Lecture # 12

Solar Photovoltaics

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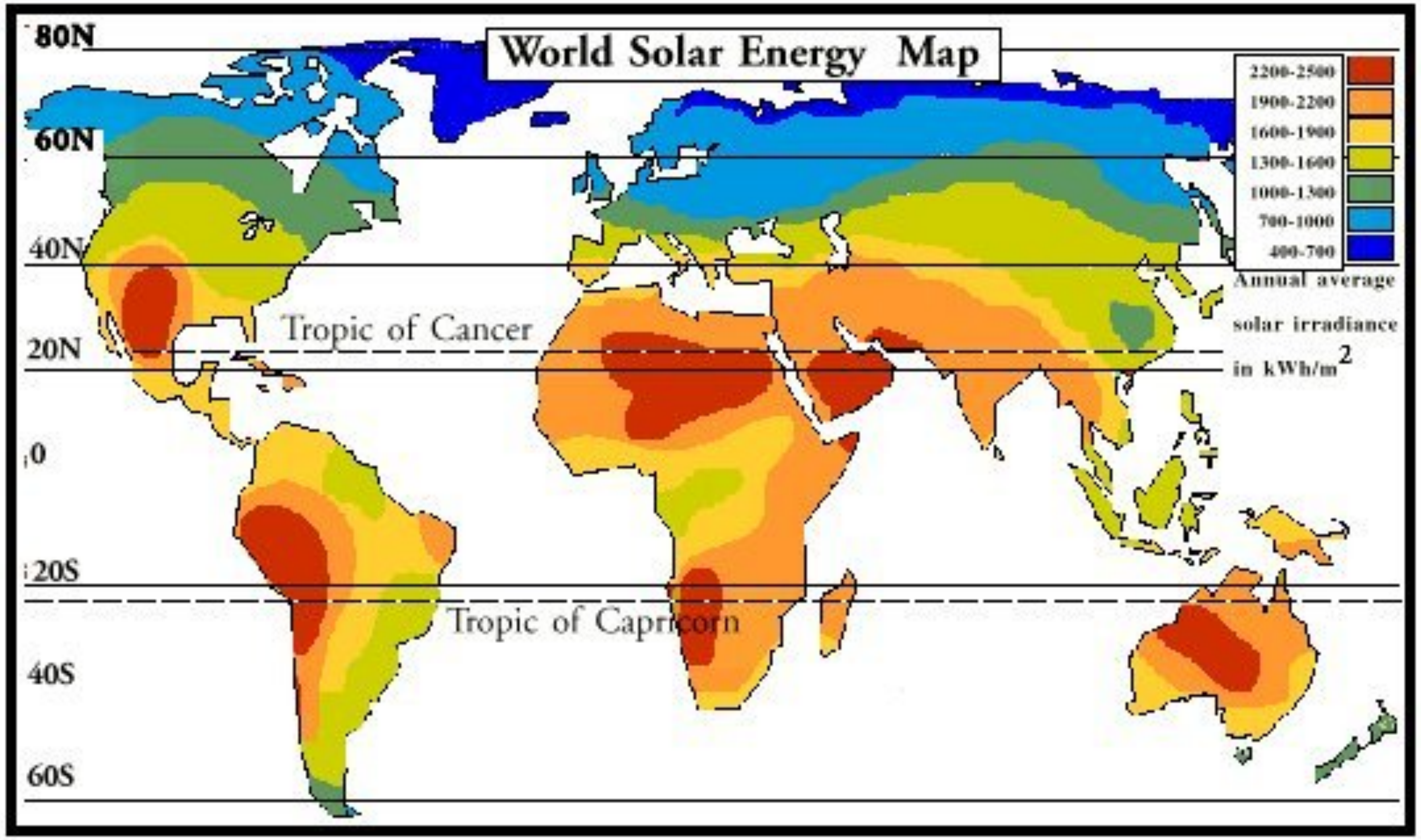
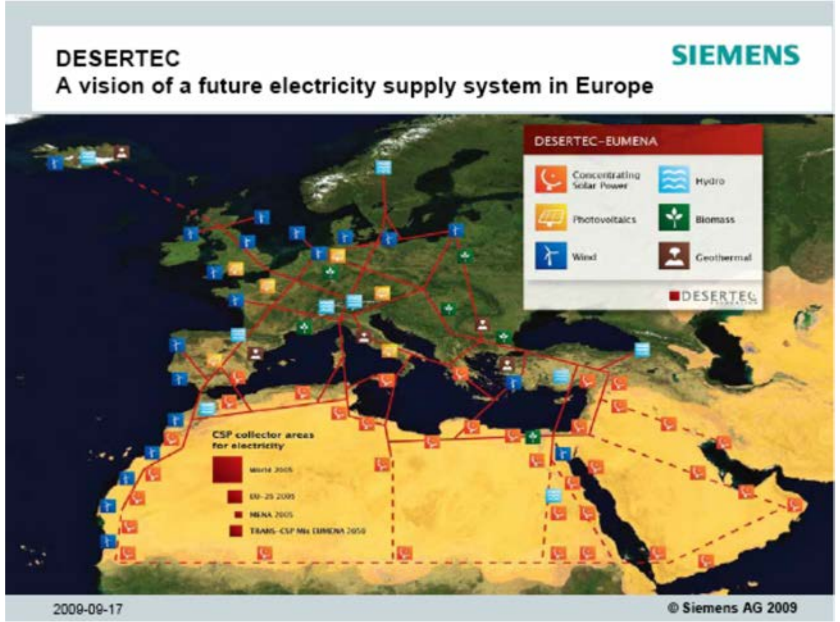
March 11, 2020

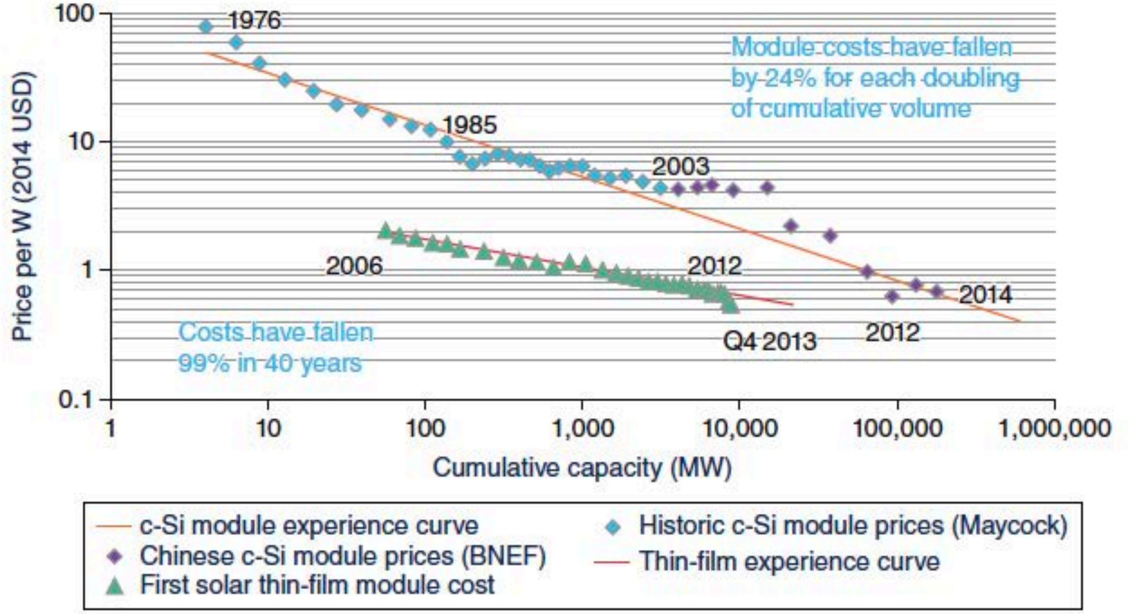
Solar resources, potential, progress, pricing ..
Semiconductor physics, p-n junction, bandgap, efficiency ..
Solar panels, fabrication, variety, farms, systems ….

Solar Energy is "Everywhere".
Opportunities vary.
Distribution networks may look different

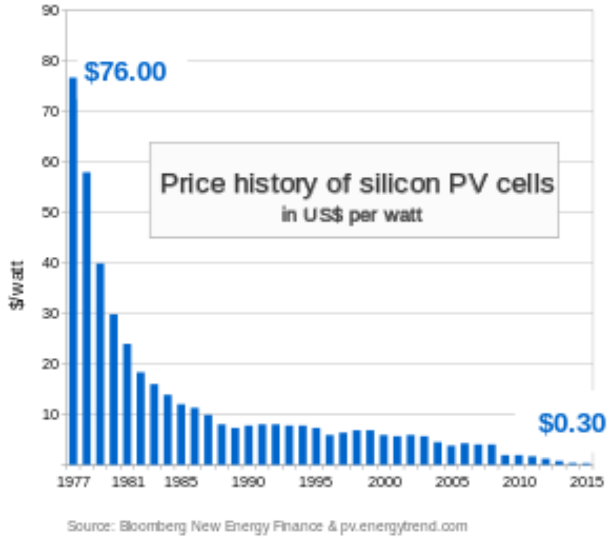


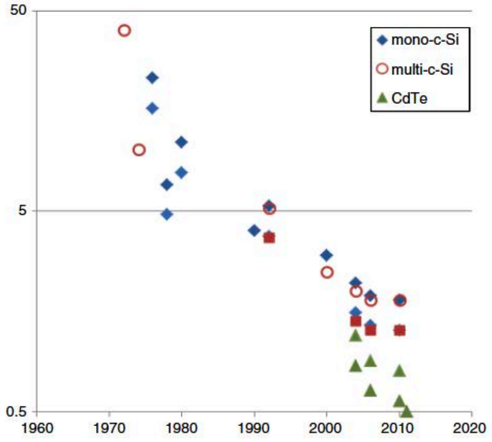


c-Si dominates the market (cheaper and mostly more efficient)

