Theory and Practice of Solar Cells: A Cell to System Perspective

Lecture 1
Overview: Sun, Earth, and the Solar Cell

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Outline

1) Introduction: A short history of solar energy

2) The story of the sun and sunlight

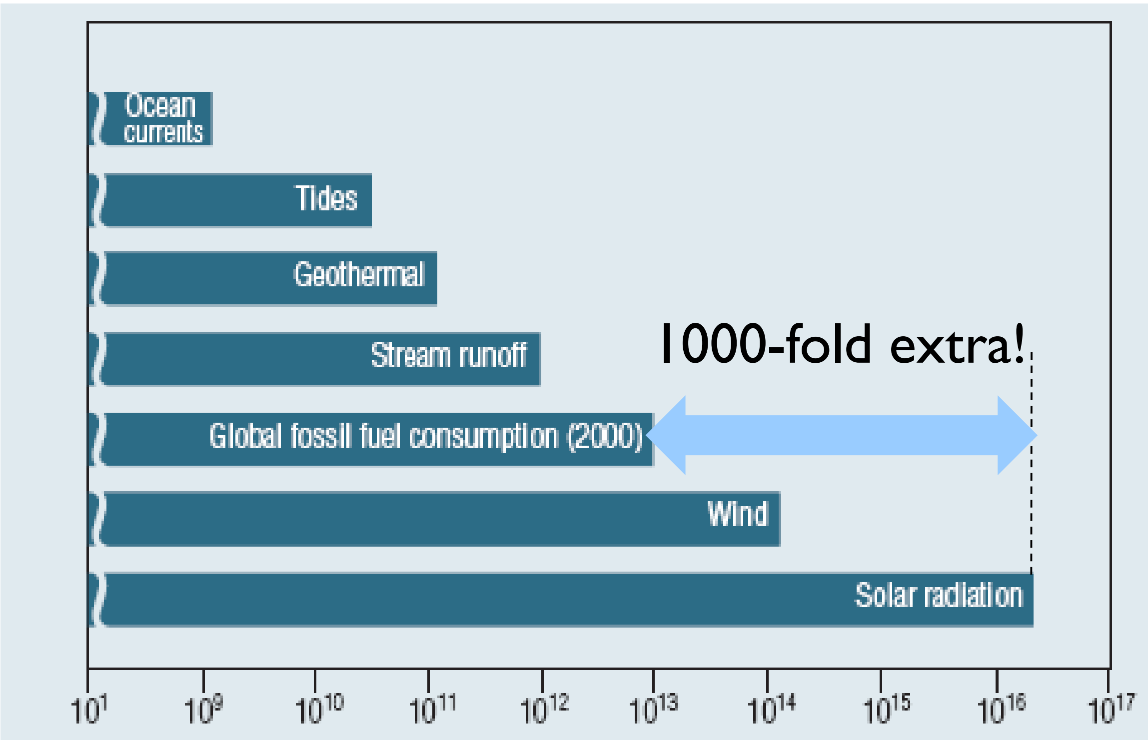
3) Earth's atmosphere determine sunlight on ground

4) Solar cells are extremely inefficient

5) Levelized cost of electricity as a savior

6) Conclusions

Solar resources and potential



Source: OECD Observer No. 258/59 December 2006

$$A = 510 \times 10^{12}\ m^2$$
$$P = 10^3\ W/m^2$$
$$D = 0.1 - 0.3$$
$$P_T \sim 50 - 150\ PW$$

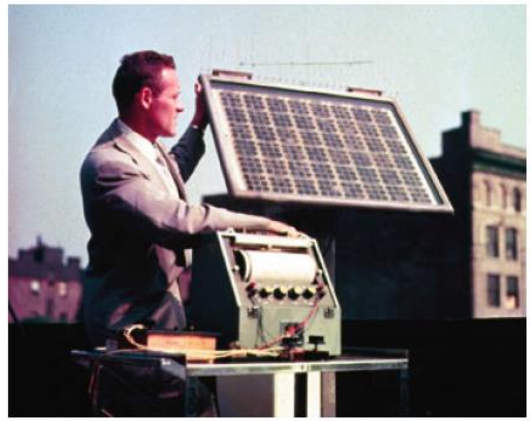
$$W = 7.7 \times 10^9$$
$$P = 2.5 \times 10^3\ W$$
$$P_T \sim 2\ \ TW$$

Solar energy can meet world energy demand

Even a small-state like Indiana..

Source: Nate Lewis (Caltech)

A brief history

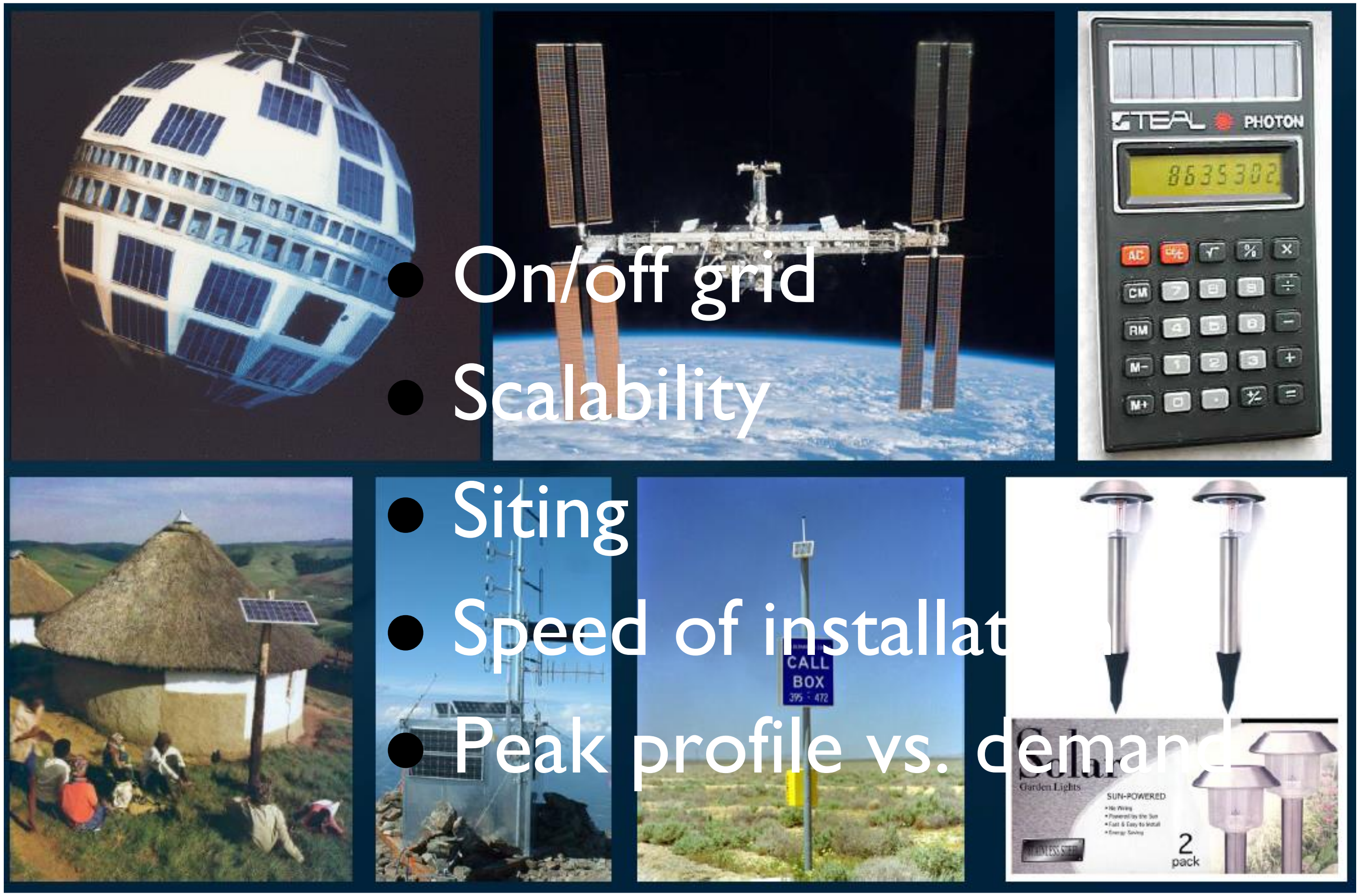


- Use in Telstar in 1962 and other satellites thereafter
- Increasing terrestrial deployment all over the world

Great benefits for telephone users and for all mankind will come
From this forward step in harnessing the limitless power of the sun.

-- Bell Telephone Laboratories, 1954.

