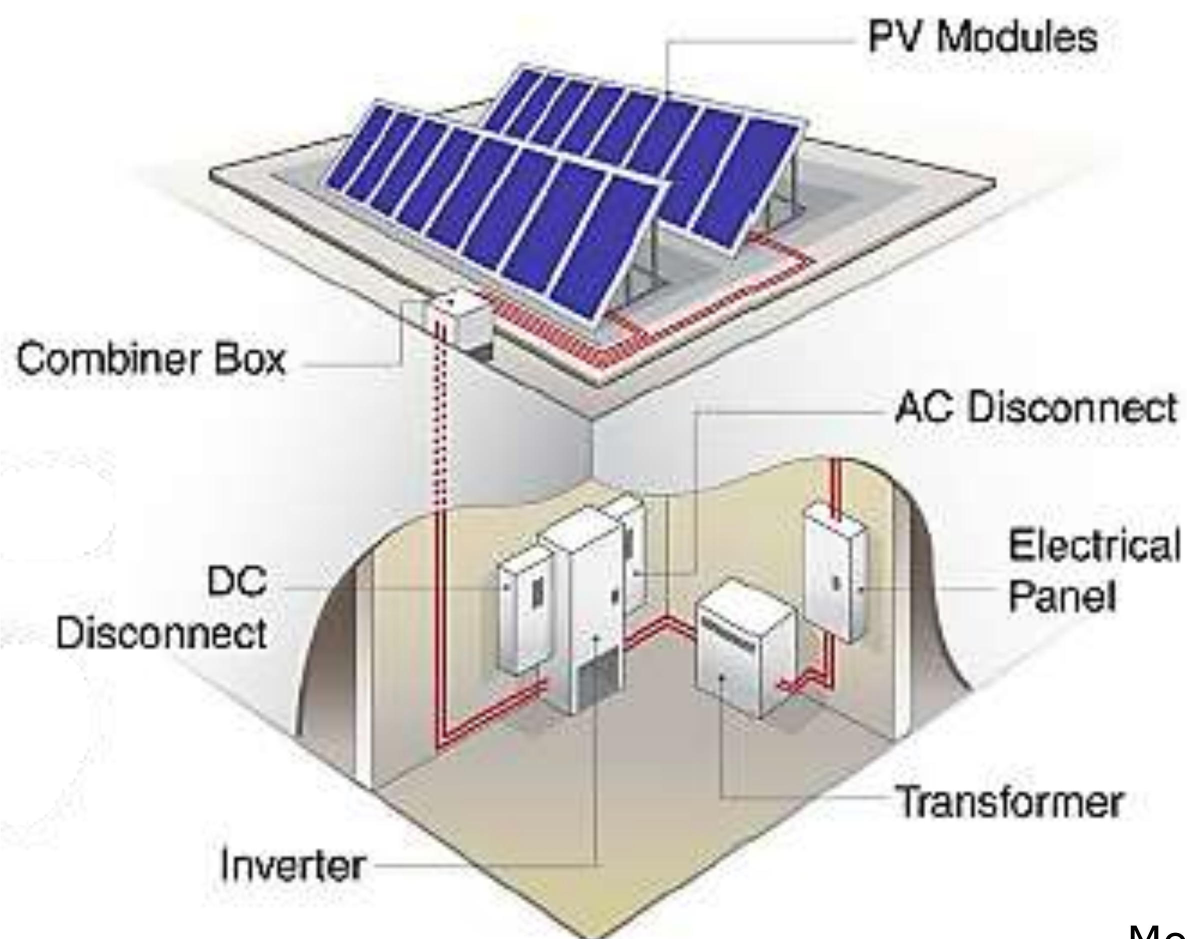
Solar thermal installation at the Allison Inn, Oregon

U.S. 2024: 4.7GW_{dc}.