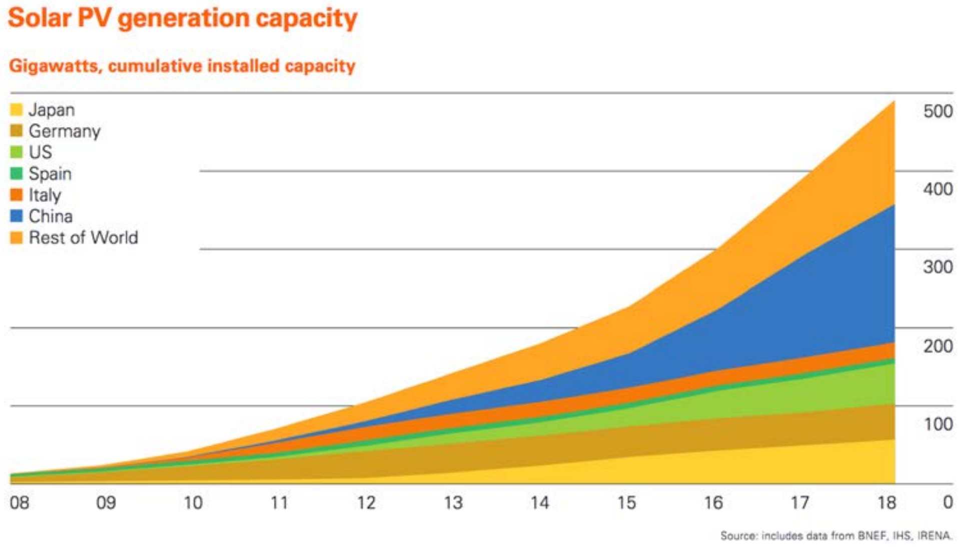


Photovoltaic Solar Energy, Reinder et al, Ed., Wiley, 217

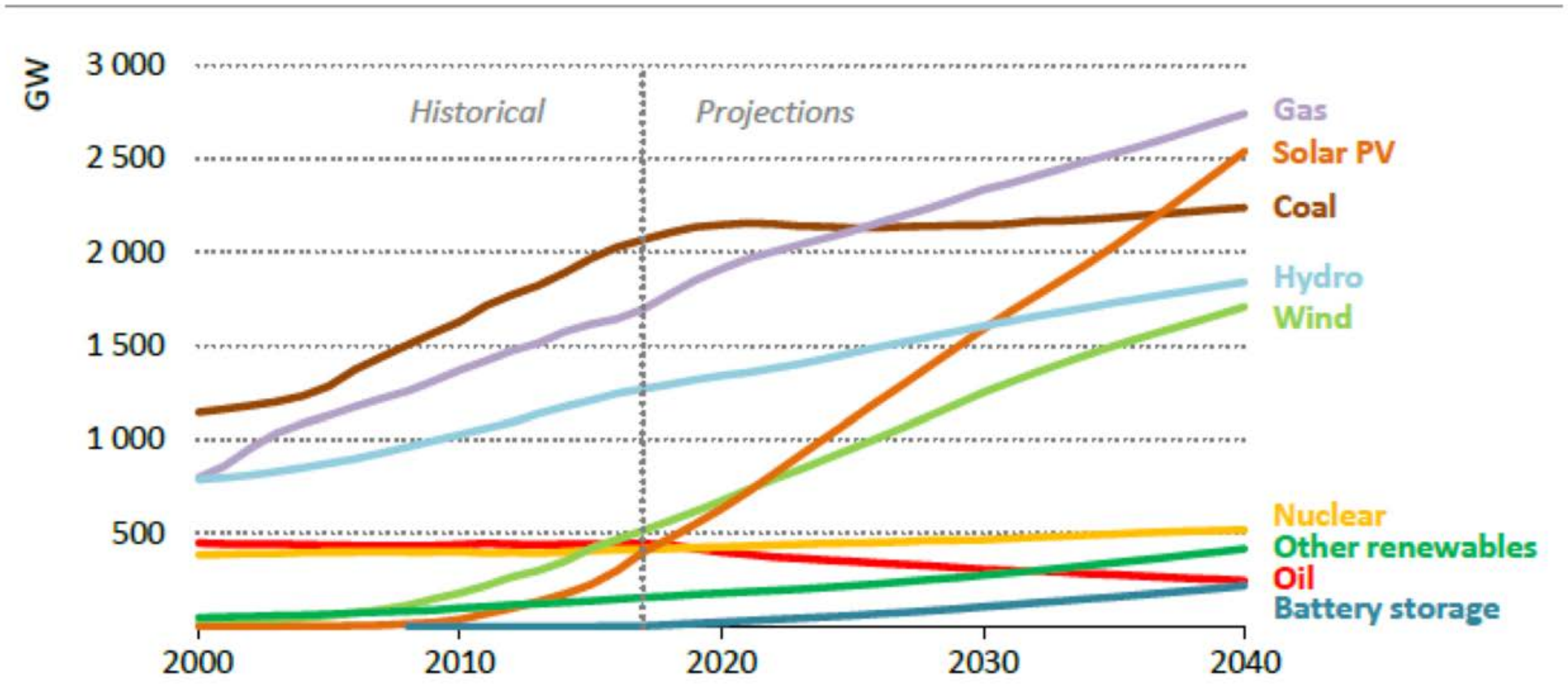




Energy payback period for different PV technologies, low numbers are for insolation of 2,400 kWh/m^2/y, high are for 1,700 kWh/m^2/y



Installed power generation capacity worldwide by source and prediction in the new policies scenario

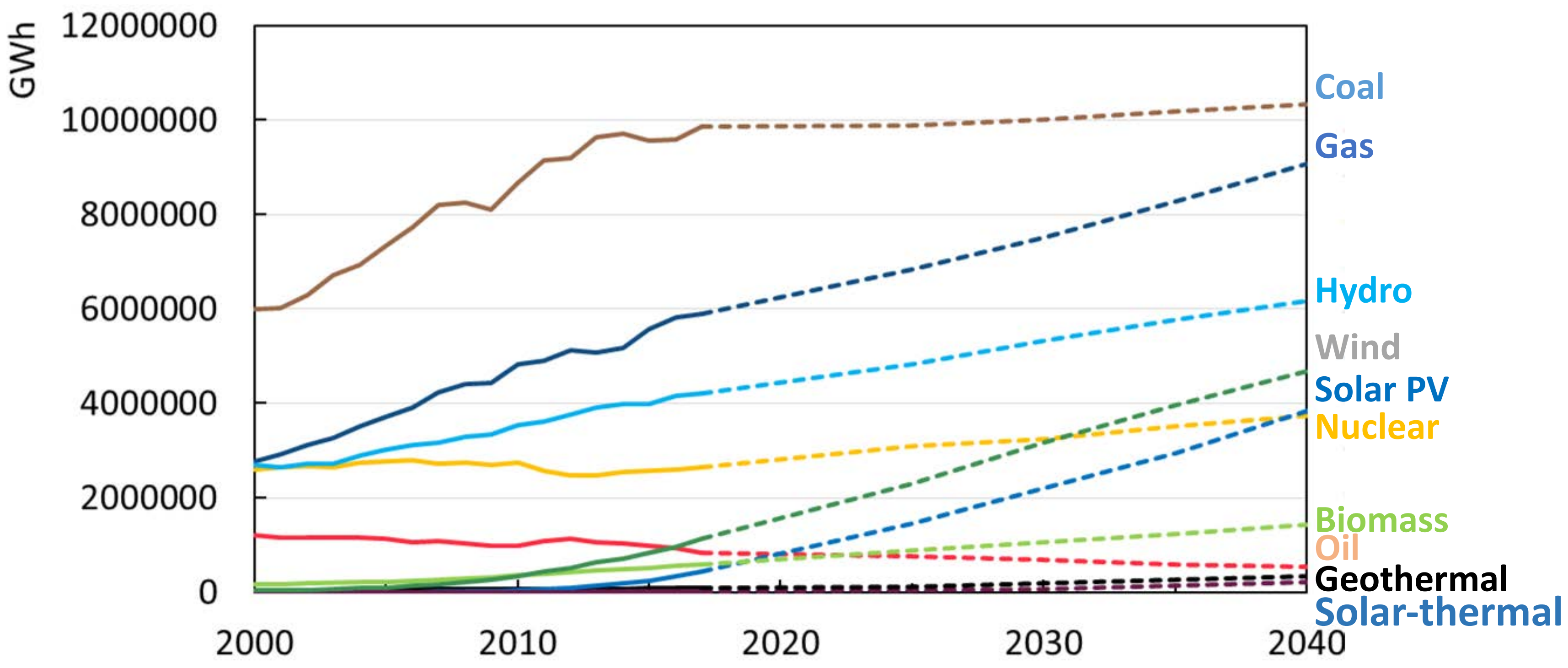


With more than 180 GW under construction, coal fuels the most capacity until the mid-2020s when natural gas overtakes it, and renewables are on the rise

Source: IEA world energy outlook 2018, P344

World electricity production by source

only electricity generated is accounted, no matter what source is from



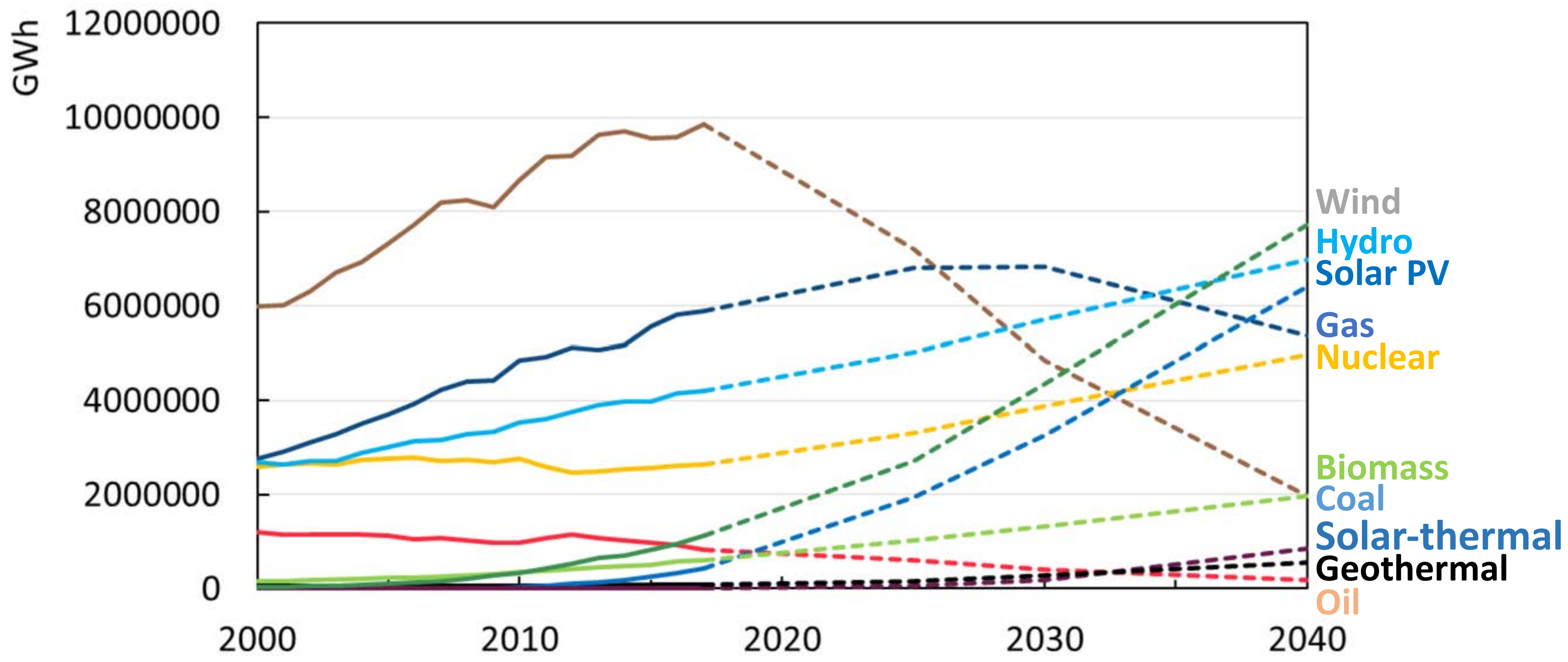
The dotted line is the prediction based on new policies to be implemented

Source: historic data from IEA website (up to 2017)

prediction data from IEA world energy outlook 2018, P528

World electricity production by source

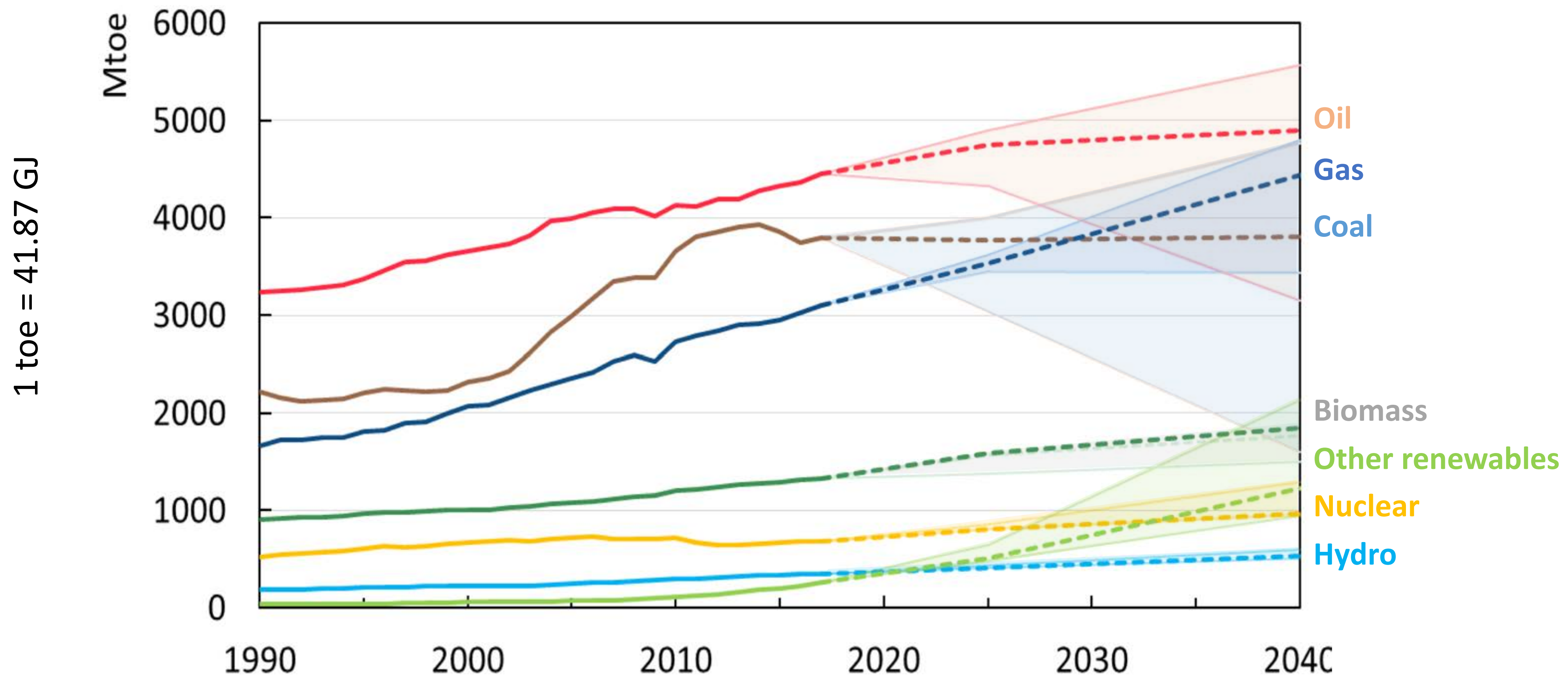
only electricity generated is accounted, no matter what source is from