Off-grid application …



- On/off grid
- Scalability
- Siting
- Speed of installation
- Peak profile vs. demand

Types of Solar Energy Converter

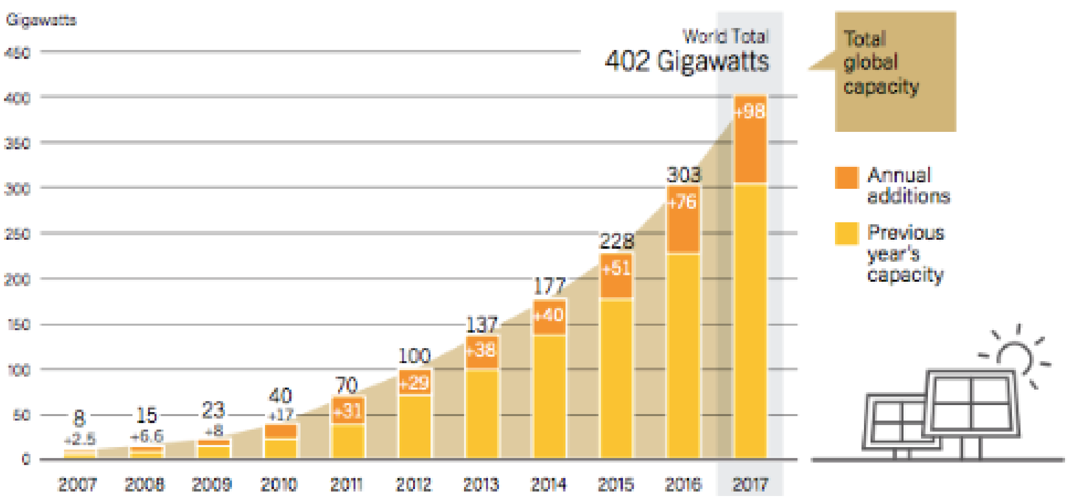
Photo: Brightsource Energy, http://ecotechdaily.com/wp-content/uploads/2008/04/brightsource2_620px.jpg

Photo: Stirling Energy Systems, www.wapa.gov/ES/pubs/esb/1998/98Aug/Graphics/Pg5b.jpg

Source: TGW, http://openlearn.open.ac.uk/file.php/1697/220880-1f1.29.jpg

Photo: Ausra, Inc., www.instablogsimages.com/images/2007/09/21/ausra-solar-farm_5810.jpg

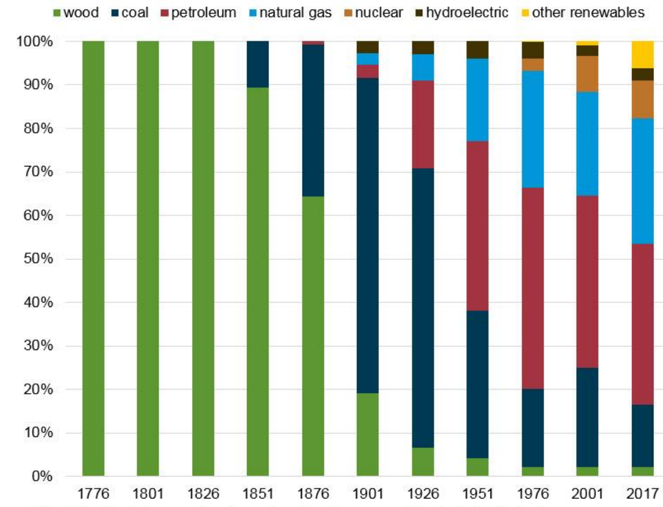
FIGURE 24. Solar PV Global Capacity and Annual Additions, 2007-2017



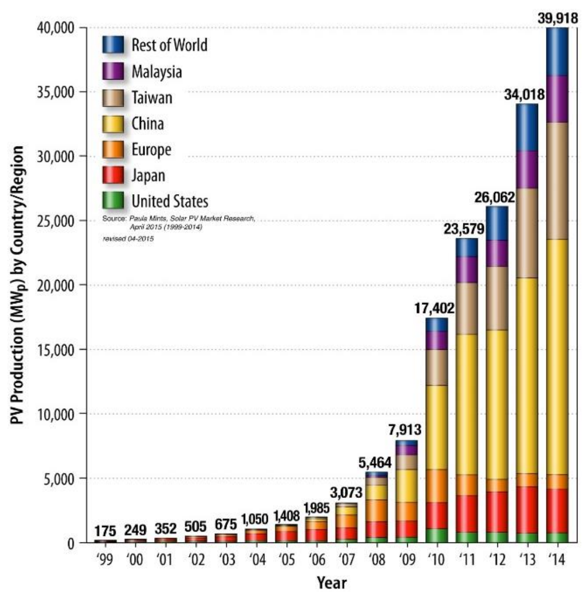
Note: Data are provided in direct current (DC). Totals may not add up due to rounding.

Source: IEA PVPS. See endnote 3 for this section.

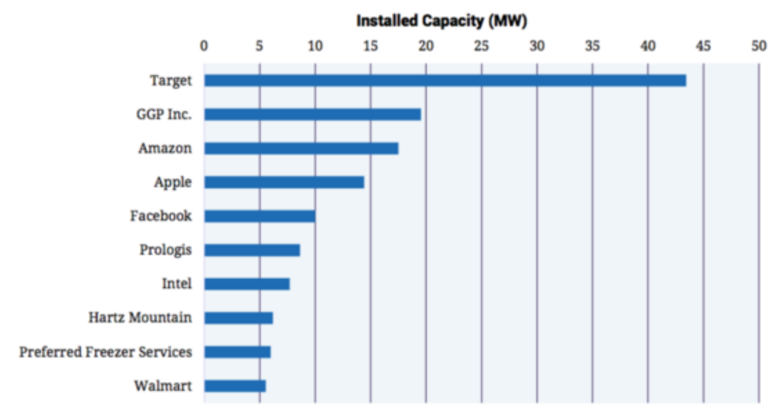
Shares of total U.S. energy consumption by major sources in selected years (1776–2017)



Note: Wood includes wood and wood waste; other renewables includes biofuels, geothermal, solar, and wind.
Source: U.S. Energy Information Administration, *Monthly Energy Review*, Appendix D.1, and Tables 1.1 and 10.1, May 2018, preliminary data for 2017



Top ten corporate users



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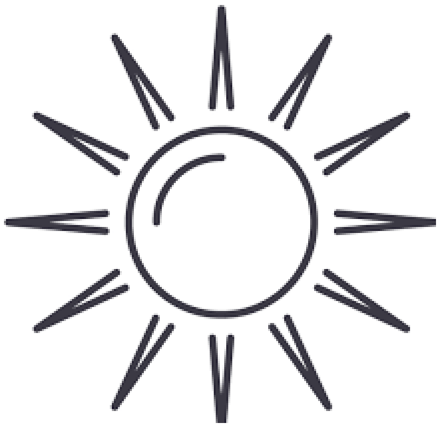
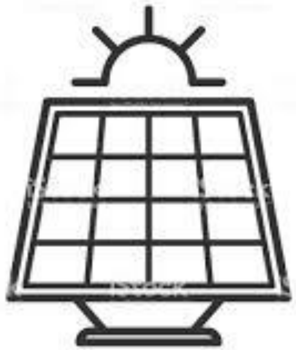
Actors: Sun, Earth, Solar cell, and bank



Sun Temp. 5777 K

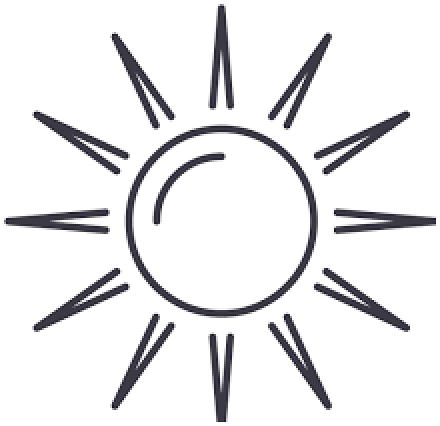
Distance: $1.496x10^{11}\ m$
Earth Radius: 4000 miles
Temperature: 300K
Irradiance ... 1000 W/m^2