2022 total: 5.9 GW_{dc} = nearly 700,000 systems installed (1,687 MW_{dc} in Q4)

Supply chain problems: China, tariffs

Residential/Commercial PV Installation



More compact setups for "Balcony Power Plants"

Agenda

- Intro

- Solar insolation, power density, solar emission spectrum
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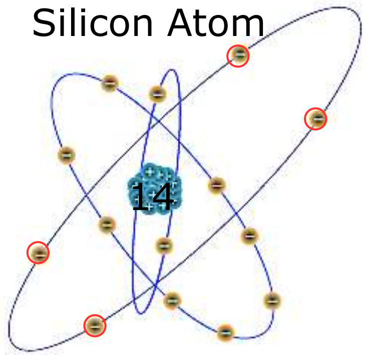
PV Basics: Properties of Semiconductors

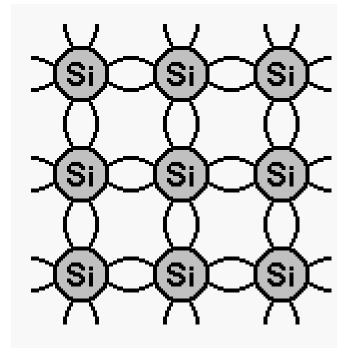
Silicon Atom



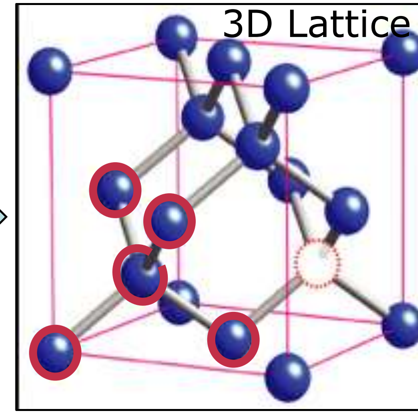
Basic idea of solar cell: Photons **electrically polarize** non-conductive cell, generate currents of charge carriers → external electric circuits.

Crystal lattice: Covalent binding of 4 valence e^- in "valence" band of states. Free ***e-*** *(**h⁺**)* in conduction bands.

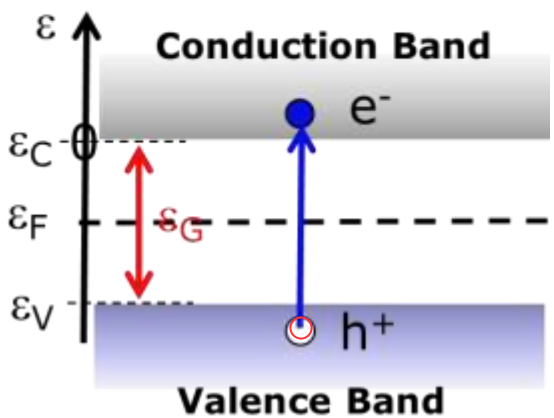
2D Structure



3D Lattice



Band Structure of Electron States in Periodic Crystal Lattices



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.

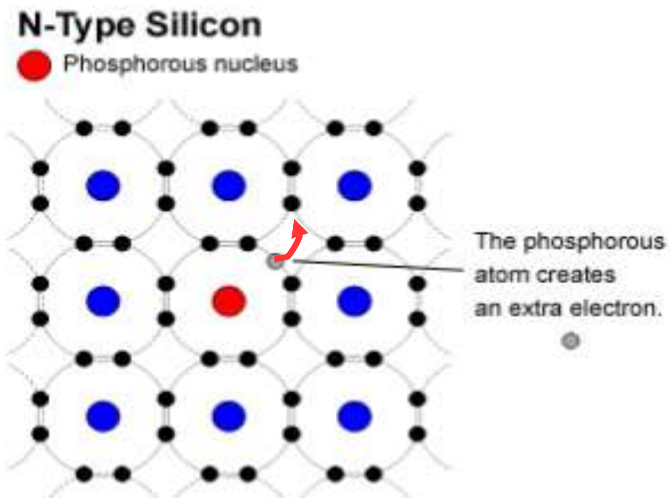
Energy band structure of all matter lattices
Semi-conductors (have small gaps) →
Thermal Boundary Fluctuations