The dotted line is the prediction based on sustainable development goals

Source: historic data from IEA website (up to 2017)
prediction data from IEA world energy outlook 2018, P529

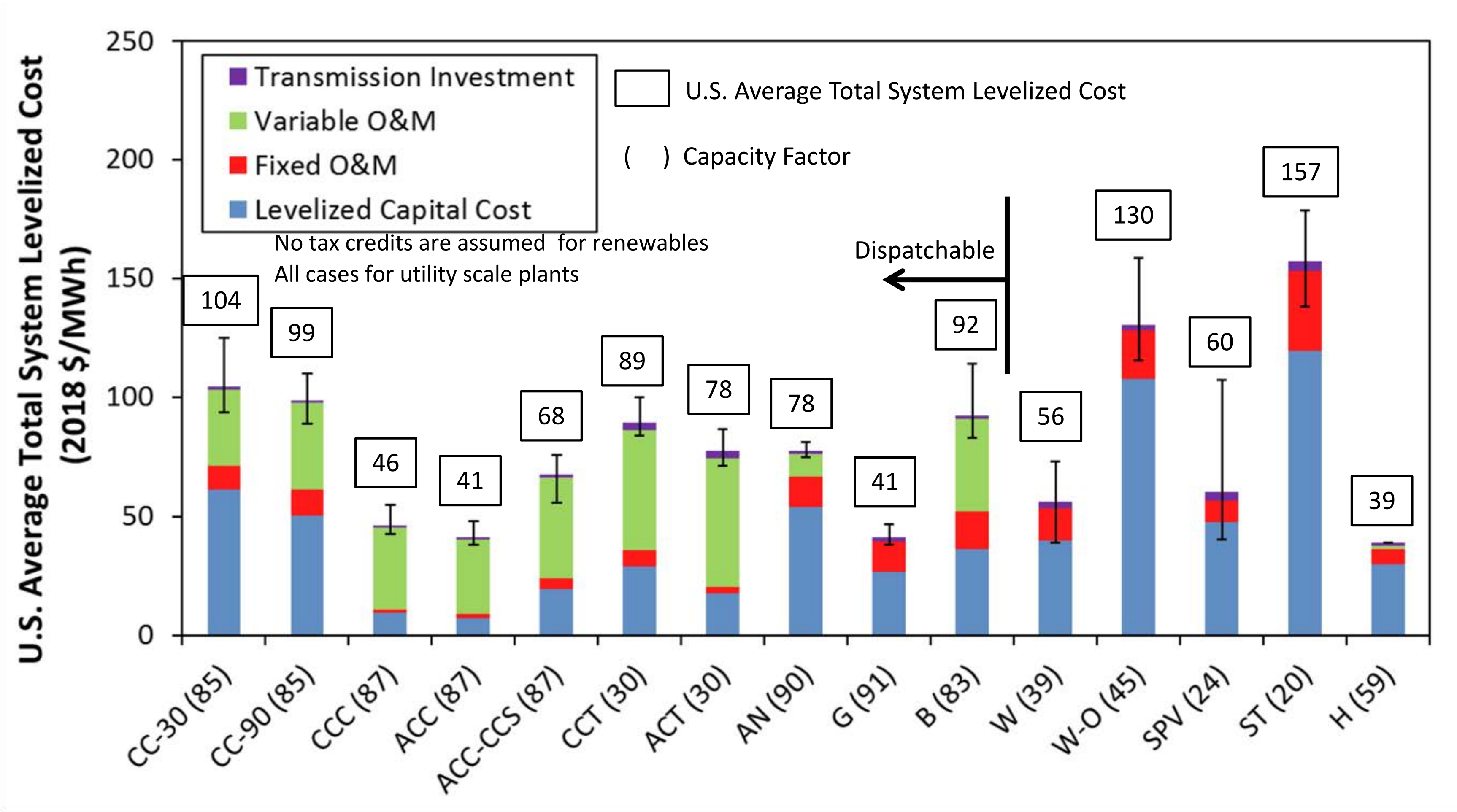
World primary energy supply by fuel/source*



The dotted line is the prediction based on new policies to be implemented. The shaded areas show the possible scenarios between current policies and sustainable development. Source: IEA world energy outlook 2018, P38

* When it comes to electricity from non-combustible sources, the IEA, in line with IRES, adopts a coherent principle across sources – the "physical content method" – by measuring the primary energy equivalent at the first point downstream in the production process for which multiple energy uses are practical. This means that hydro, wind and solar become "energy products" in the statistical sense at the point of generation of electricity, and that their "primary energy equivalent" is computed as the electricity generated in the plant, while the kinetic energy of the wind or the water does not enter the "energy balance", although being "energy" in a scientific sense.

Estimated (in 2019) Levelized Cost of Electricity Generation Plants in 2023



CC-30: Coal with 30% CCS
CC-90: Coal with 90% CCS
CCC: Conventional Combined Cycle
ACC: Advanced Combined Cycle
ACC-CCS: Advanced CC with CCS

CCT: Conventional Combustion Turbine
ACT: Advanced Combustion Turbine
AN: Advanced Nuclear
G: Geothermal
B: Biomass

W: Wind – Onshore
W-O: Wind – Offshore
SPV: Solar PV
ST: Solar Thermal
H: Hydroelectric

Image courtesy of U.S. Energy Information Administration (EIA).

Source: U.S. Energy Information Administration, Annual Energy Outlook 2019, Feb 2019.

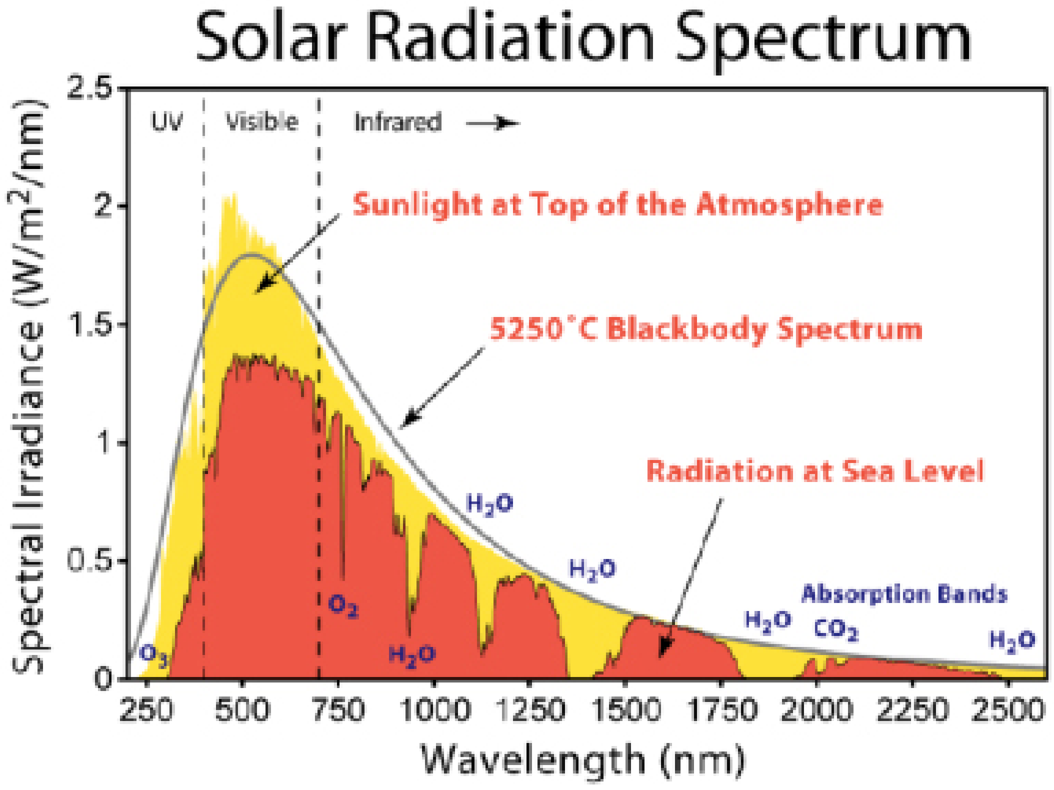
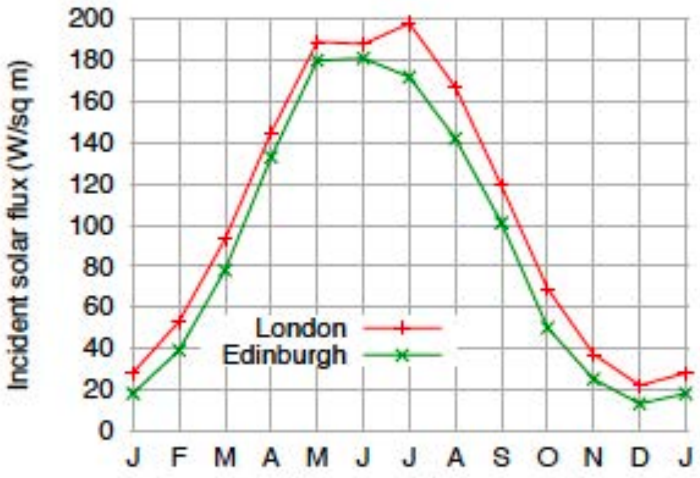
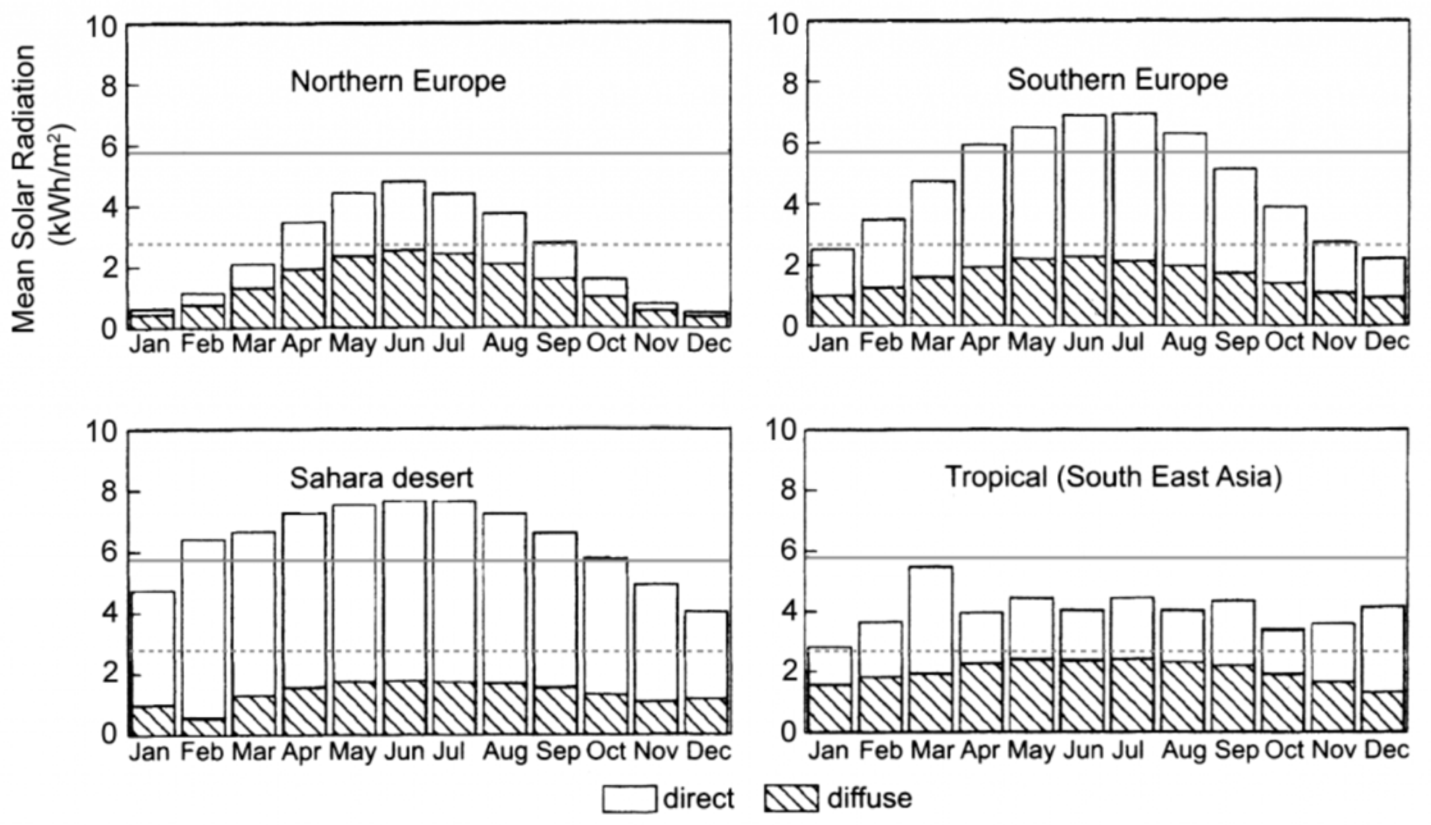