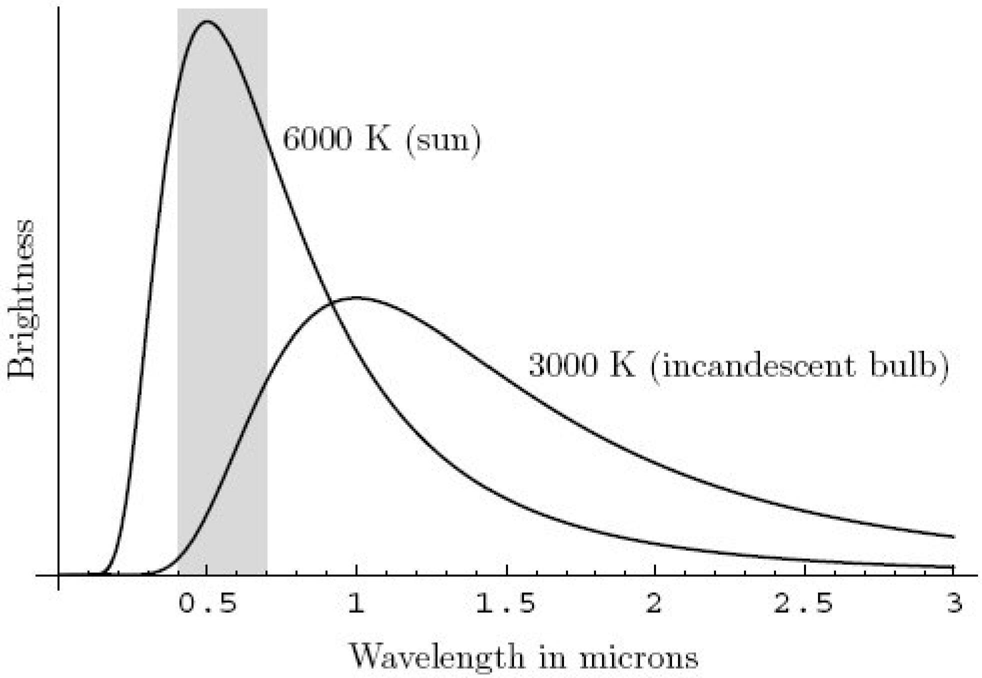


PV Max. Efficiency = 1/3

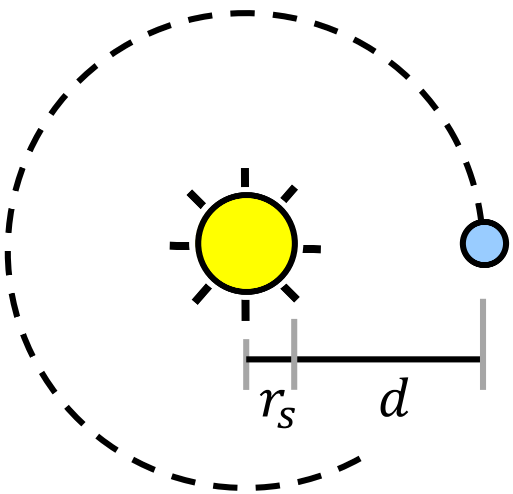
Bank interest – 4-5%

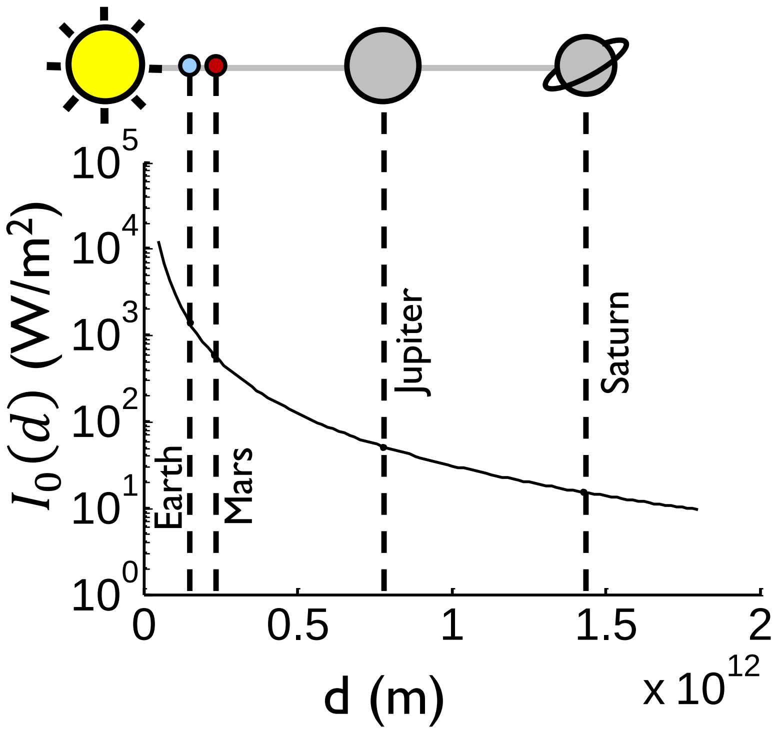
Sun is a nuclear reactor





The extraterrestrial solar intensity is easily calculated





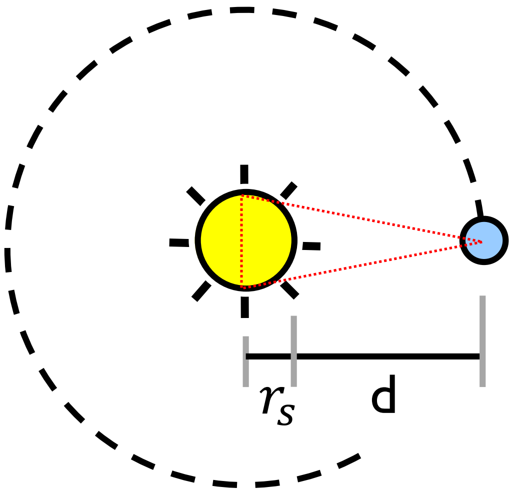
$$I_s = \sigma T_s^4$$

$$\sigma = 5.67 \times 10^{-8} \frac{\mathrm{W}}{\mathrm{m^2 K^4}}$$

$$I_0(d) = I_s \left(\frac{r_s}{d}\right)^2$$

Measuring sun's temperature without a thermometer

$$I_0(d) = \sigma T_s^4 = I_s \left(\frac{r_s}{d}\right)^2$$



σ is known from SB relation
I_s is known from balloon experiment

Measure θ by angle-ratio
d is known by Newton's law
r_s is determined.

$$\theta = 2\, r_s/d$$

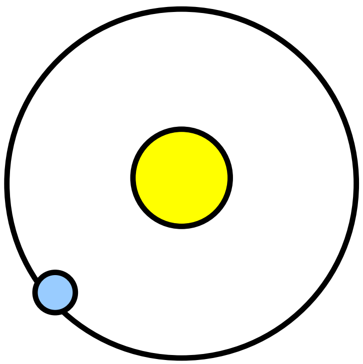
Temperature of the Sun

$\sigma = 5.67 * 10^{-8} \frac{W}{m^2 K^4}$ (SB constant)

$I_0(r_p) = 1367\ W/m^2$ (solar constant)

$r_p = 1.496 \times 10^{11}\ m$ (earth to sun radius)

$r_s = 6.963 \times 10^8$ (radius of sun)



$$T_s = \left(\frac{I_0(r_p) \times 4\pi r_p^2}{\sigma\ 4\pi\ r_s^2} \right)^{\frac{1}{4}} = 5775.8\ K$$

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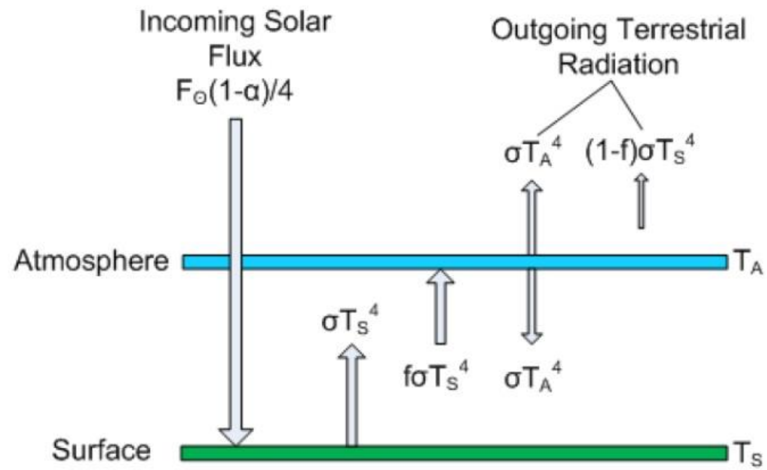
Only a fraction of sunlight arrives at the ground (and that is a very good thing!)

$$P_{abs} = (1-\alpha) P_{planet}$$
$$P_{emit} = \epsilon\, \sigma\, T_p^4 \times 4\, \pi\, r_p^2$$
$$P_{emit} = P_{abs}$$



$$T_p = T_s \sqrt{\left(\frac{r_s}{2d}\right)\sqrt{\left(\frac{1-\alpha}{\epsilon}\right)}}$$

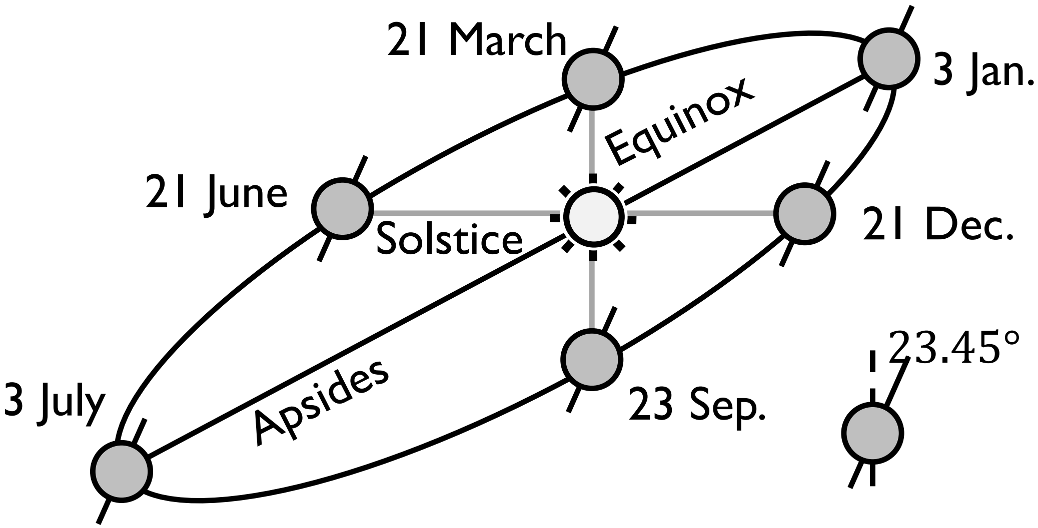
$$1382.62 \times (1-\alpha) = 987\ \mathrm{W/m^2}$$