→ Pure elements of Group IV (Si, Ge,…)
→ Binary compounds (GeAs, InSb, SiC, CdSe,...)
→ ….. oxides
→ Organic compounds (COP)

Need spontaneous spatial charge separation →
Not achieved with single homogeneous SC →
join 2 SCs with chemical/electrical pots $\varepsilon_{F1} \neq \varepsilon_{F2}$
→ n-silicon & p-silicon

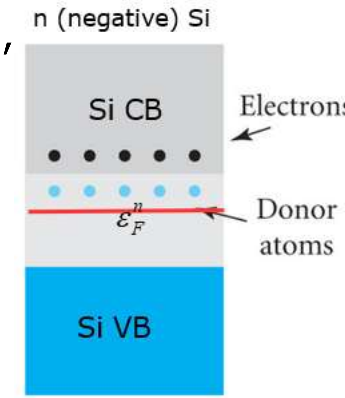
Diversification: Silicon Doping

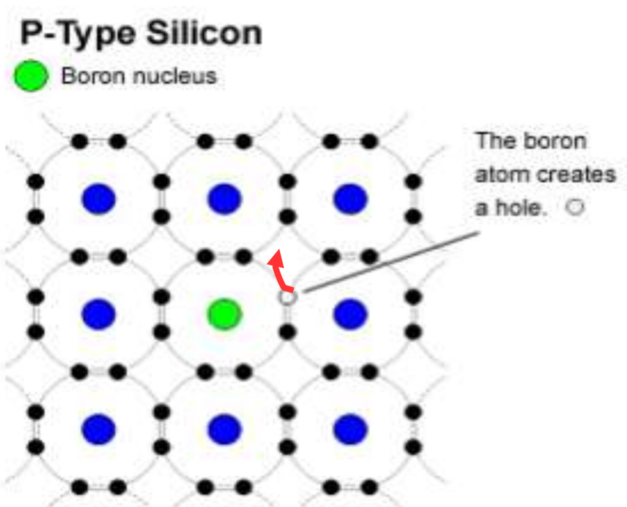
Desired: semi-conductor materials with different e^-/h^+ mobilities →"doping" Si crystals



P (phosphorus, Group V element)
one valence electron more than Si,
less bound → Si-conduction band.

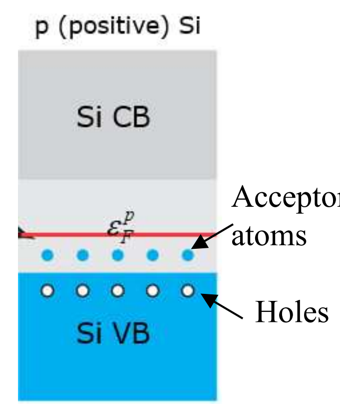
P-doped Si= ***N-type silicon***
P is an electron donor.