Figure 3: The solar spectrum above the atmosphere and at sea level

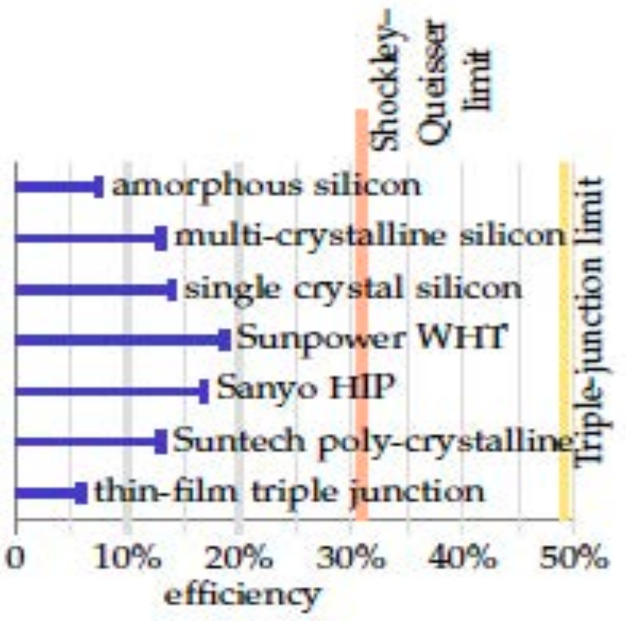
- Extra-terrestrial total irradiance (insolation: incident solar radiation) ~ 1367 W/m^2
- Irradiance at Earth's surface is made of beam (direct) and diffuse components
- Total terrestrial irradiance depends on location (north, south ..), hours/days of sun, cloud coverage, etc. When averaged over one day:
  - Clear ~ 590 - 1000 W/m^2
  - Cloudy days ~ 120 W/m^2
  - Average ~ 300 W/m^2 (strong function of location)



In London, solar intensity, average over the year is ~ 100 W/m^2
MacKay

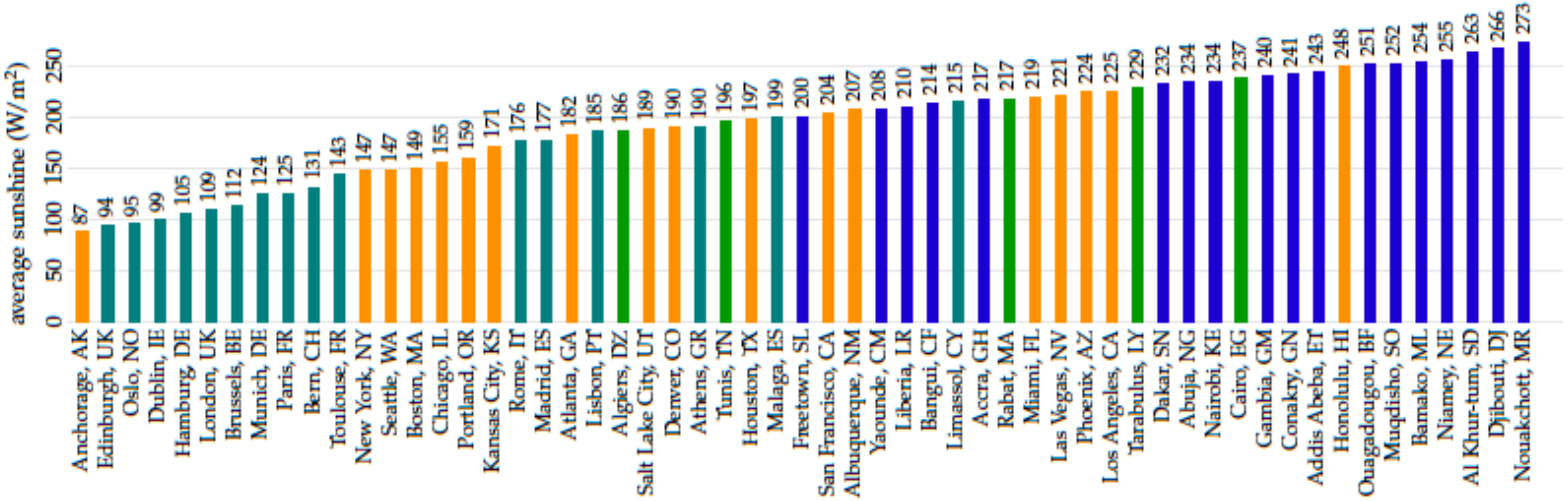


The yearly variation of the mean total daily solar radiation (total per day) for different locations, the dashed lines is at 2.88 kWh/m^2.day and solid line is at 5.75 kWh/m^2.day, showing both direct and diffuse radiation. Location affects number of hours/day of sun, solar angle, weather conditions, ..



With an average solar power of 100 W/m^2, and PV efficiency of 15%, electric power production is 15 W/m^2 (much higher than sun-to-biomass-to electricity, which would be less than 1 W/m^2)

Mackay, Sustainable Energy, Cambridge, 2009



Semiconductors

Photovoltaic Solar Energy, Reinder et al, Ed., Wiley, 217

- Electrons orbit the nucleus at different bands, the outer-most band is typically called the *valence band*.
- It takes energy to move an electron outwards from one band to the next.
- The energy required to pull electrons from the valence band to the *conduction band* is called the ***bandgap***. Electrons in the (electrical or thermal) conduction band are free to move within the semiconductor.

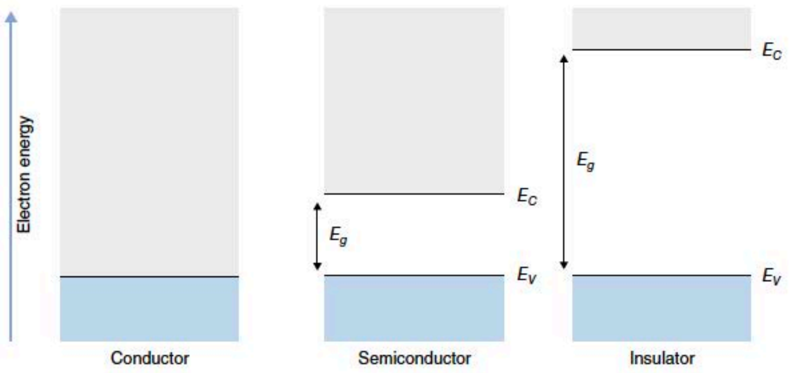


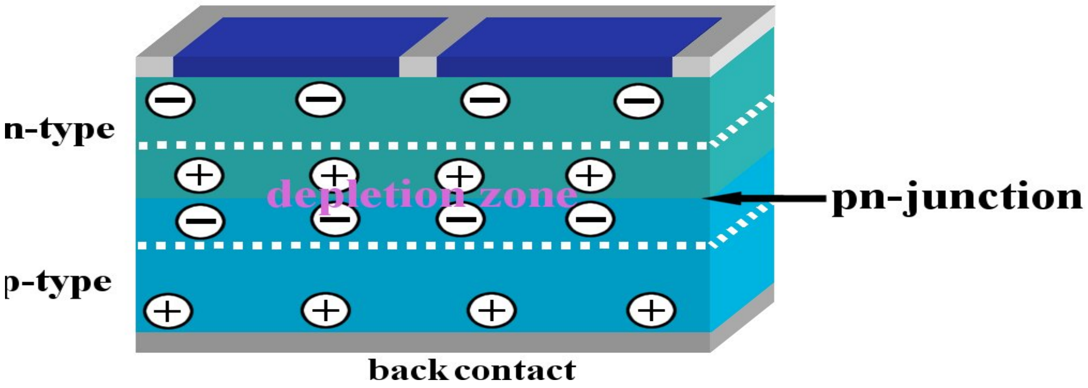
Figure 2.1.3 Energy band diagrams for a conductor, a semiconductor and an insulator

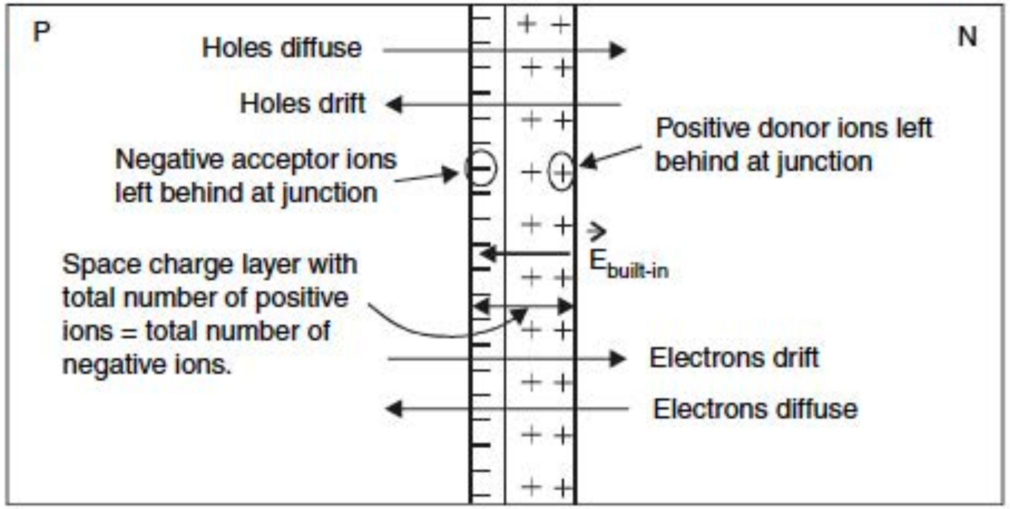
The electron volt [eV] is the energy required to move an electron (charge) across a 1 V potential, eV=1.6 10-19 J

- *Intrinsic semiconductors* have intermediate bandgap values (<3 eV). They have average number of valence electrons (4 in the case of silicon)
- When *doped* with other metal, they can increase or decrease the number of electron in their valence band depending on the dopant.

A p-n junction

- *n-type semiconductors* have more valence electrons than Si (phosphorous has 5).
- *p-type* have less valence electrons than Si (boron has 3).
- At *a p-n junction*, the interface region between the two doped semiconductors, some electrons from the n-side move to the p-side (leaving an electron *hole* behind) hence giving the structure more uniform electron distribution, and creating *charge separation* at the interface (diode effect) and an associated *potential difference*.