α = albedo of the planet

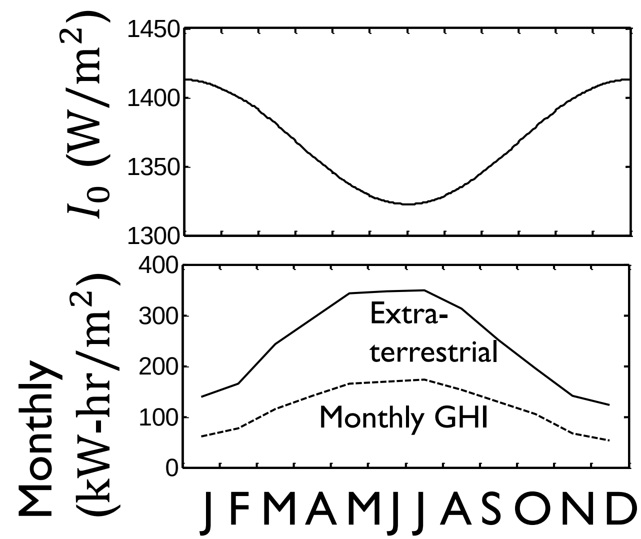
ϵ = emissivity of the planet

d = planet – earth distance

Sunlight varies with seasons

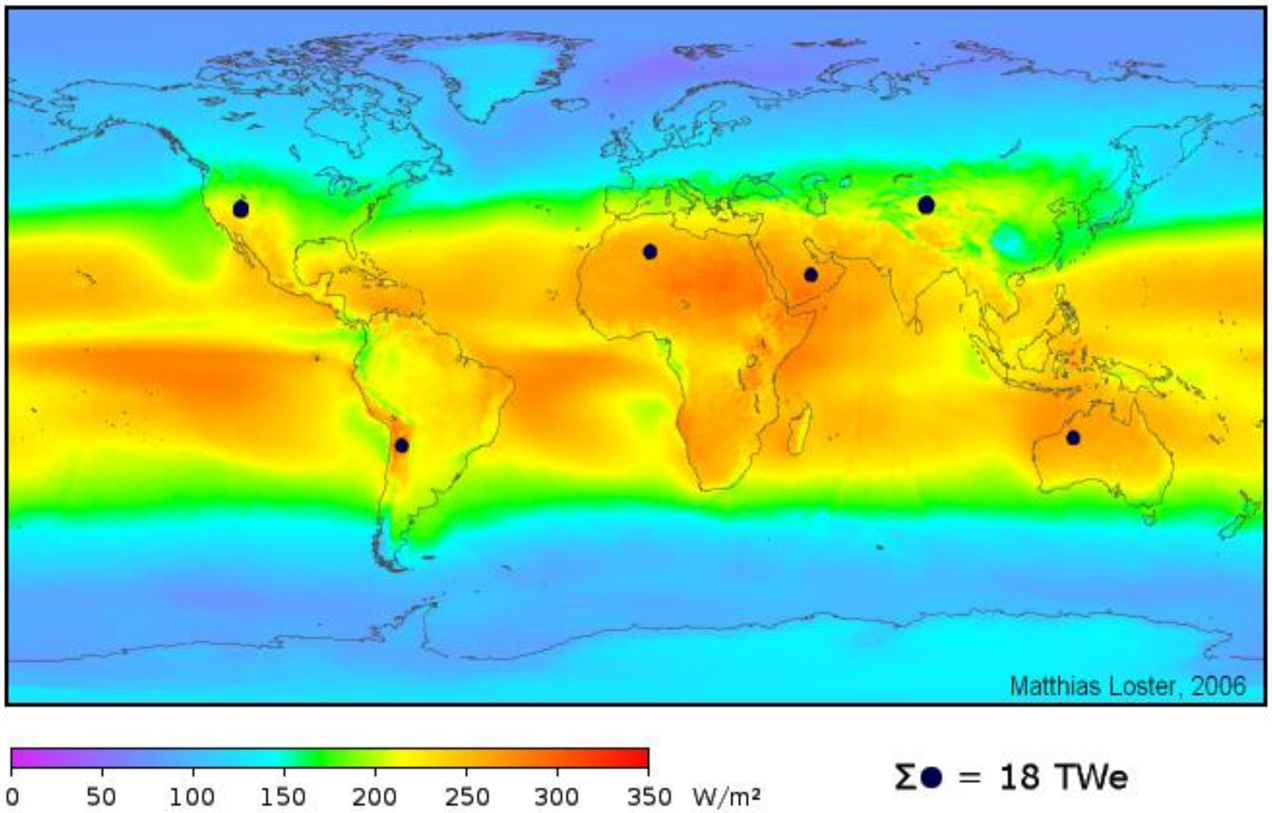


$$\Delta = 2(R_{\max} - R_{\min})/d$$



$$I_0(d_n) = I_0(d)(1 + \Delta \cos 2\pi\, d_n / D)$$

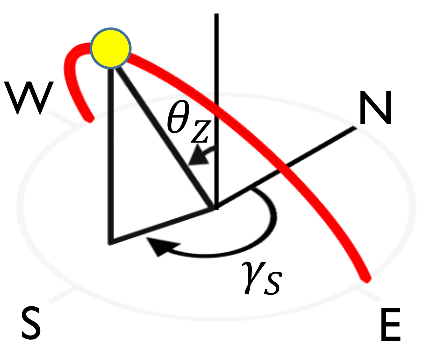
Sunlight depends on latitude

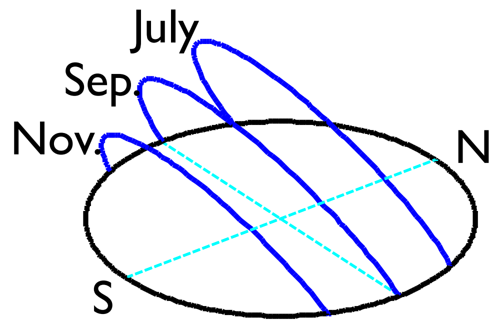


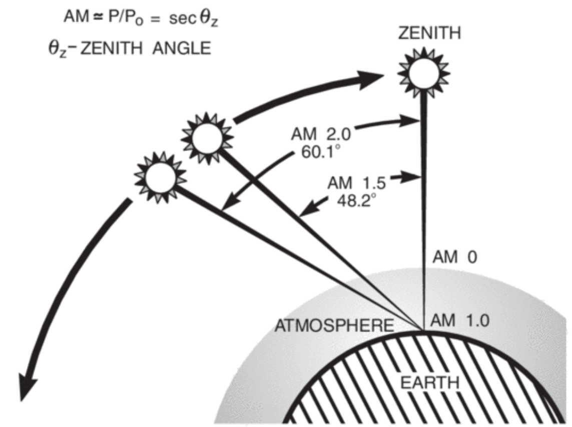
http://www.ez2c.de/ml/solar_land_area/

Solar intensity changes with day, season, and latitudes

Direct normal irradiance (DNI)