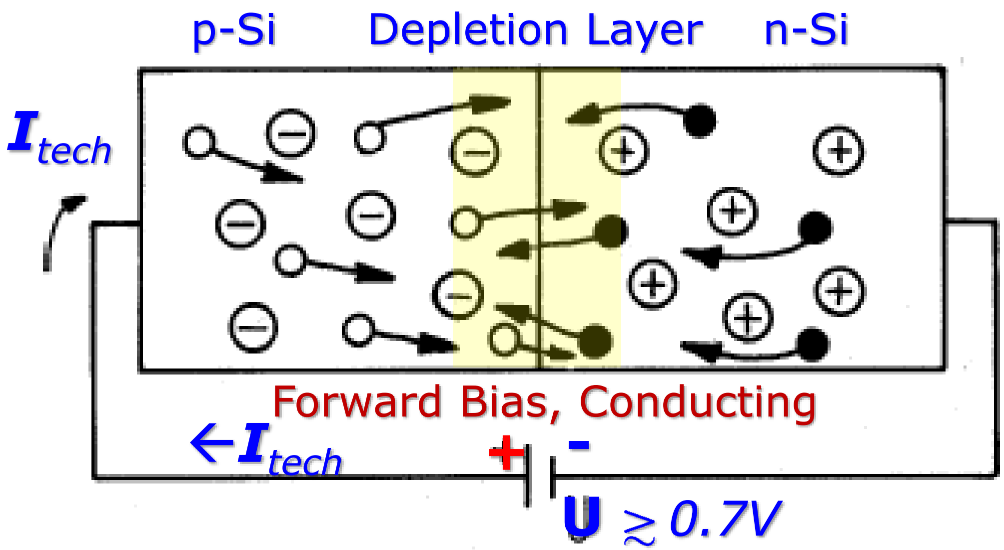


B (boron, Group III element)
one electron less than Si,
extra hole in → Si-valence band
moves in that band.

B-doped Si = ***P-type silicon***,
B is an electron ***acceptor***.

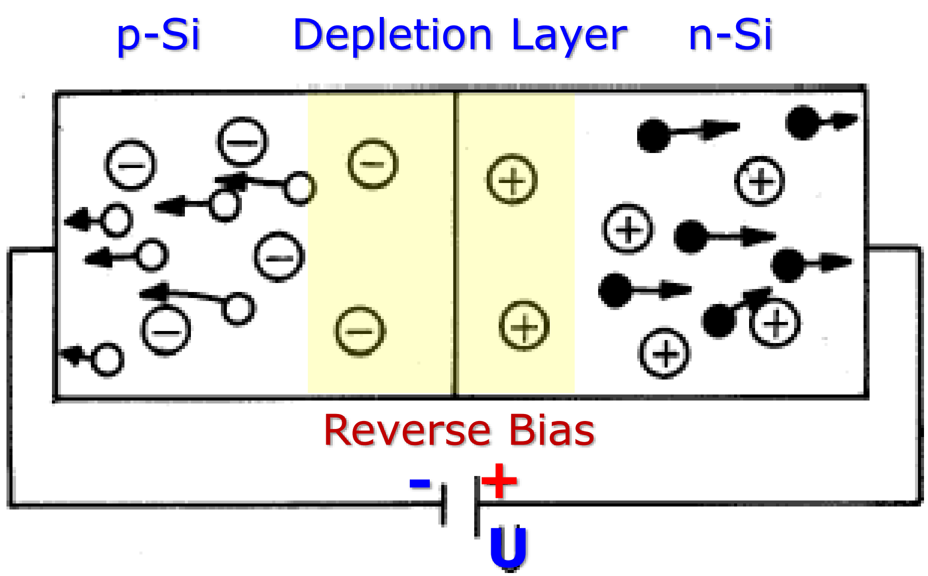


p-n Junction Diode

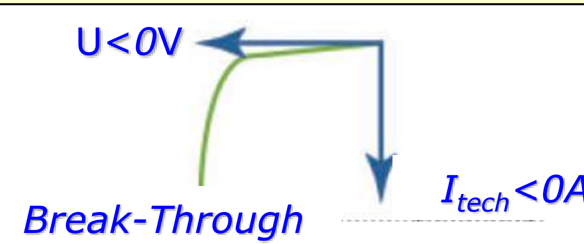


Cross diffusion of e^- and h^+ in junction zone → recombination & Potential E diffusion barrier B(Si)=0.7eV → Depletion Layer (DL): has no free charge carriers