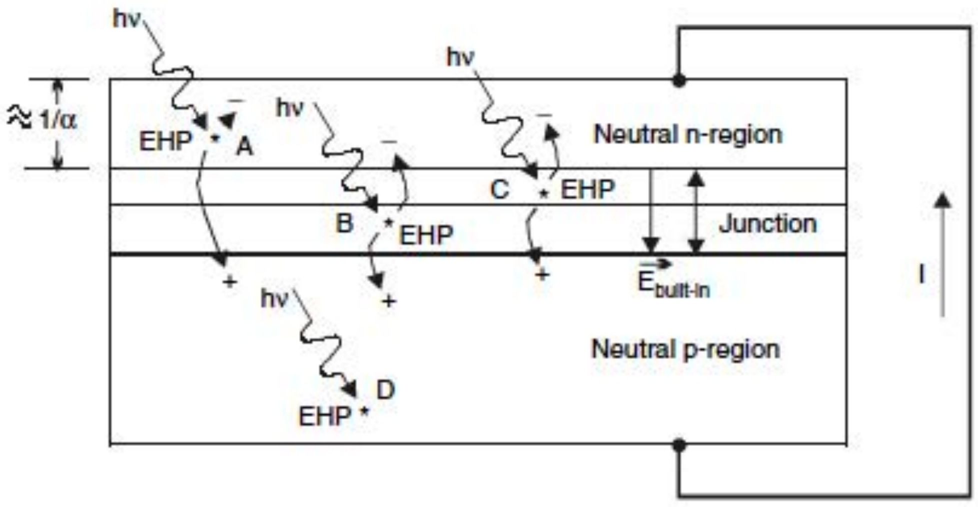


A typical p-n junction showing charge separation by the migration of electrons across the interface

Goswami and Kreith, Energy Conversion, CRC Press, 2008.

An “illuminated” p-n junction

- An electron in the valence band on the n-type side can absorb an *energetic photon (whose energy is > e_{bg})* raising its energy and moving it to the conduction band (where it moves freely) if the photon energy is higher than the *bandgap energy* of the semiconductor.
- In a p-n junction this free electron can leave the semiconductor (if the thickness of the n-type layer is sufficiently small), generating an external current.
- Typical thicknesses of the two layers on the two sides of the junction are microns or less.
- The electron can also move across the junction towards the p-type.



The illuminated p-n junction showing the formation of electron-hole pair by the adsorption of a photon
(EHP: electron-hole pair)

Goswami and Kreith, Energy Conversion, CRC Press, 2008.

The Photoelectric Effect

light is made of photons whose energy is given by:

$$\varepsilon_{ph} = h_{Planck} \nu_{ph} = h_{Planck} C_{light} / \lambda_{ph},$$

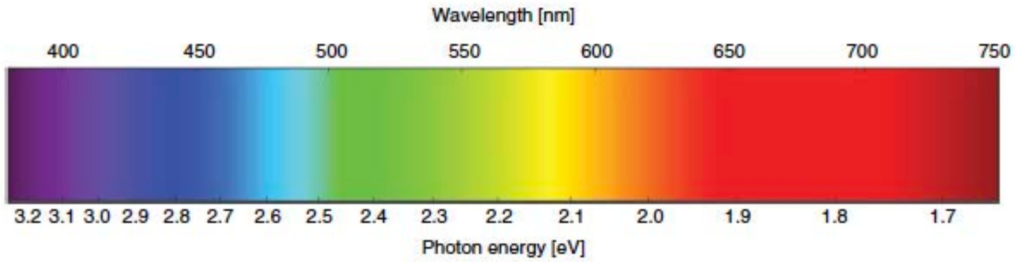
$$h_{Planck} = 6.62\ 10^{-34} \text{ J.s,}$$

$$\text{and } C_{light} = 3\ 10^{8} \text{ m/s}$$

$$\varepsilon_{ph} = 1.24 / \lambda_{ph} \text{ [eV],}$$

$$\text{with } \lambda_{ph} \text{ measured in } \mu\text{m,}$$

$$\text{eV} = 1.6\ 10^{-19} \text{ J.}$$



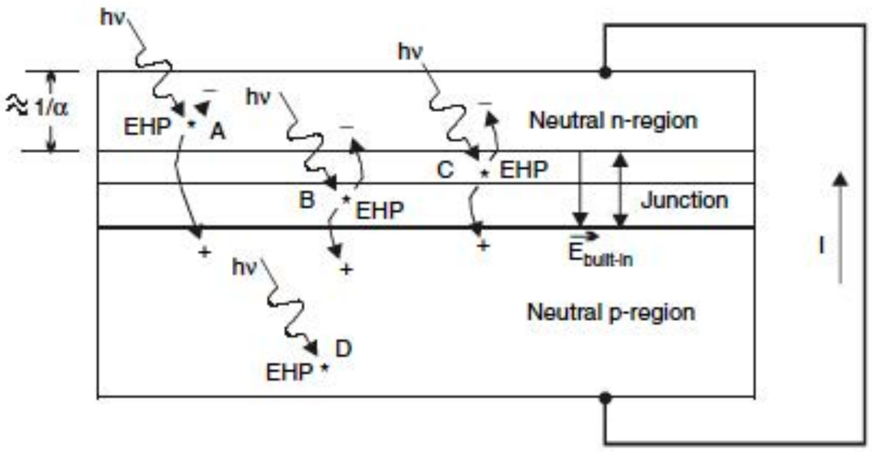
The wavelength/color of visible light and its energy

Photovoltaic Solar Energy, Reinder et al, Ed., Wiley, 217

- For Si, the *bandgap energy* is e_{bg} ~ 1.1 eV, and adsorbed photons with $\lambda < \lambda_{bg} = 1.13\ \mu$m (near the infrared part of the solar spectrum) can move an electron to the conduction band (where it is free to move within the semiconductor).
- An adsorbed photon with energy < e_{bg} (wavelength > λ_{bg}) dissipates its energy

The Photoelectric Effect

- An adsorbed photon with energy > e_{bg} (wavelength < λ_{bg}) still moves a *single* electron to the conduction band (one electron/ photon), with the remaining energy dissipating into heat.
- The photon-induced current, which is proportional to the incident photon intensity, can move across the junction or to an *external circuit*.
- Freed electron (and electron holes) could be reabsorbed within the material unless the distance between the junction and the circuit is less than the diffusion length of electrons.

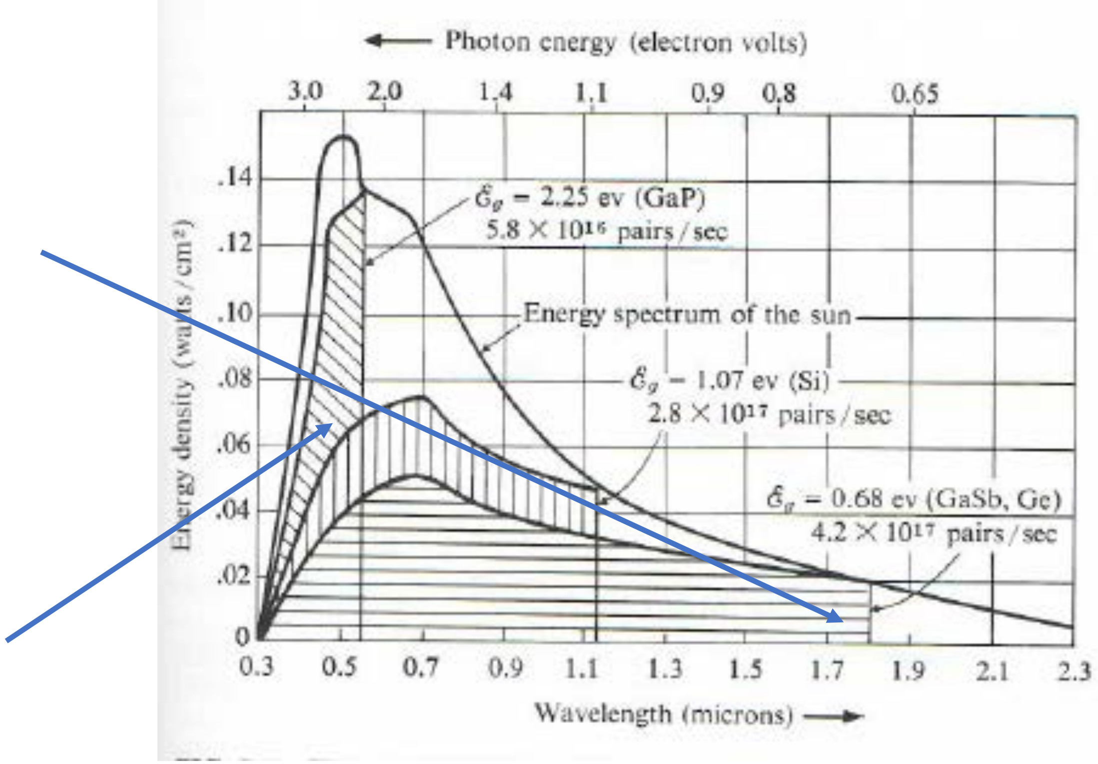


The illuminated p-n junction showing the formation of electron-hole pair by the adsorption of a photon

Impact of Band Gap Width on efficiency:

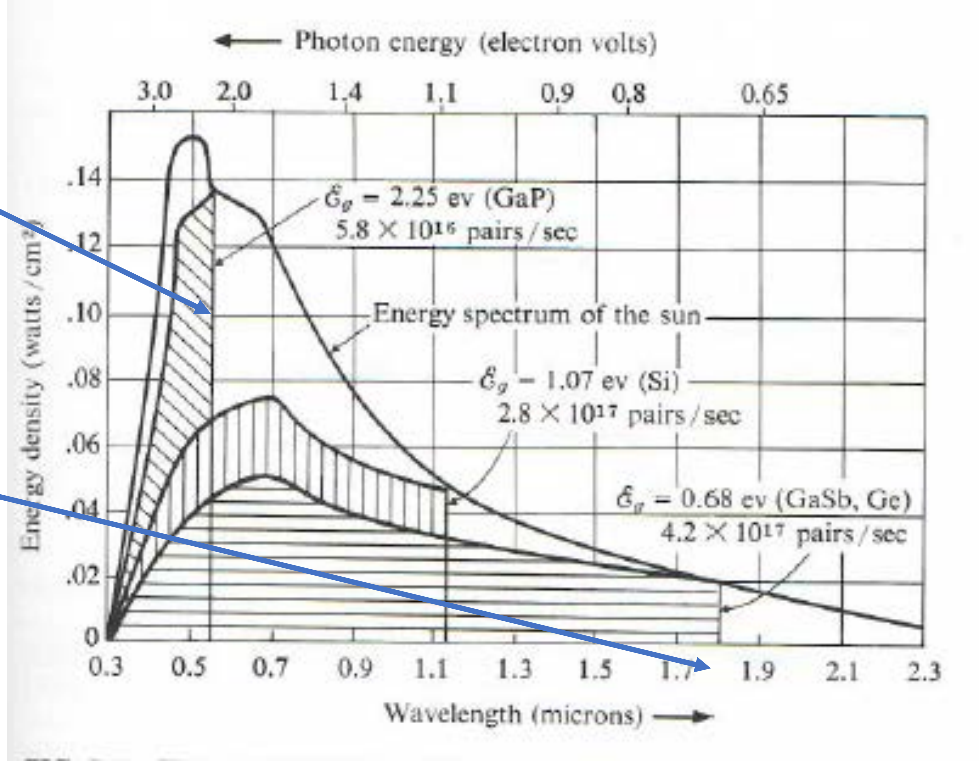
$$\varepsilon_{ph} = 1.24 / \lambda_{ph} \text{ [eV]}$$

- Different semiconductors have different efficiency, depending on their bandgap e_{bg} or λ_{bg}
- Semiconductors with low bandgap energy e_{bg} (or high λ_{bg}) take advantage of most of the solar spectrum, but their efficiency can be low because of the high dissipation from the more energetic electrons (the electron only captures the semicondustor e_{bg}).
- Semiconductors with high bandgap energy (low λ_{bg}), take advantage of a smaller fraction of the spectrum.