$$I_{DNI} = I_0(d_n)T(\theta_Z(t))$$

$$T\big(\theta_Z(t)\big) = c_1\tau^{AM(t)^{c_2}}$$

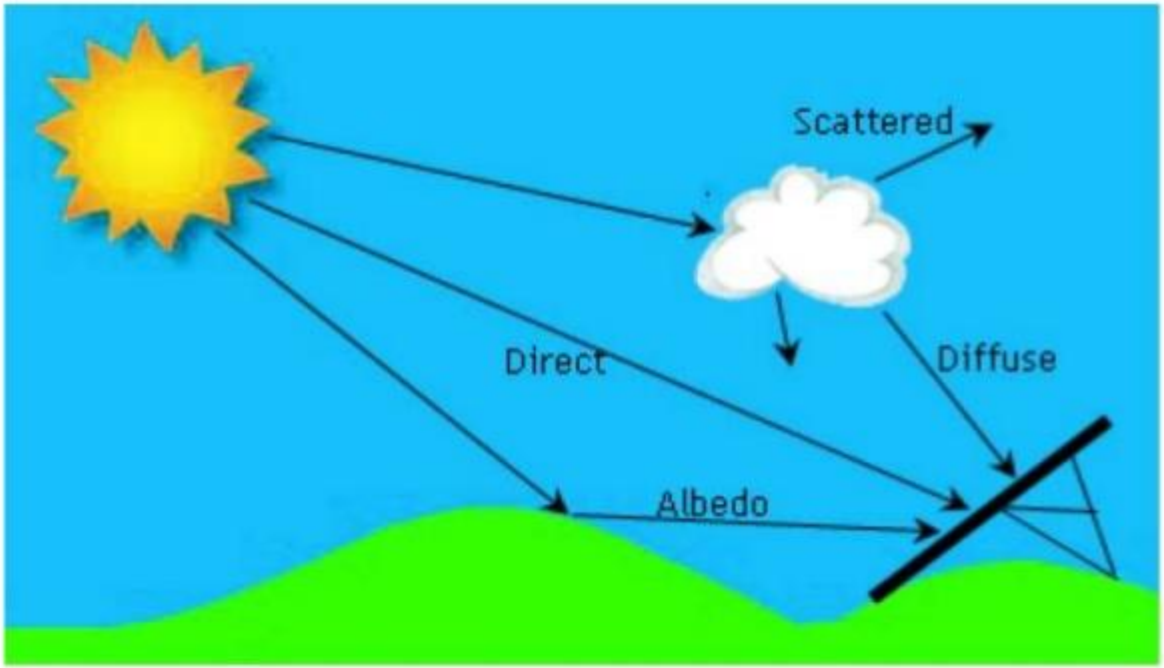
$$\tau \equiv 1 - \alpha$$

$$c_1 \sim 1, \qquad c_2 \sim 0.67$$

$$AM(t) = 1/\cos(\theta_Z(t))$$

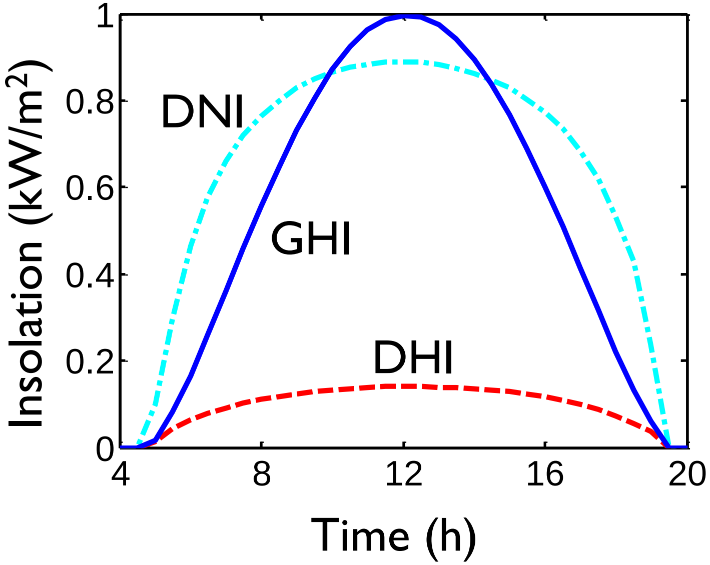
Direct and diffused light

Diffused horizontal irradiance
Global horizontal irradiance

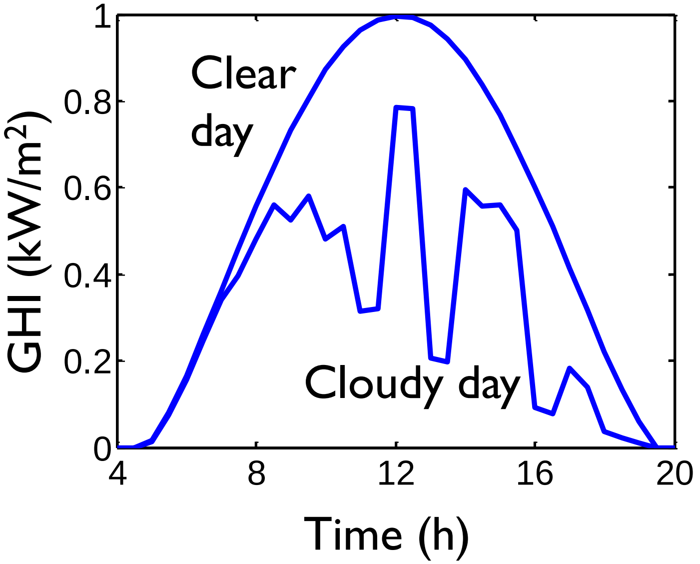


$$I_{GNI} = I_{DNI}\cos(\theta_Z) + I_{DHI} \qquad k_t = I_{GHI}/I_0\cos(\theta_z)$$

PV intensity is easily determined



(a)



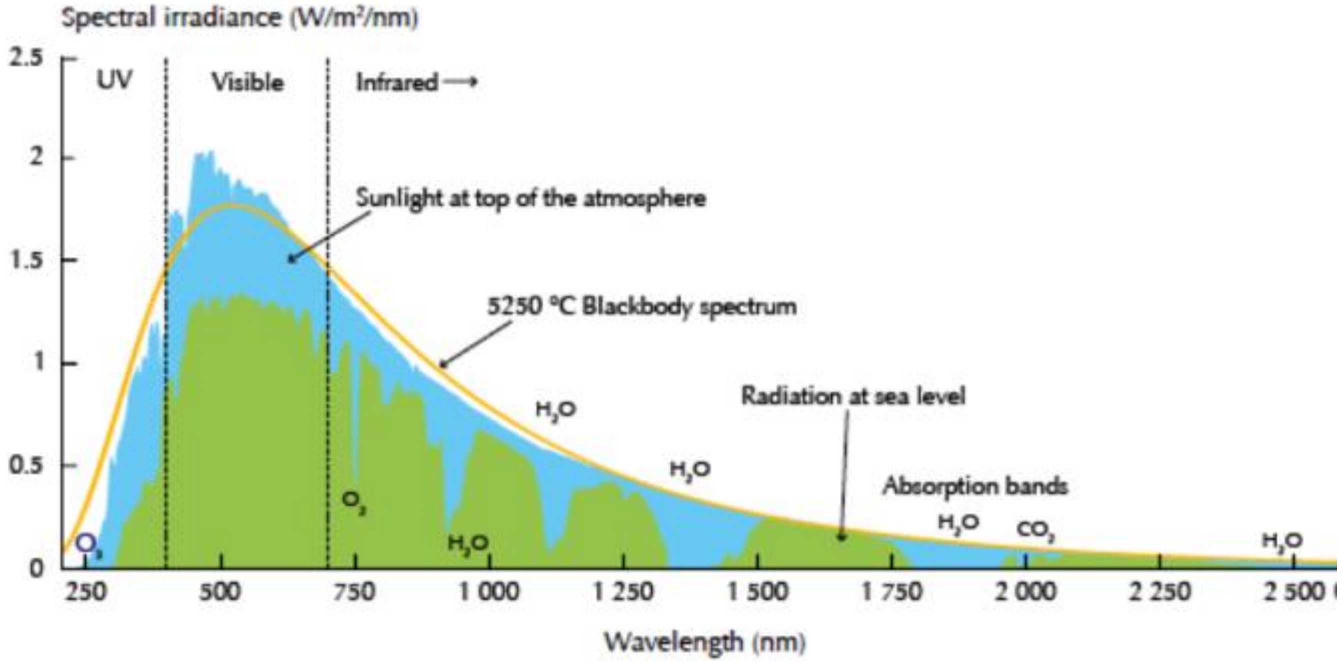
(b)

Washington DC (June 15, 2014, clear; June 19, 2014 cloudy)

Atmosphere and solar spectrum

$$F_{BB} = \frac{E^2}{4\pi^2\hbar^2c^2}\frac{1}{e^{E/(k_BT_s)}-1}$$

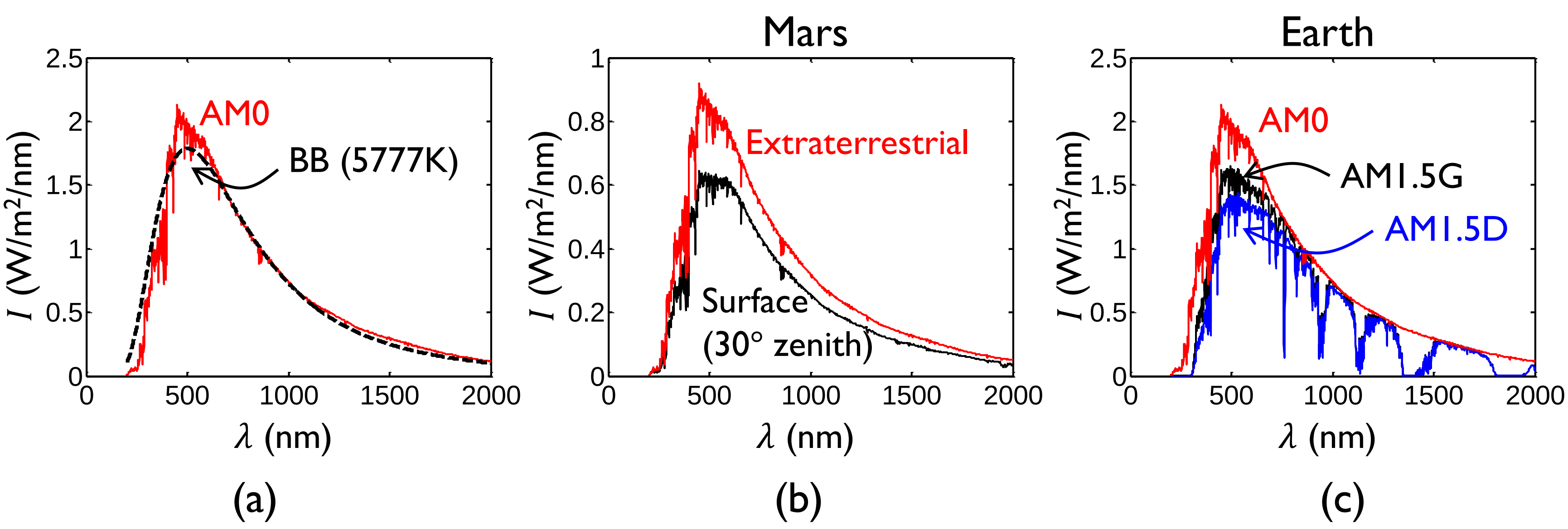
$$E_{peak} \sim 2.8\, k_B\, T_s$$
$$E_{avg} \sim 2.7\, k_B\, T_s$$



Standard olar spectrum and air-mass (AM)

$$F_{BB} = \frac{E^2}{4\pi^2\hbar^2c^2}\frac{1}{e^{E/(k_B T_s)}-1}$$

$$E_{peak} \sim 2.8\, k_B\, T_s$$
$$E_{avg} \sim 2.7\, k_B\, T_s$$



Global (G) includes diffused light, but direct (D) does not.