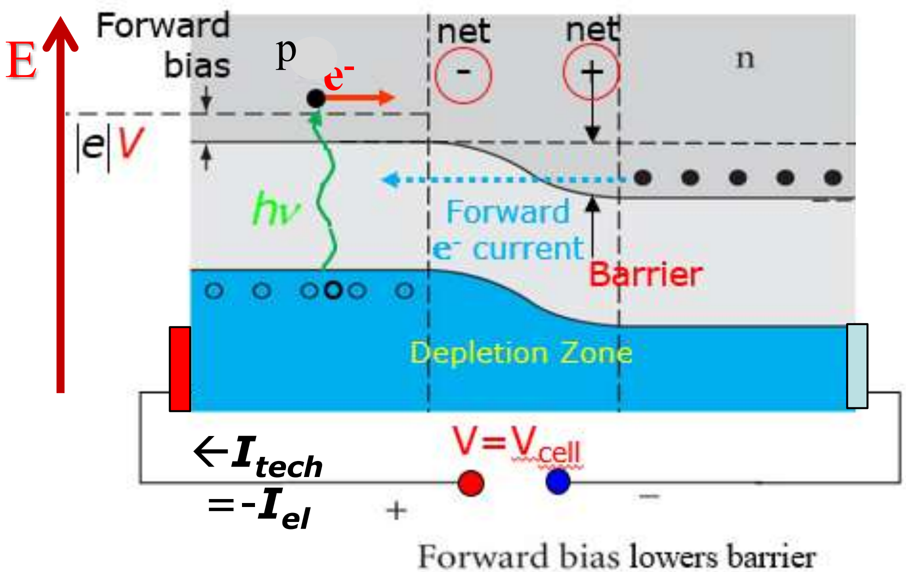
Forward bias *U* ≳ *+0.7V* (@Si) reduces barrier & width of DL: n-Si electrons move through p-Si part → ≈"short circuit"



Reverse bias *U* < *0V increases* barrier & width of DL: n-Si electrons are repelled from DL through → ≈"open circuit"

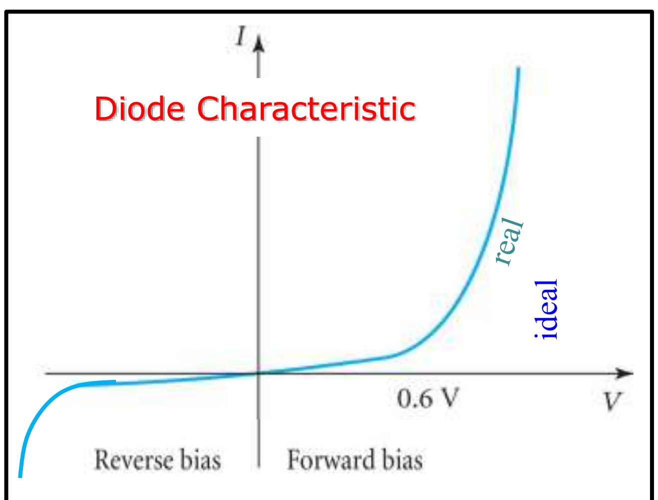


Semiconductor Junction Diodes



Forward: normal $\boldsymbol{I_{el}} = -\boldsymbol{I_{tech}}$: n→p across junction due to thermal→ No Bias applied → $I \approx 0$
Forward bias lowers barrier
→ $I \neq 0$, increases. *Opto-induced current in opposite direction*

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



$$Thermal\ \ Dark\ \ Current\ tunneling \sim \exp\left\{+e \cdot V/kT\right\}$$

$$\rightarrow in\ \ normal\ \ n \rightarrow p\ \ (diode\ conduction)\ \ direction$$

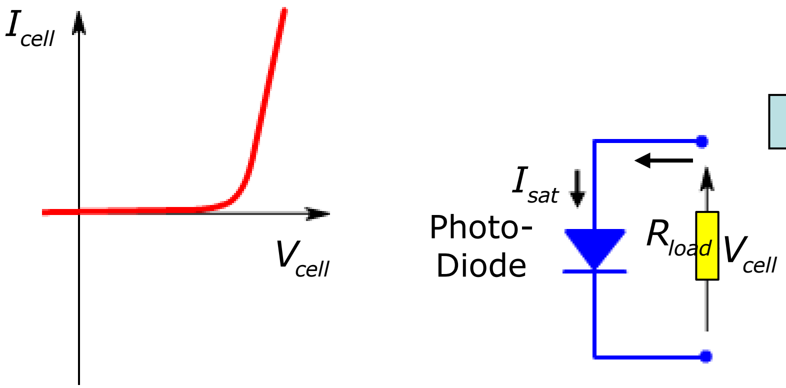
$$V-induced \qquad I(V) = I_{sat} \cdot \left\{e^{+e \cdot V/kT} - 1\right\}$$