Impact of Band Gap Width on efficiency:

- Moreover, semiconductors with high bandgap energy (low λ_{bg}), have higher cell voltage (*$V_{bg}=e_{bg}/\varepsilon_0$ and ε_0 is the charge of an electron*) but produce less electrons.
- While semiconductors with low bandgap have low cell voltage and produce more electrons.
- It is not possible to capture the full spectrum using a single semiconductor, and the maximum theoretical efficiency using a single or "homo" junction ~ 30% (the Shokley limit)



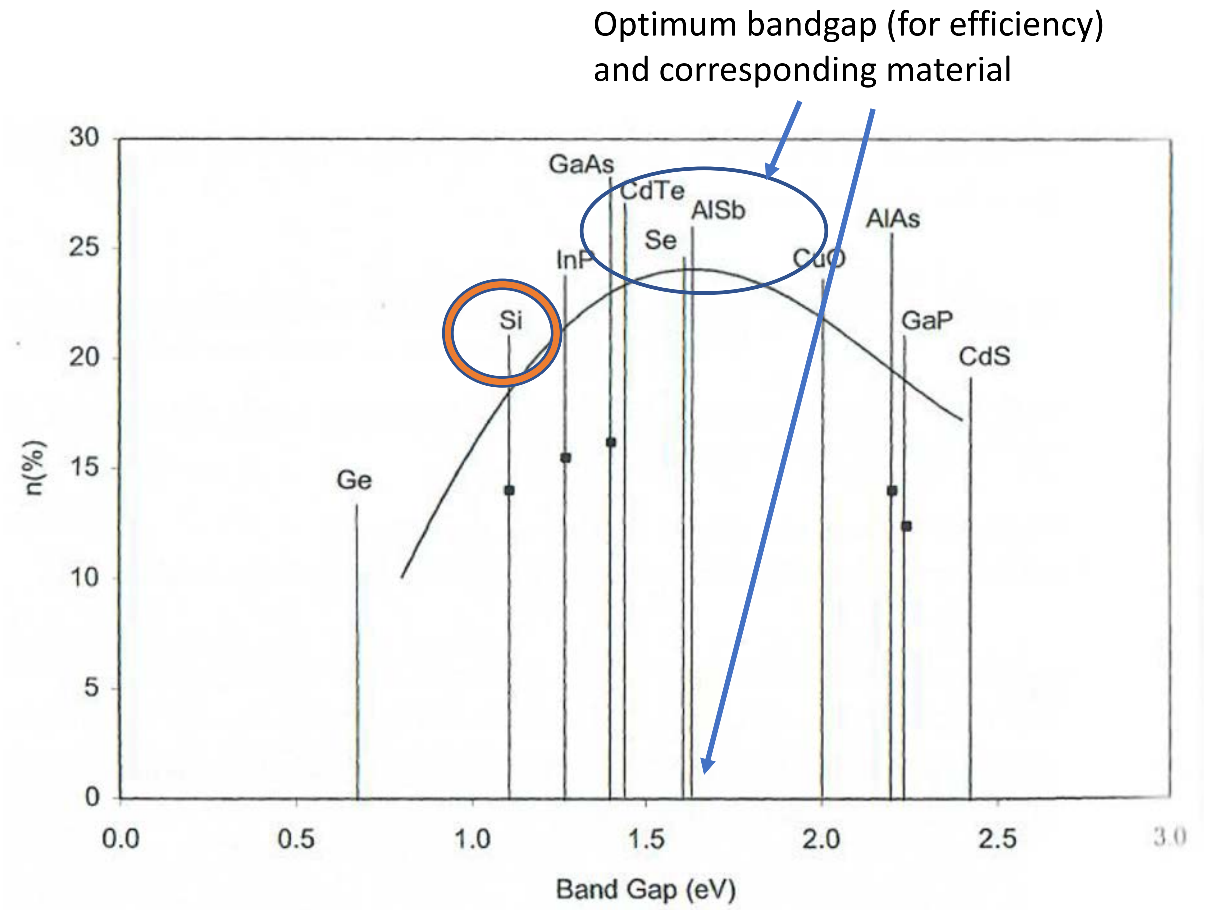
- Hetero or multi junction (layered homojunctions) could be used to overcome this limit (semiconductor layers with different bandgaps can capture photons with different wavelength).

Impact of Band Gap Width on efficiency:

alloy	Bandgap eV	alloy	bandgap
c-Si	1.12	Zn_3P_2	1.5
a-Si	1.7	$CuInSe_2$	1.04
GaAs	1.43	$CuGaSe_2$	1.68
InP	1.34	$Cu(In,Ga)Se_2$	1.2
CuS	1.2	$CuInS_2$	1.57
CdTe	1.45	$Cu(In,Ga)(S,Se)_2$	1.36

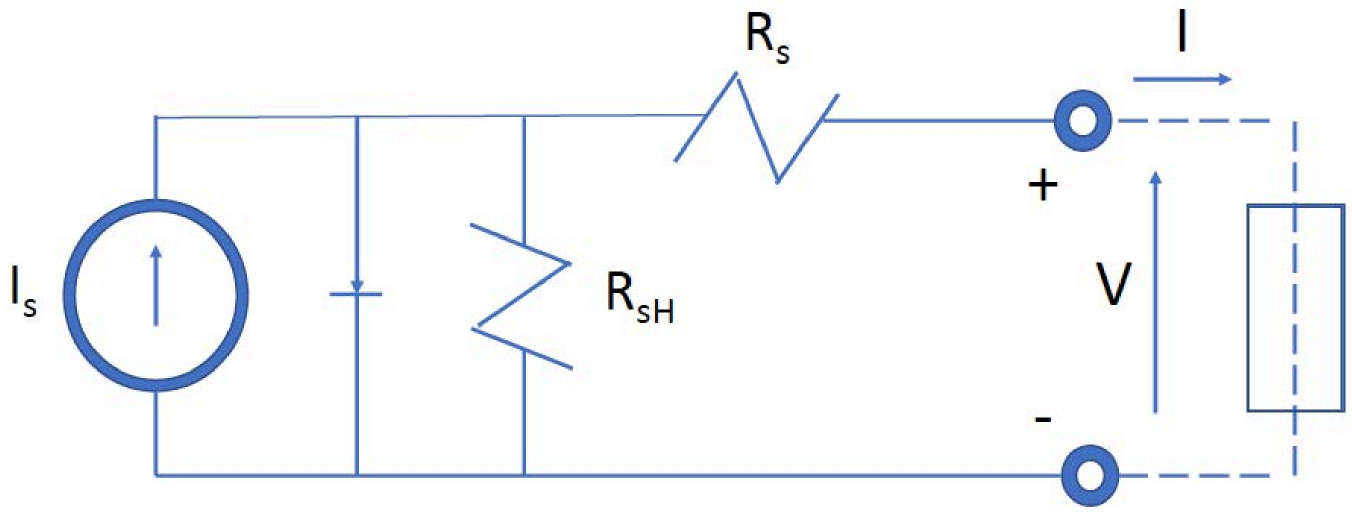
c-Si: crystalline silicon
a-Si: amorphous silicon

Si: silicon	Zn: zink
Ga: gallium	P: phosphorus
As: arsenide	In: indium
Cu: copper	Se: selenium
S: sulfur	Ge: germanium
Cd: cadmium	Sb: antimony
Te: telluride	Al: aluminum



The curve shows the ideal maximum (extraterrestrial) solar energy conversion efficiency as a function of the semiconductor bandgap. The measured value is shown by a solid square.

$$\eta = \int \eta_\lambda I_\lambda \, d\lambda / \int I_\lambda \, d\lambda$$



R_s is the zero series resistance (=0 under ideal conditions)
R_{sH} is the shunt resistance (= ∞ under ideal conditions)

For the following slides describing the modeling of the cell, See
Ginley and Cahen, Fundamentals of materials for energy and environmental sustainability, Cambridge, 2011.
Chen, Physics of Solar Energy, Wiley, 2011
Also Aliza Khurram 2019 term paper on Mars Mission

The external current density-voltage, J-V, relation of an illuminated p-n junction is:

$$j = j_s - j_0\left(\exp\left(\frac{e_0 V}{nkT}\right) - 1\right) \approx j_s - j_0 \exp\left(\frac{\varepsilon_0 V}{nkT}\right)$$

j_s : zero voltage (short circuit) current $V = 0$

(also known as the photogenerated current).

j_o : dark current (current in the absence of illumination)

ε_0 : electron charge = $1.602\ 10^{-10}$ Coulombs (J/V)

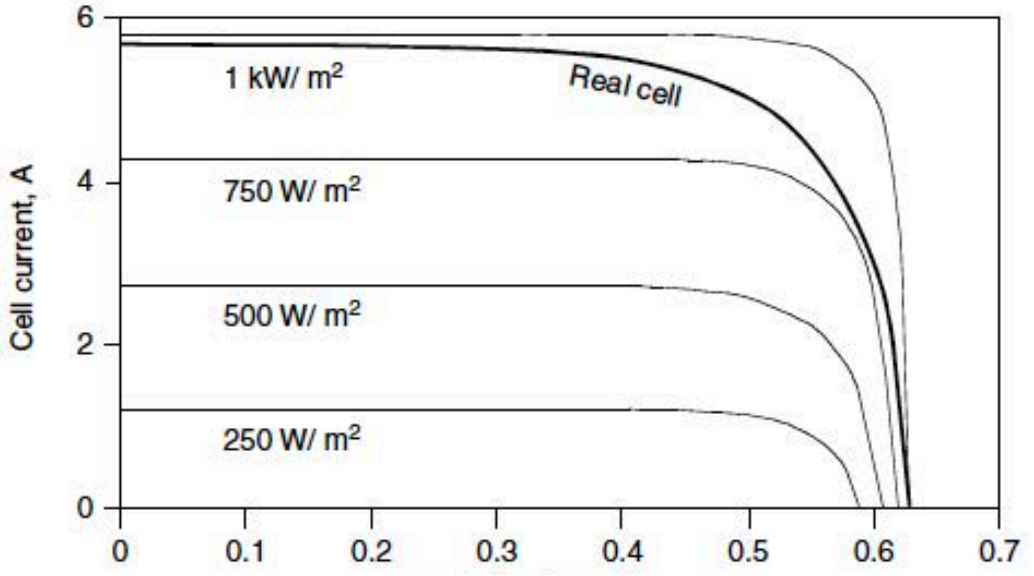
V : voltage

n: =1-2 (known as the diode ideality factor)

k : Boltzman constant=$1.381\ 10^{-23}$ J/K

At zero current, $I = 0$,

$$V_{OC} = \frac{nkT}{e_0}\ln\left(\frac{j_s}{j_0} + 1\right) \approx \frac{nkT}{e_0}\ln\frac{j_s}{j_0}$$



The I-V curve of a real PV cell (dark), and the ideal curves for a cell subjected to different illumination levels (or photon flux)

Goswami and Kreith, Energy Conversion, CRC Press, 2008.

$$j_0 = A\exp\left(-\varepsilon_o \frac{E_g(T)}{kT}\right)$$

$A \sim 1.5 10^8 \,\mathrm{mA/cm^2}$ (empirically determined)

$E_g(T) \sim E_g(0) - \left(\frac{\alpha T^2}{T+\beta}\right)$: bandgap energy

material	Eg(0) in eV	αx10^{-4} in ev K^{-1}	β in K
Si	1.1557	7.021	1108
Ge	0.7412	4.561	210
GaAs	1.5216	8.871	572

$$j_s = \varepsilon_o \int_0^\infty \eta_\lambda(\lambda)\phi(\lambda)\,d\lambda$$

η_λ : is the quantum efficiency

$\phi(\lambda)$; is the spectral flux

j_s is often measured experimentally

$$V_{OC} \approx \frac{nkT}{e_0}\ln\frac{j_s}{j_0} \sim V_{OCn} + \frac{nkT}{e_0}\ln\frac{G}{G_n}$$