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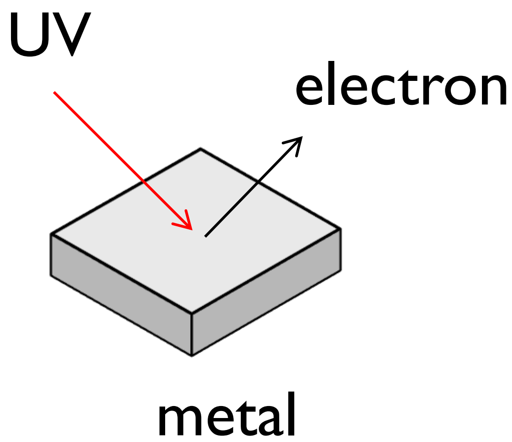
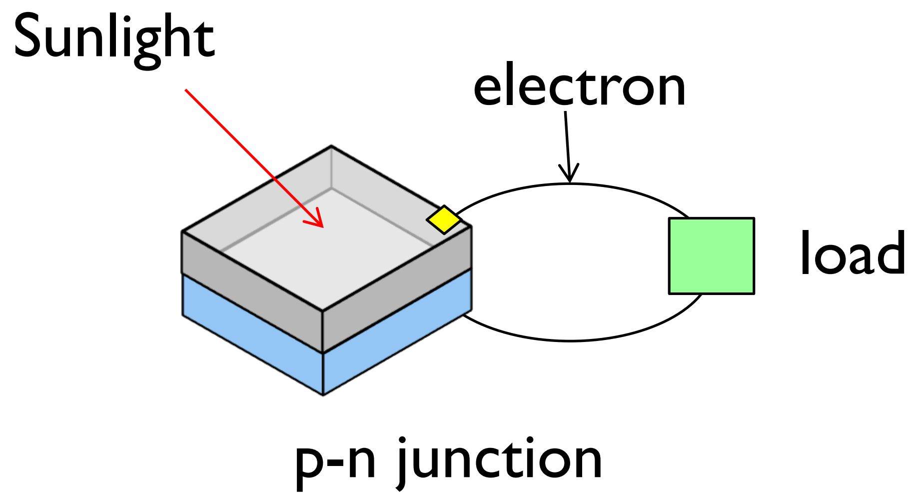
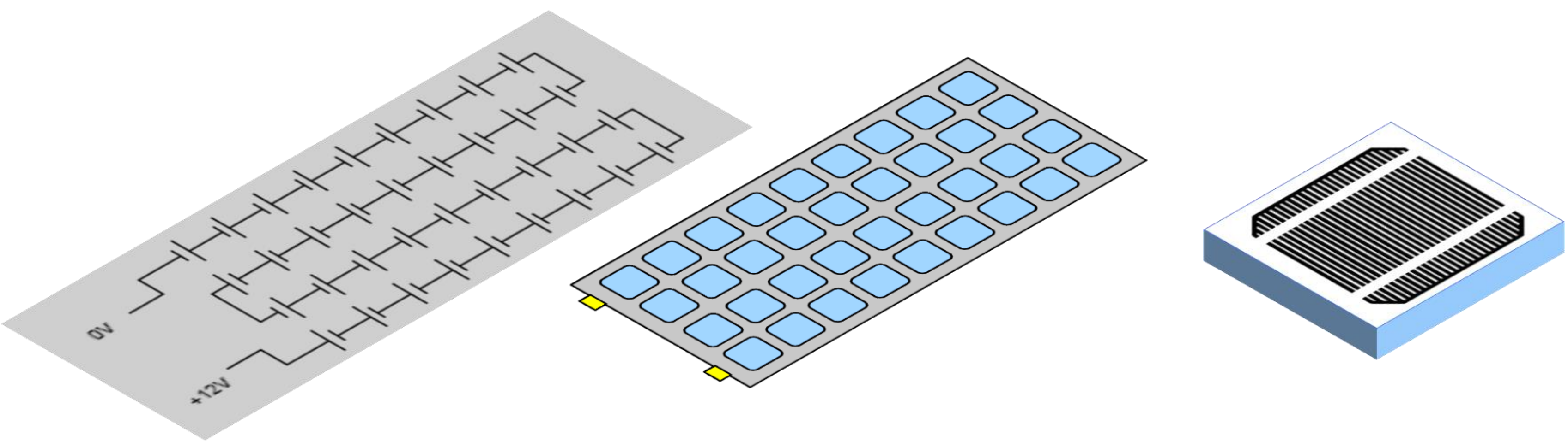
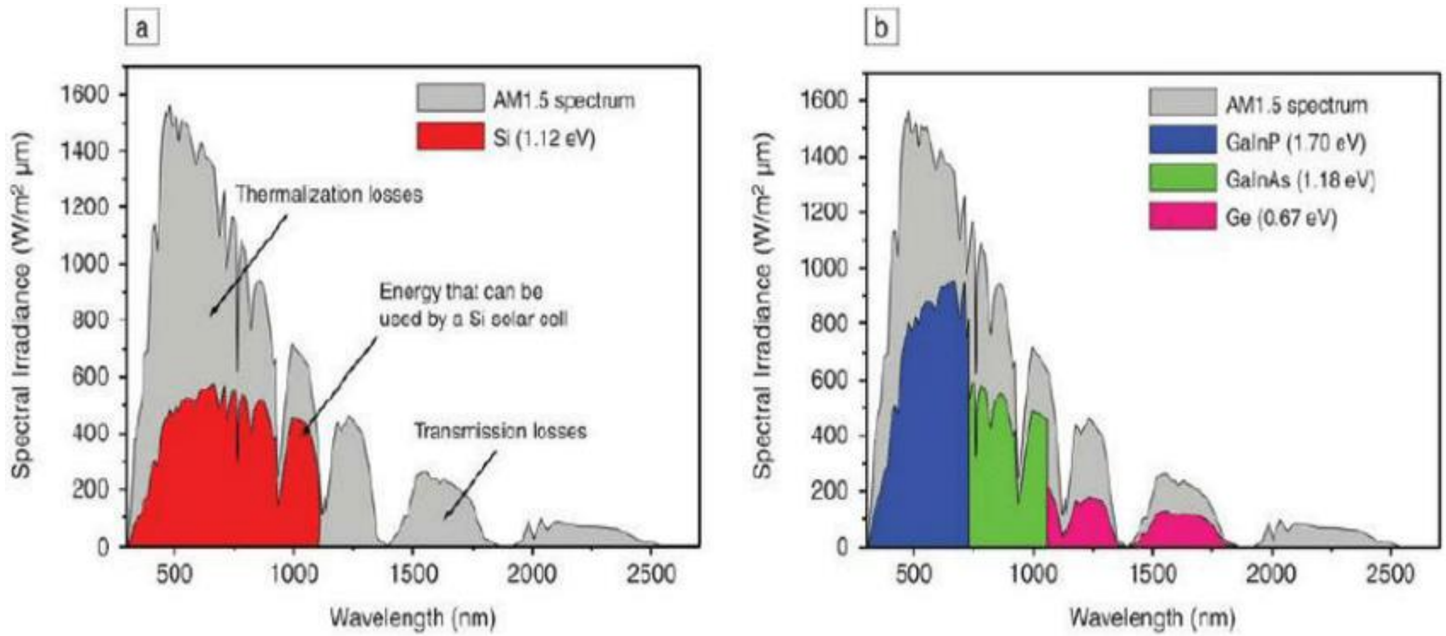
Photoelectric effect and solar cells