$$Ambient\ \ T: \ \ kT = 25\ meV\ @\ T = 293K$$

$$Elementary\ \ charge\ \ e,$$

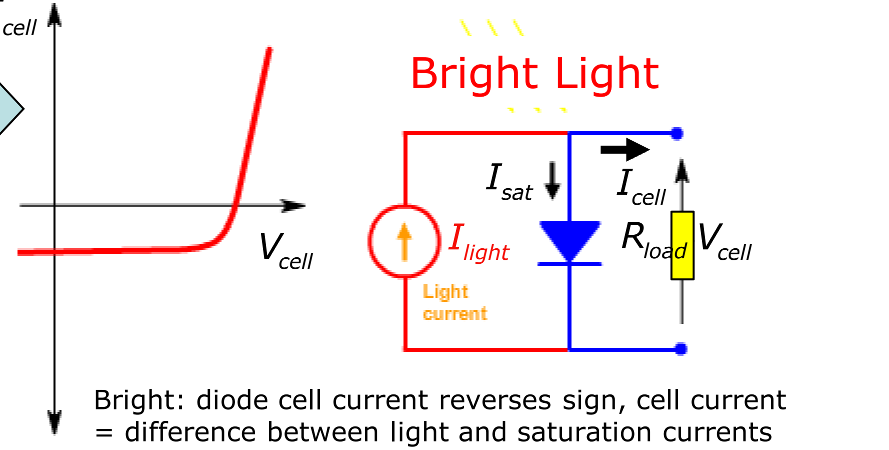
$$"Saturation"("dark", "field")\ current\ \ I_{sat}$$

Cell Equivalent Electronic Circuits

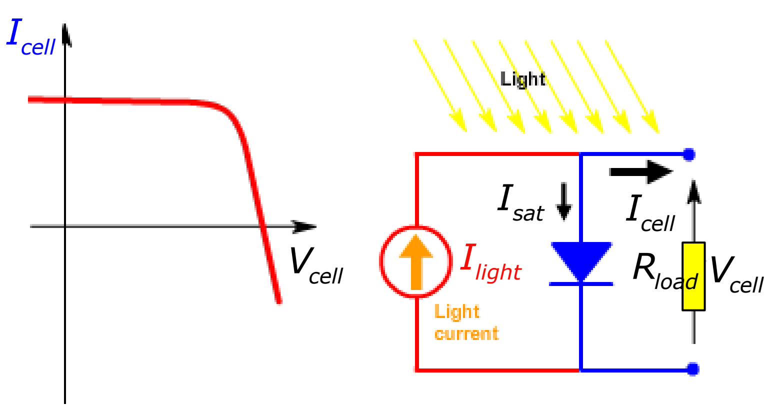


Dark: normal diode functions, saturation dark current

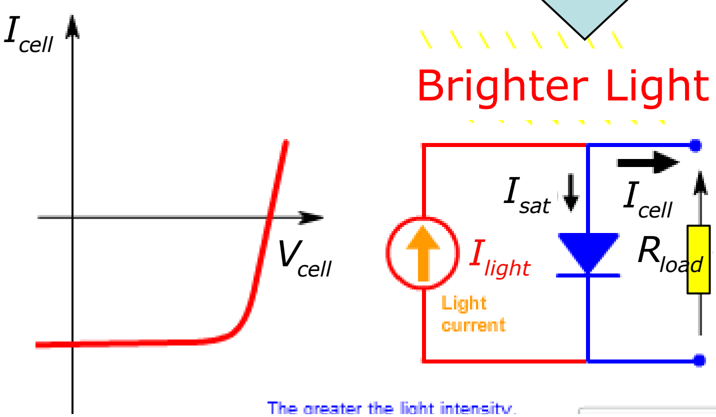
I_{cell} can be measured via R_{Load}



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



Convention: define cell current as positive.