V_{OCn} : open circuit voltage under normal conditions

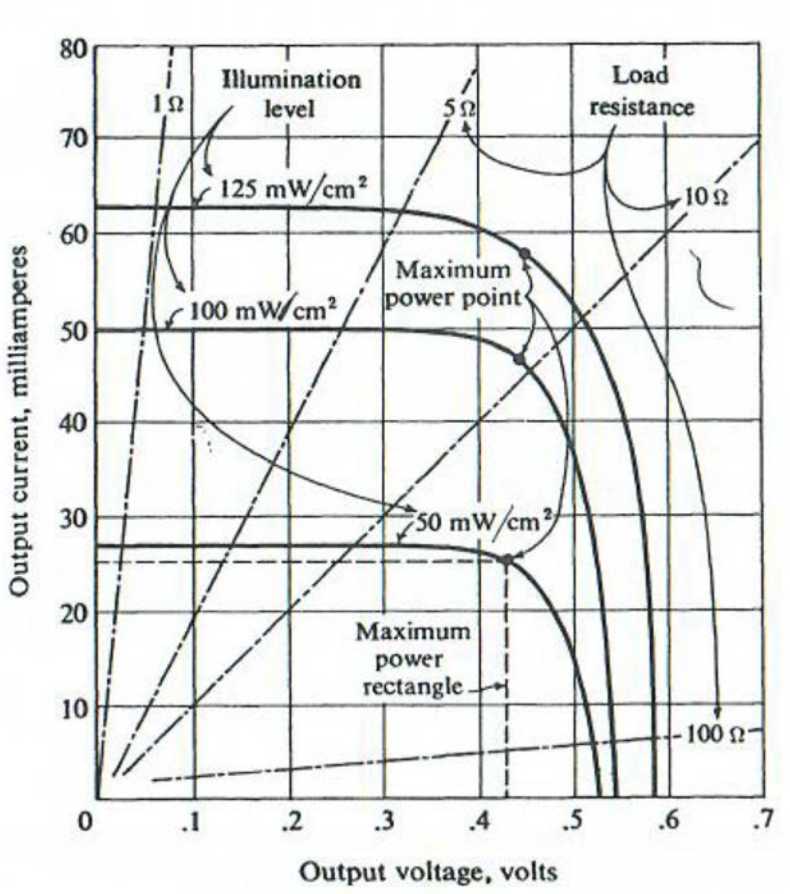
G and G_n : solar irradiance under actual and noraml conditions the fill factor measure the quality of the cell

$$FF = \frac{P_{\max}}{P_{th}} = \frac{j_{MP}V}{j_S V_{OC}}$$

j_{MP} : current at max power

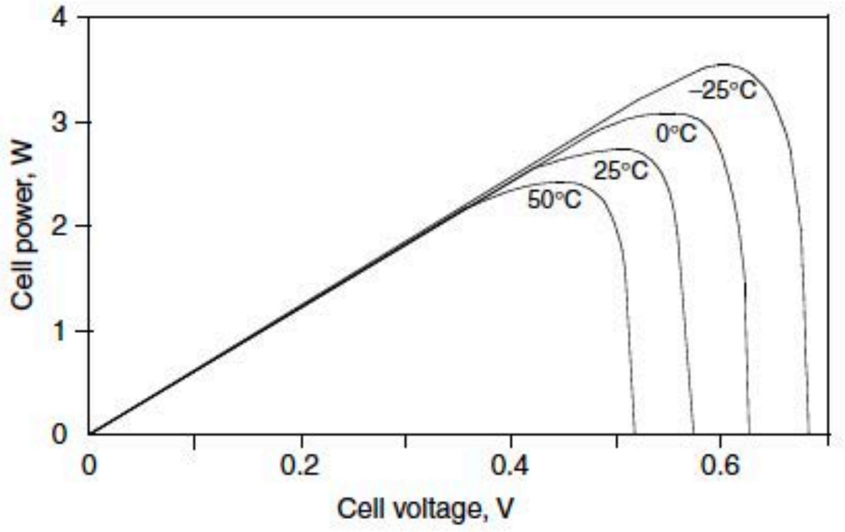
The conversion efficiency is: $\eta = \frac{P_{\max}}{P_{in}} = \frac{FF\, j_S V_{OC}}{G}$

Typical I-V curve of a Si cell showing the effect of illumination and local resistance



Angrist, Direct Energy conversion, 1976.

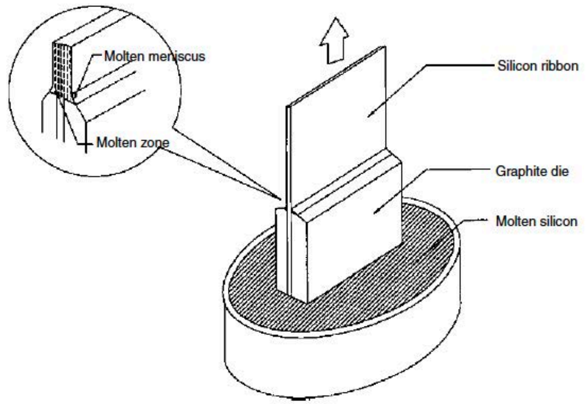
Impact of operating temperature on Power-Voltage curve of a PV cell.



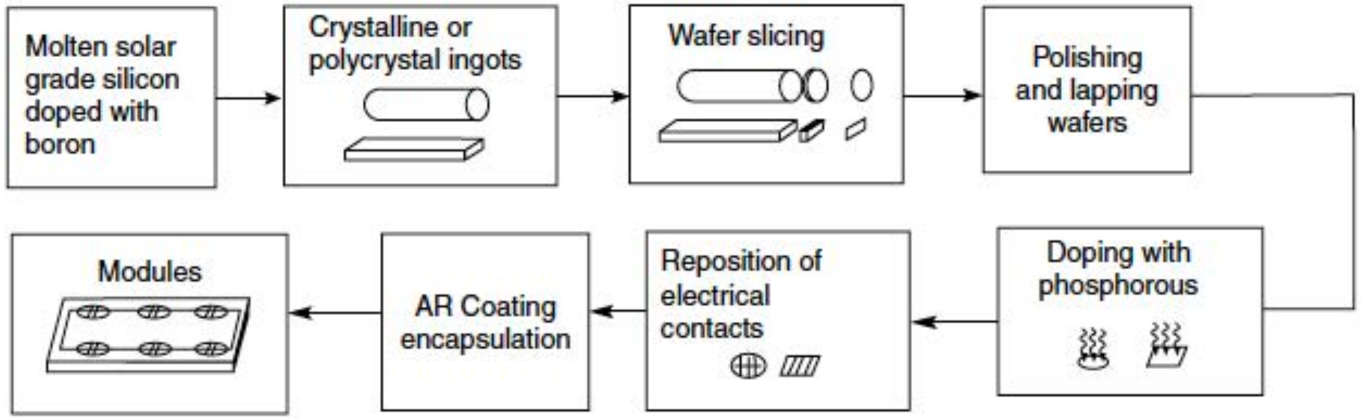
Goswami and Kreith, Energy Conversion, CRC Press, 2008.

Some solar cell manufacturing techniques

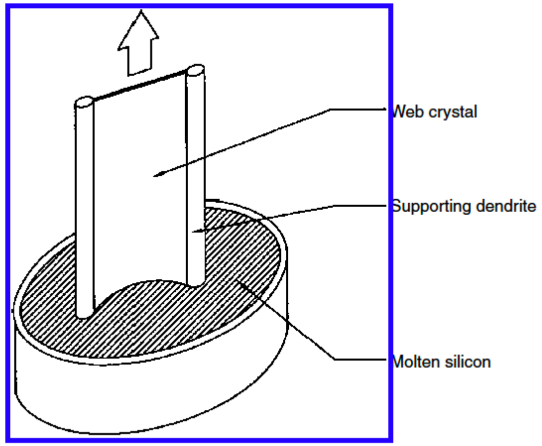
- PV cells use purified silicon (produced by reducing silicon oxides) but not necessarily electronic grade.
- All methods start with a molten solar grade silicon (doped with different impurities to produce the p or n semiconductor, or to pacify some of the defects).
- Production of solar cells is energy intensive (with some pay-back energy period).



Edge-define film-fed growth (EFG) methods for growing thin films



Processes involved in manufacturing crystalline and polycrystalline PV cells by slicing 250 micron wafers and fusing n-layer into the p-layer.



String-ribbon production of a thin-film cell

Goswami and Kreith, Energy Conversion, CRC Press, 2008.

The cell and the panel

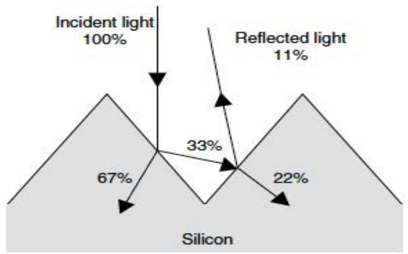


Figure 3.2.2 Effect of a textured surface on the reflectivity of silicon

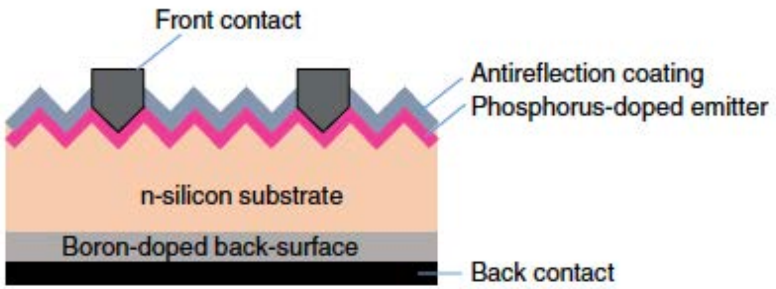


Figure 3.2.8 n-type rear emitter silicon solar cell

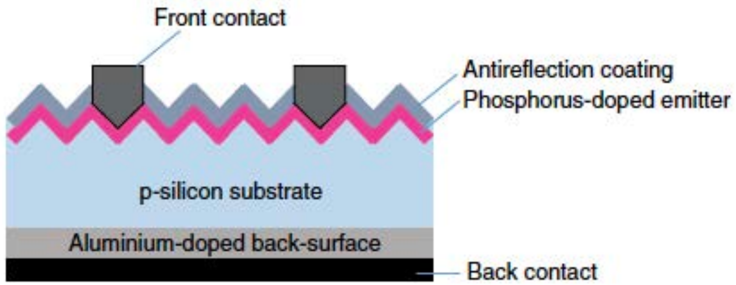


Figure 3.2.4 Screen-printed silicon solar cell

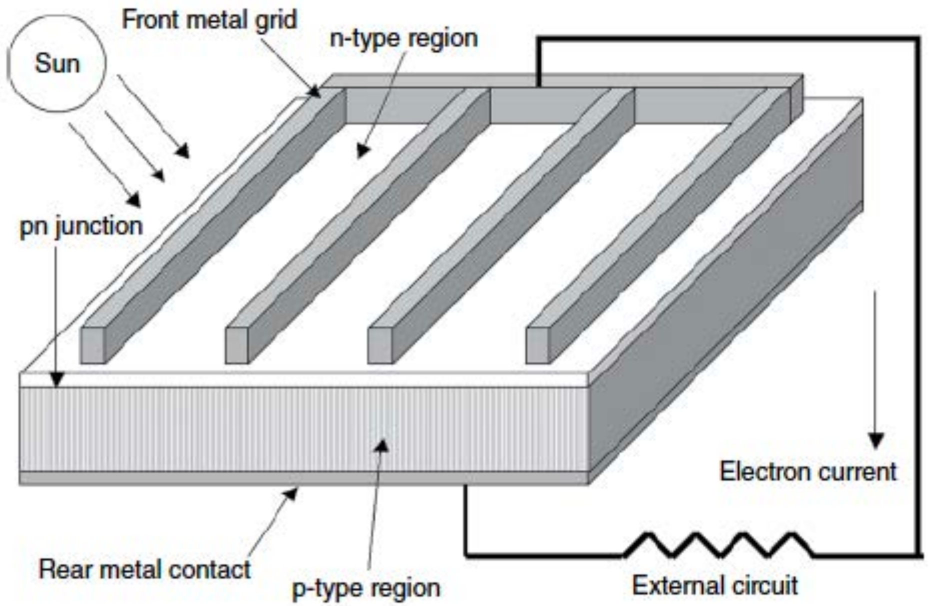
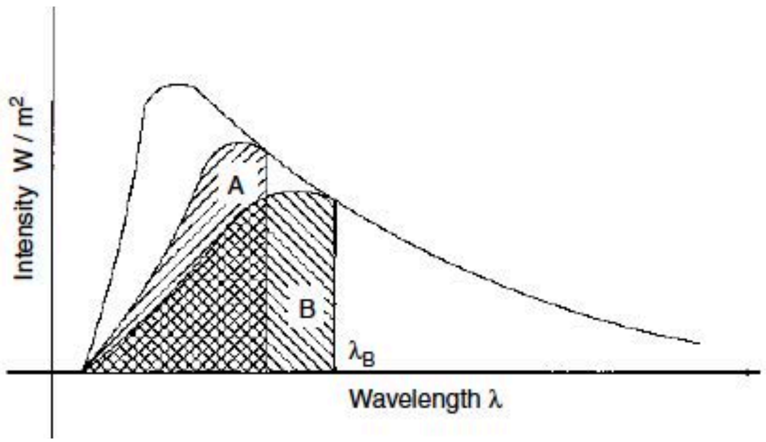


Figure 3.2.1 Schematic of a typical solar cell

Photovoltaic Solar Energy, Reinder et al, Ed., Wiley, 217

Heterojunction Devices

- Efficiency can be improved using multi layer cells (tandem devices), with high bandgap material at top and low bandgap material below (low frequency radiation penetrates better).
- The open circuit voltage of the stack is the sum of the open circuit voltages of the individual cells.
- Multijunction devices using Silicon and Gallium Arsenide are the most efficient solar cells to date, reaching as high as 39% efficiency. They are also the most expensive.