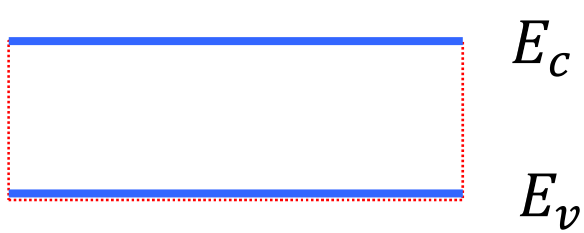






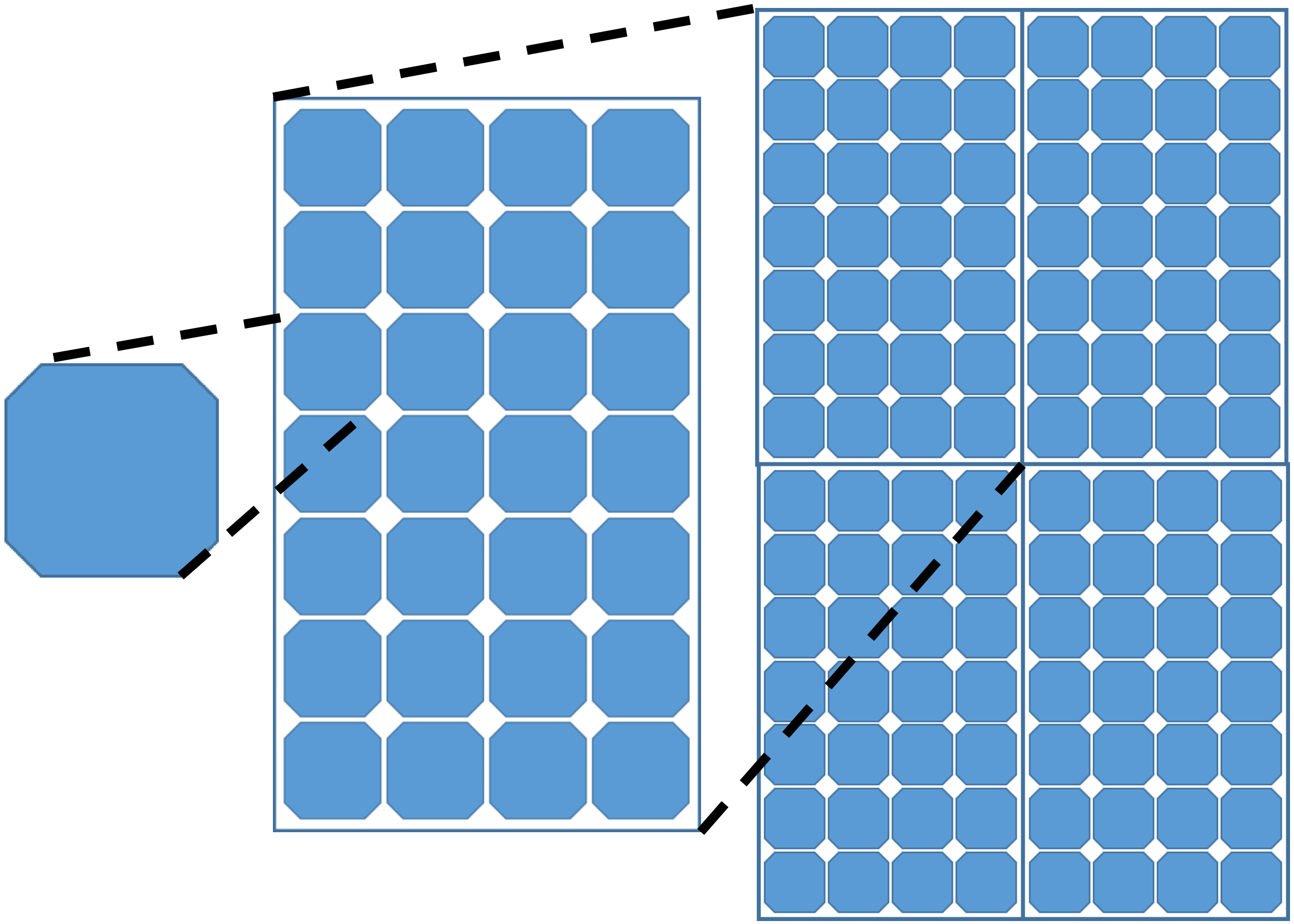
Why PV spectrum matters



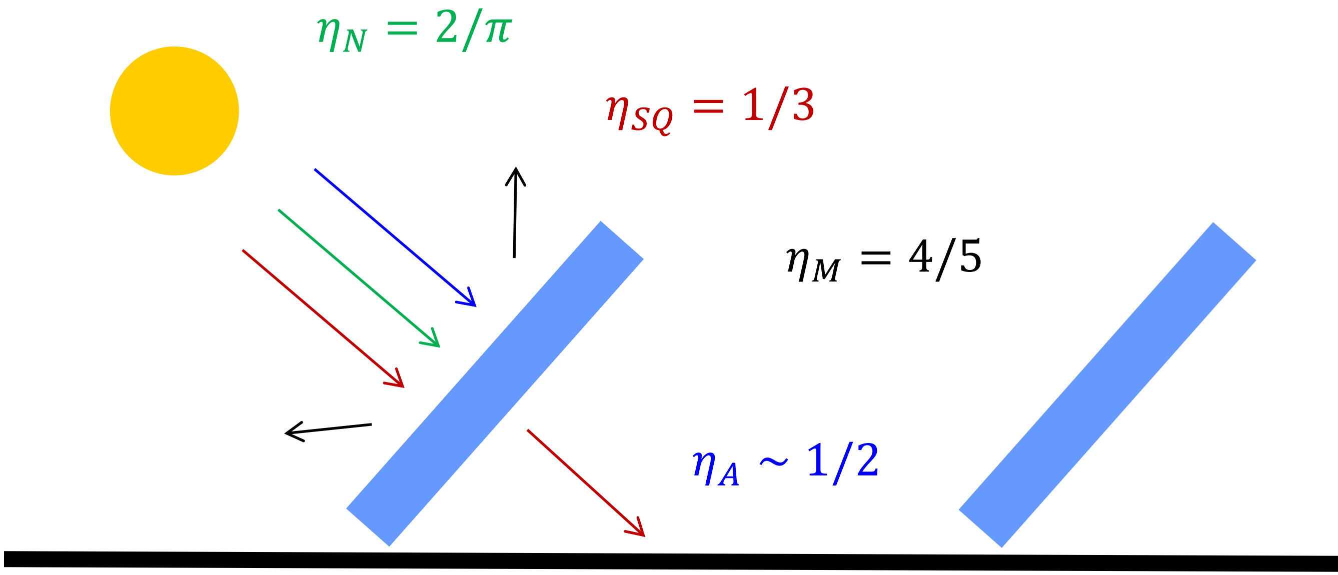


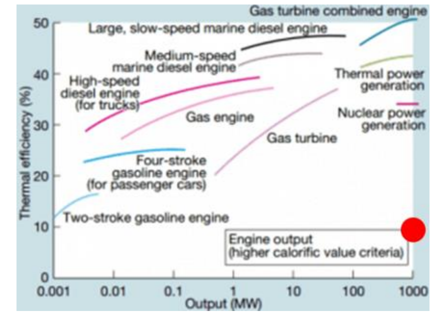
Only 33% efficient

Lost in cell-to-module transition



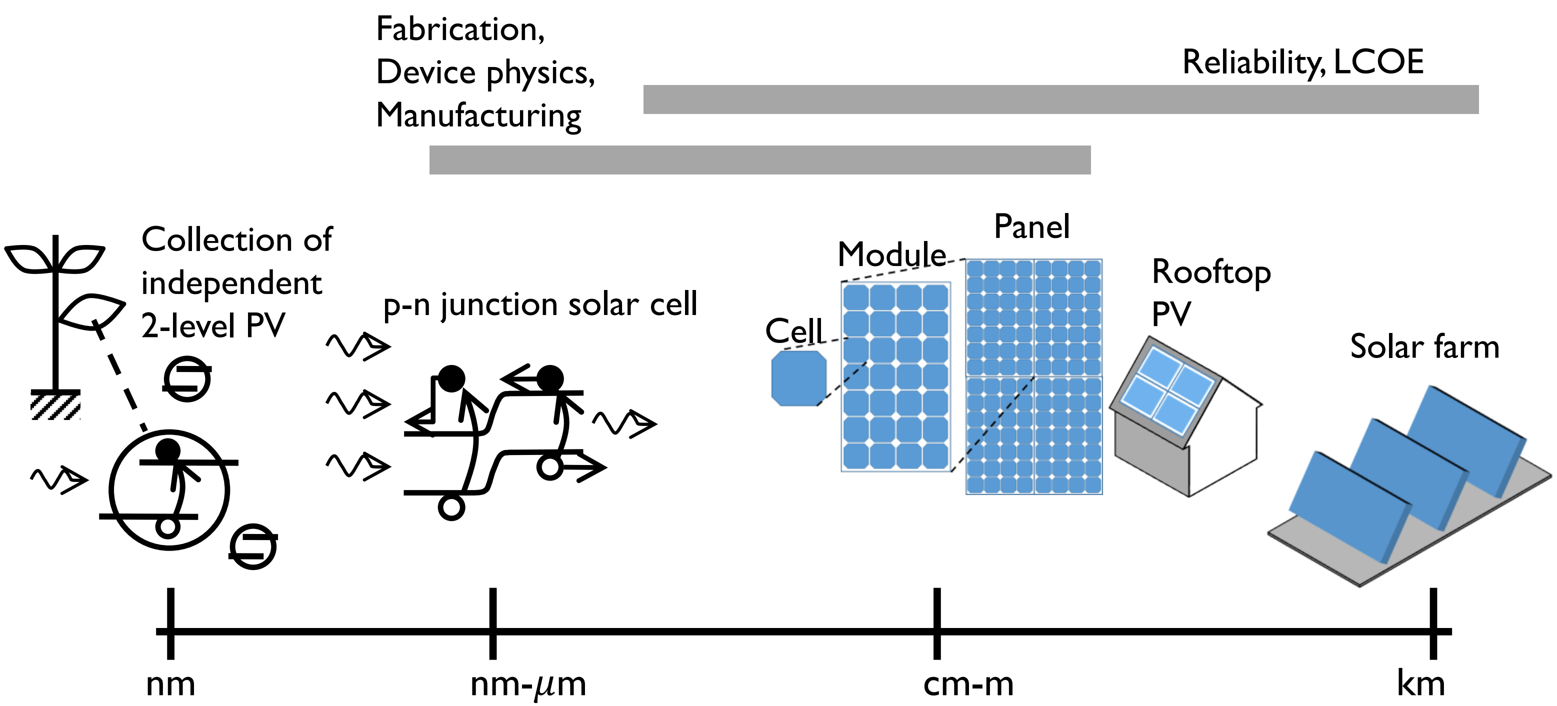
An Inefficient Machine!



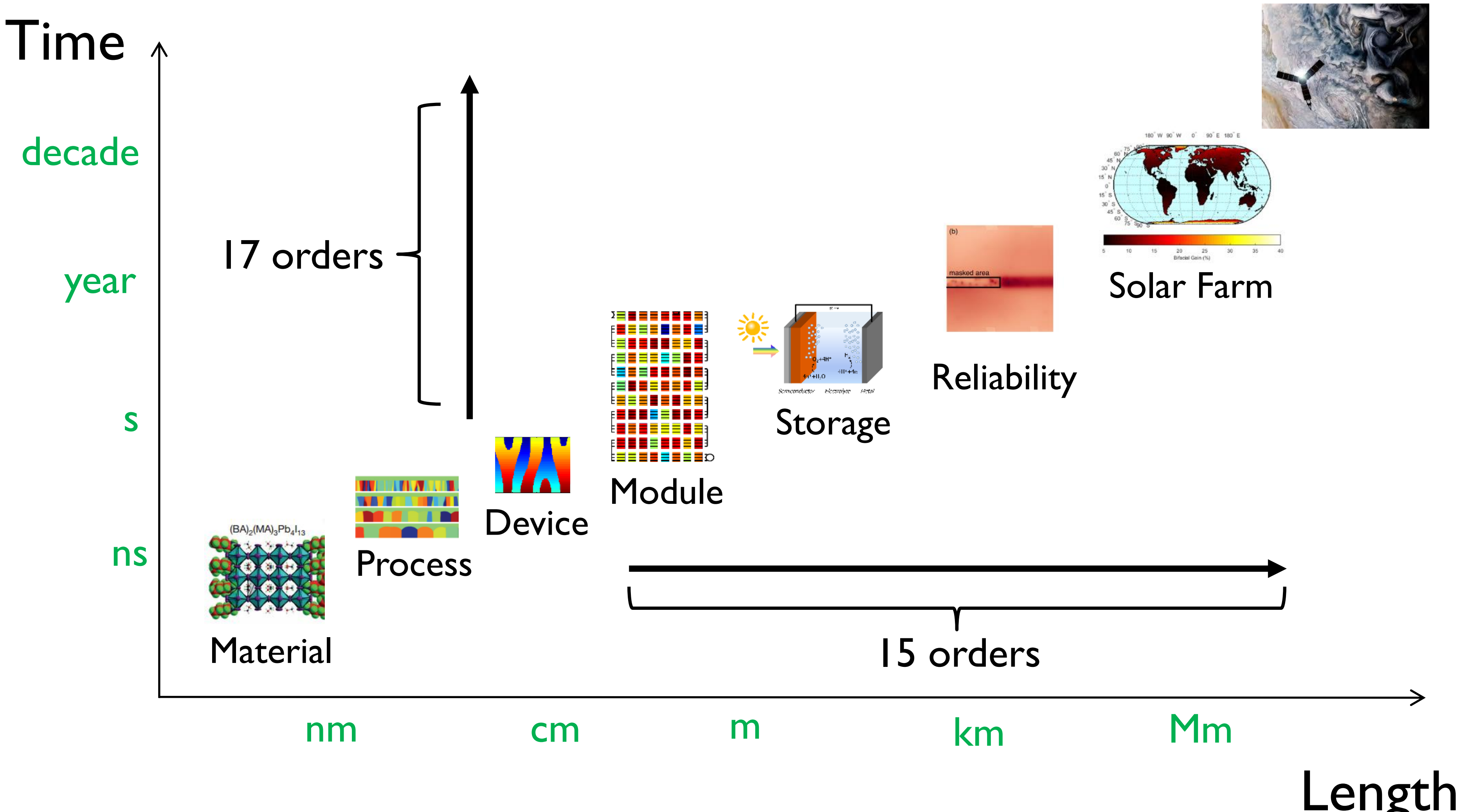


$$\eta = \eta_N \times \eta_{SQ} \times \eta_M \times \eta_A = \frac{2}{\pi} \times \frac{1}{3} \times \frac{5}{6} \times \frac{1}{2} \sim \frac{1}{10}$$

Course outline: A multiscale problem



A magnificent multiscale problem: Atom-to-farm perspective



An atom-to-system approach for PV research.