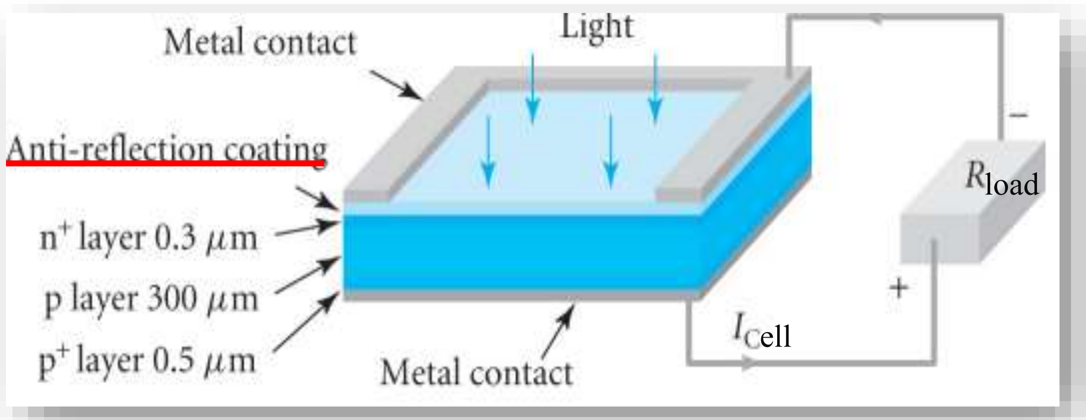


Brighter: diode current becomes more negative, cell current = difference between light and saturation currents increases.

By Convention

Observables in Photocell Operation

Observables: V_{cell}, I_{cell}



+ indicates extra doping, lower resistance.

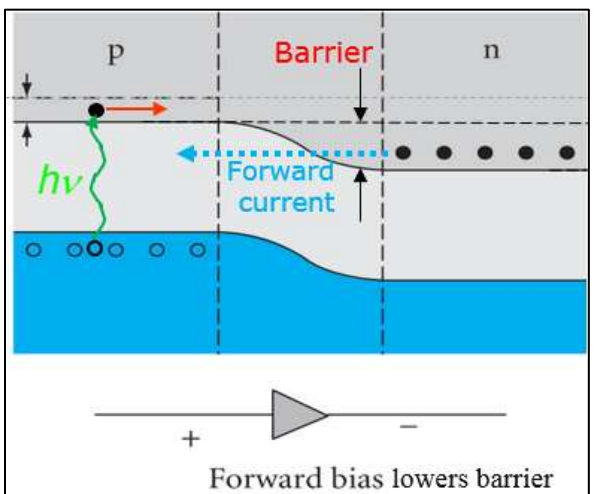
Light sensitive (solar) cell
Mode of operation

$$\varepsilon_G(Si) = 1.1\ eV$$
$$\lambda_G = \frac{hc}{\varepsilon_G} = \frac{1.24\,eV}{\varepsilon_G}\,\mu m$$

$\rightarrow e^- -$ *hole excitation if* $\lambda \le \lambda_G$

dissipates extra e^- *kin. energy*

I_{cell} dependence on R_{load} →



Photon $h\nu$ produces e⁻/hole pair in *depleted* domain → reverse current of electrons (and holes) $\vec{I}_{Light}\ \uparrow\downarrow\ \vec{I}_{sat}$

$$I_{cell} = I_{Light} - I_{sat}\cdot\left\{e^{\,e\cdot V_{cell}/kT} - 1\right\} =$$
$$= I_{Light} - I_{sat}\cdot\left\{e^{\,R_{Load}\cdot I_{cell}/V_{th}} - 1\right\}$$