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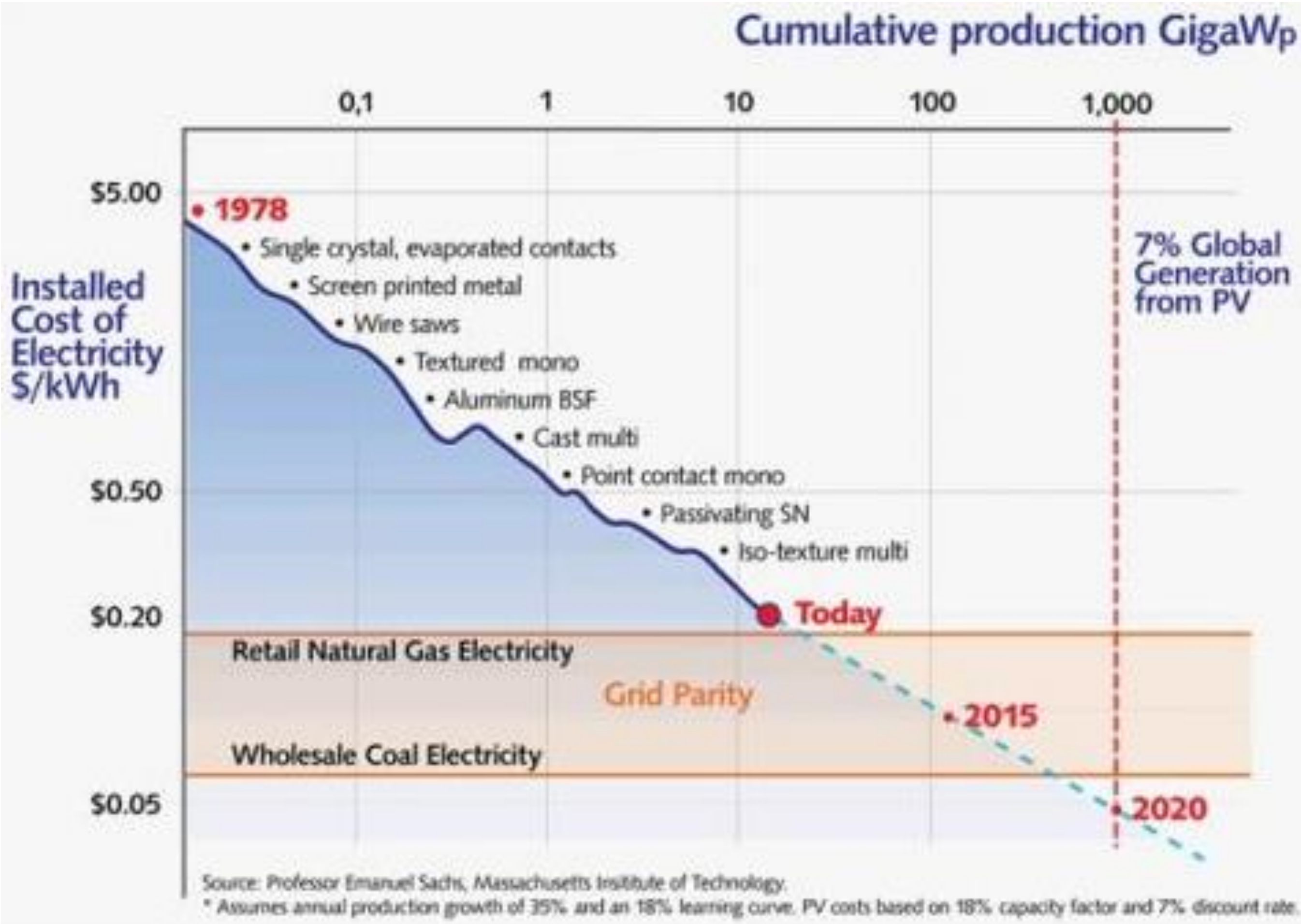
Solar energy is not free

$$\text{LCOE} = \frac{\text{Cost}}{\text{Energy produced}}$$

Cost = cost of converter + maintenance + interest

Energy produced = Insolation x efficiency x lifetime

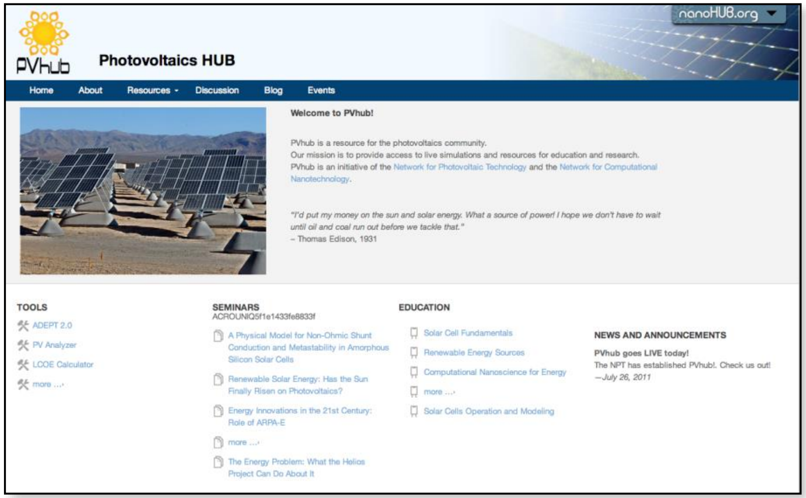
… with drop cost of energy produced

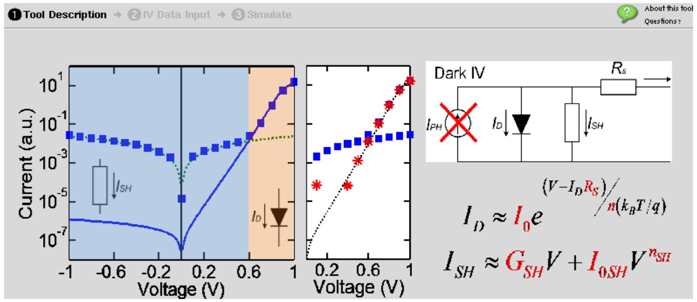


Acwa Power
5.84 cents!

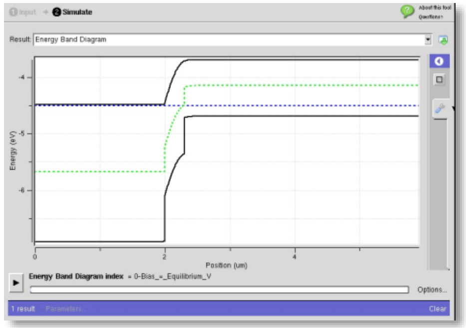
Taqnia
5 cents!

Resources (http://nanohub.org/groups/pv)

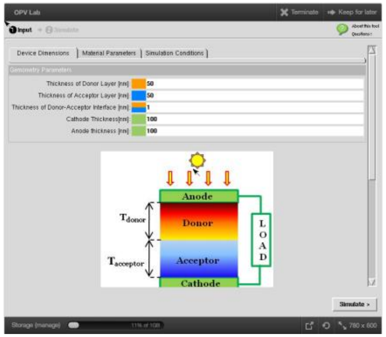




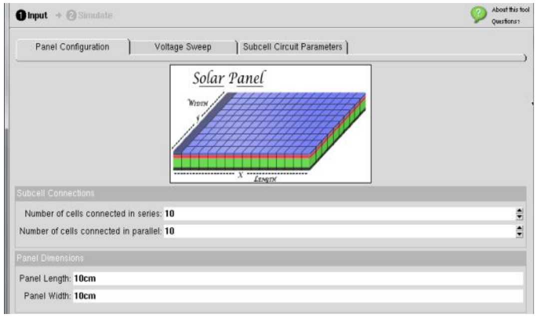
PV Analyzer



ADEPT 1D



OPV Lab



PV Panel Sim

Conclusions

- Photovoltaics is an important source of renewable energy
- The combination of sun, earth, PV technology, and financing determine the trajectory of the industry.
- The spectacular drop in cost has fueled the growth of the PV industry.
- Our goal is the end-to-end understanding of PV technology.

Self-test questions

What is the peak and average energy of the solar spectrum? What is the energy flux density on the surface of the sun?

What fraction of the sky (in solid angles) does the sun cover?

What wavelengths of light are absorbed by atomospheric oxygen?

What is the difference between AM0 vs. extraterrestrial spectrum?

Calculate the DNI intensity on June 15 for at time when the Azimuth angle is 50 degrees?