"Thermal voltage"
$V_{th} := kT/e = 25mV$
Ohm's Law $V_{cell} = I_{cell}\cdot R_{Load}$

$R_{Load} \rightarrow \infty$ (*open circuit*): $I_{cell} \rightarrow 0$, $V_{cell} =: V_{OC}$

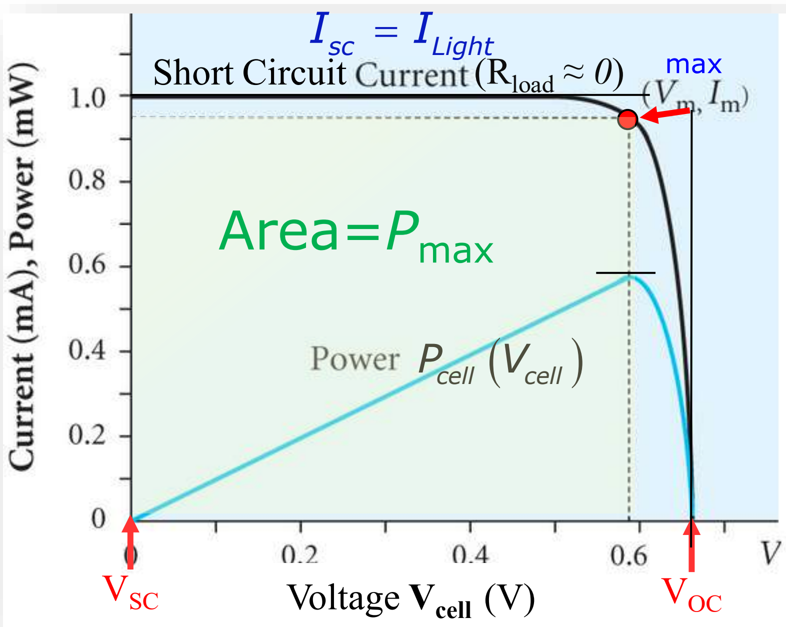
$$V_{OC} = V_{th}\cdot Ln\left[1 + \frac{I_{Light}}{I_{sat}}\right] \approx V_{th}\cdot Ln\left[\frac{I_{Light}}{I_{sat}}\right]$$

$V_{OC} = (V_{cell})_{max}$
$I_{Light} \gg I_{sat}$

$R_{Load} = 0$ (*short circuit*): $I_{cell} = I_{sc} = I_{Light}$

Cell Power Characteristic

Cell Current-Voltage Characteristic



Power P_{cell} generated by illuminating cell, scan by varying light intens. or R_{load}

(R_{Load} « R_{diode}) → (R_{Load} > R_{diode})

Rise and fall between short-circuit (SC) (**V_{cell}** ≈ 0) and open circuit (**I_{cell}** ≈ 0).

Between above limits, power evolution :

$$P_{cell} = I_{cell} \cdot V_{cell}$$

$$P_{cell} = I_{cell}^2 \cdot R_{load} \quad (Ohm's\ Law)$$

Current **I_{cell}** and power **P_{cell}** decrease with decreasing light intensity.

Typical nominal values: **I_{cell}** = 1mA, **I_{sat}** = 10^{-12} A, **V_{OC}** = 0.66 V,

Actual **P_{cell}** ≤ **P_m**=0.58 mW, **V_{cell}** ≤ V_m=0.58V →const **I_{cell}** ≤ I_m=I_{sc}=0.95 mA

$$\text{"Fill Factor"}: FF = P_{max} / (I_{SC} \cdot V_{OC})$$

$$Deduce\ from\ \{I_{SC}, V_{OC}\} \rightarrow P_{max} = FF \cdot I_{SC} \cdot V_{OC}$$

FF=Ratio of area under power curve to limiting rectangle→ measure of steepness (ideal) of diode I-V characteristic.