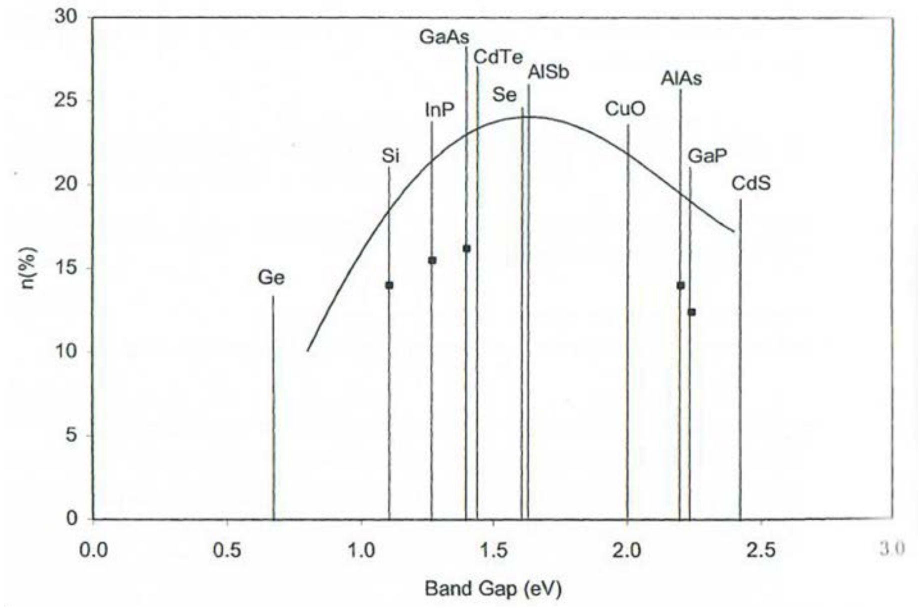


Part of the spectrum captured by a two layered tandem cell

Goswami and Kreith, Energy Conversion, CRC Press, 2008.

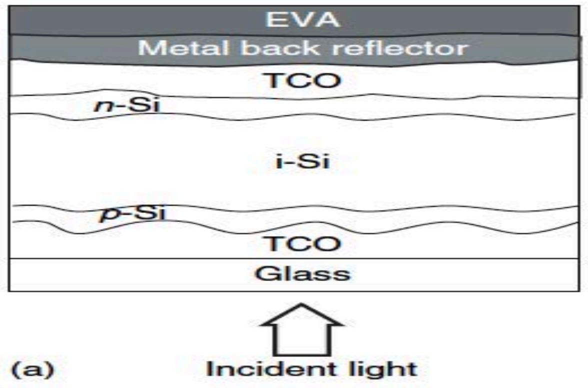
Thin film technology

- Material with bandgap close to 1.5 eV should be used to achieve higher efficiency (than Si), but they are expensive (CdTi, GaAs, InP, Zn3P2, …)
- Can only be used in thin film form to be economical
- Because of the thin film (few microns), material should also have high optical absorption coefficient to achieve high efficiency.
- And because they are used in thin film, it is possible to build tandem or heterojunction cells
- But they need good substrate to deposit the thin film on



Goswami and Kreith, Energy Conversion, CRC Press, 2008.

A single p-i-n junction thin film a-Si with transparent conduction oxide (TCO), metal and glass as outer layers and a vinyl acetate (EVA) cover.



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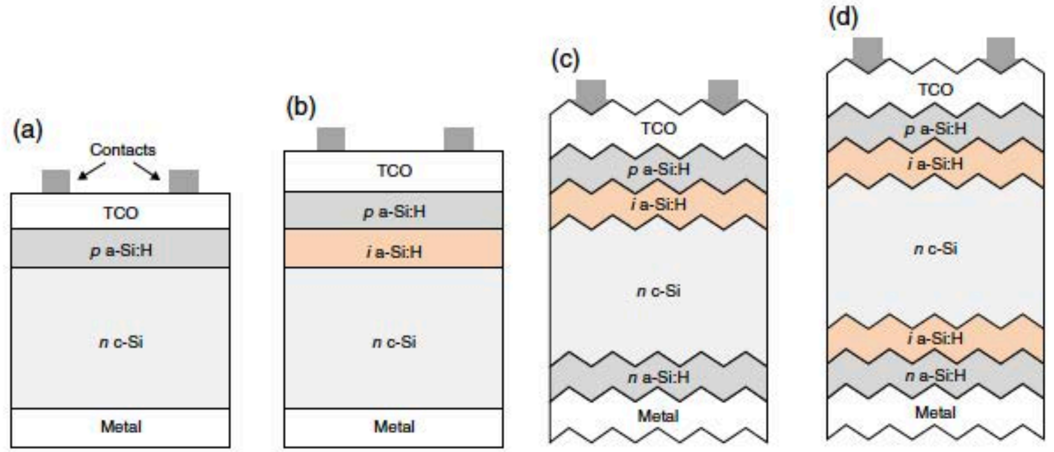

Figure 3.4.3 Schematic structure of heterojunction a-Si:H/c-Si solar cells. (a) basic structure with transparent conductive oxide and metal as top and back contact; (b) idem, with intrinsic a-Si:H layer sandwiched between p a-Si:H and n c-Si; (c) idem, with textured interfaces and back-surface field layer of n a-Si:H, (d) idem, with additional *i* a-Si:H. Note, drawings are not to scale

- Si has also been used with thin film technology, with and intrinsic (i) layer between the p- and n-, and transparent conducting oxides (TCO) between the p-n junction and the outer layers.
- Crystalline Si has better conversion efficiency than amorphous Si but less optical absorption. The efficiency of a-Si is improved be hydrogen alloying (Si:H).

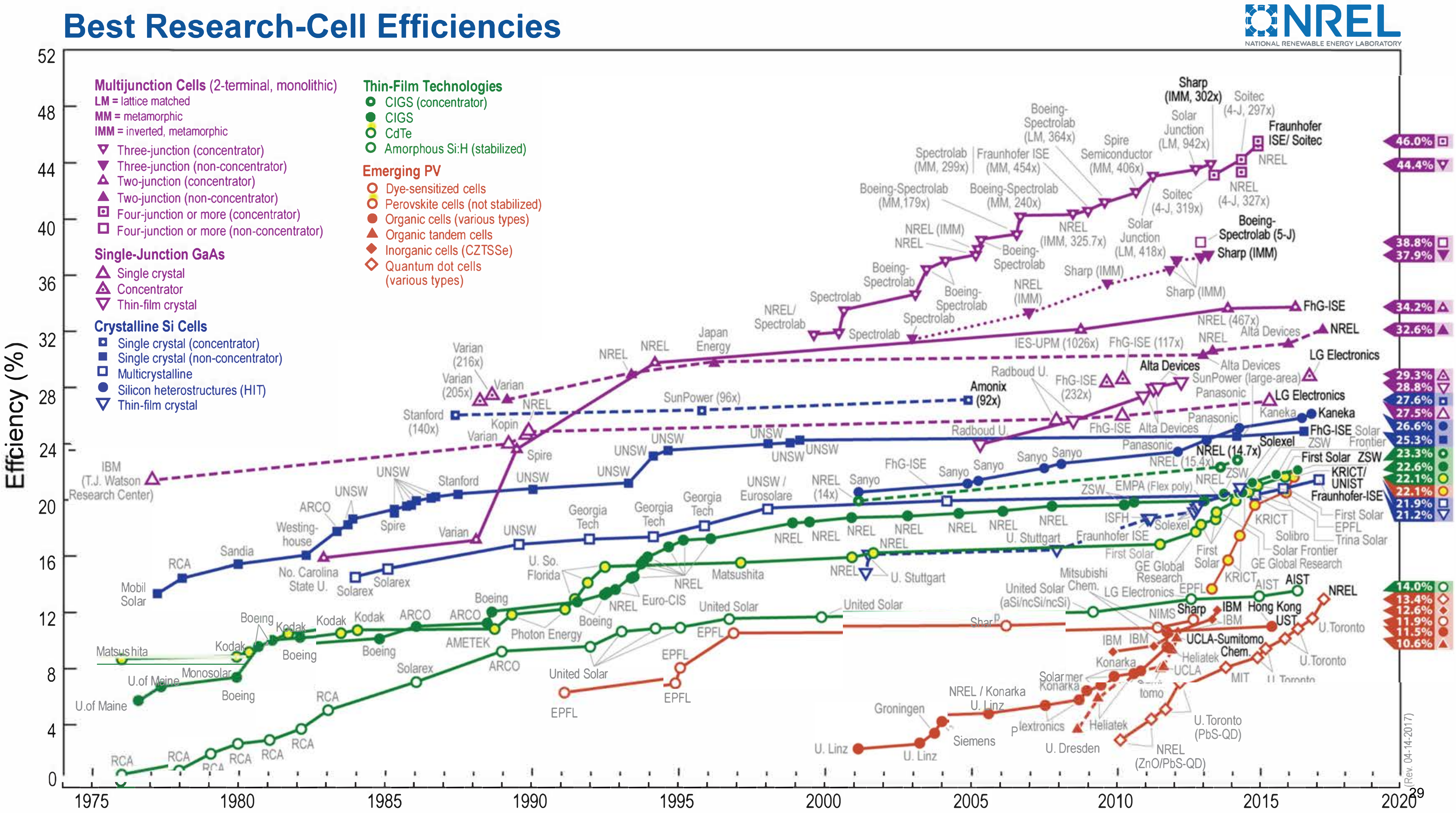

Image courtesy of NREL, DOE.

PV Farms

Fixed tilt systems:
Least expensive. Ideal tilt for annual production is the site azimuth angle (determined by latitude) ± 15–20 degrees. Wind loading, etc., tends to favor tilts less than azimuth angle.

Single-axis Tracking (N-S) axis:
Energy capture is enhanced as much as 25% over fixed tilt systems. Simpler and less expensive than two-axis tracking systems. Typical tracker rotation range is 45 degrees East and West.

Two-axis tracking:
Maximum power: keep the PV plane normal to the sun direct beam throughout the day and seasonally. Energy yield is as high as 40% over fixed tilt systems. High structural, space, and cost requirements.

(a) (b)

Figure 11.1.5 PV systems with (a) a single-axis horizontal tracker, and (b) a single-axis tilted tracker. Sources: (a) NEXTracker™ (2015); (b) Nellis AFB (2007)

Photovoltaic Solar Energy, Reinder et al, Ed., Wiley, 217

“Soiling”

Modules covered by dirt, dust, and other particulates can cause annual energy production losses up to 10% or more if not cleaned periodically

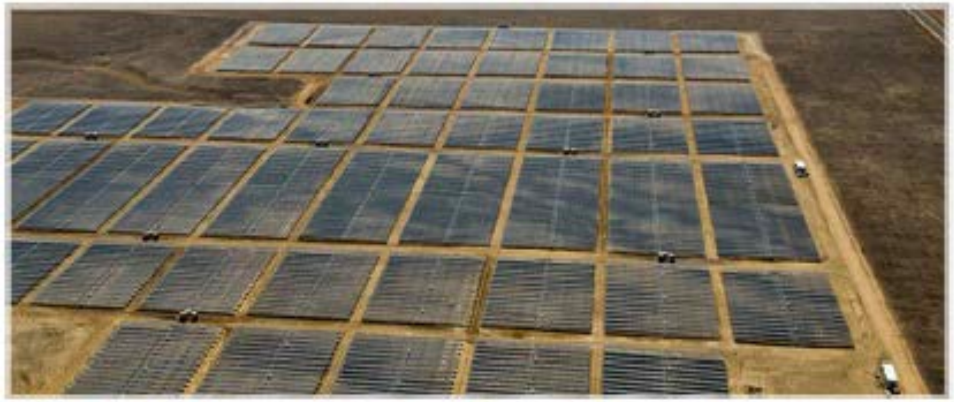

Figure 11.1.6 250 MWac ground-mounted system in California. Source: SunPower

Benban 150 MW plant, Aswan Egypt

Figure 13.1.3 Solar tracking system with robotic cleaning

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Inverter efficiency:

Inverter DC-AC conversion efficiency is important to the overall system efficiency. Typical range is 94–98% and expressed in terms of peak and weighted output efficiency. Inverter maximum power point tracking (MPPT) efficiency typically can result in additional 0.5–1% loss (see next slide).

Transformer losses:

Additional external transformers are sometimes required to interconnect with utility distribution or transmission systems. Losses on an annual basis typically in range of 0.5–1.5%.

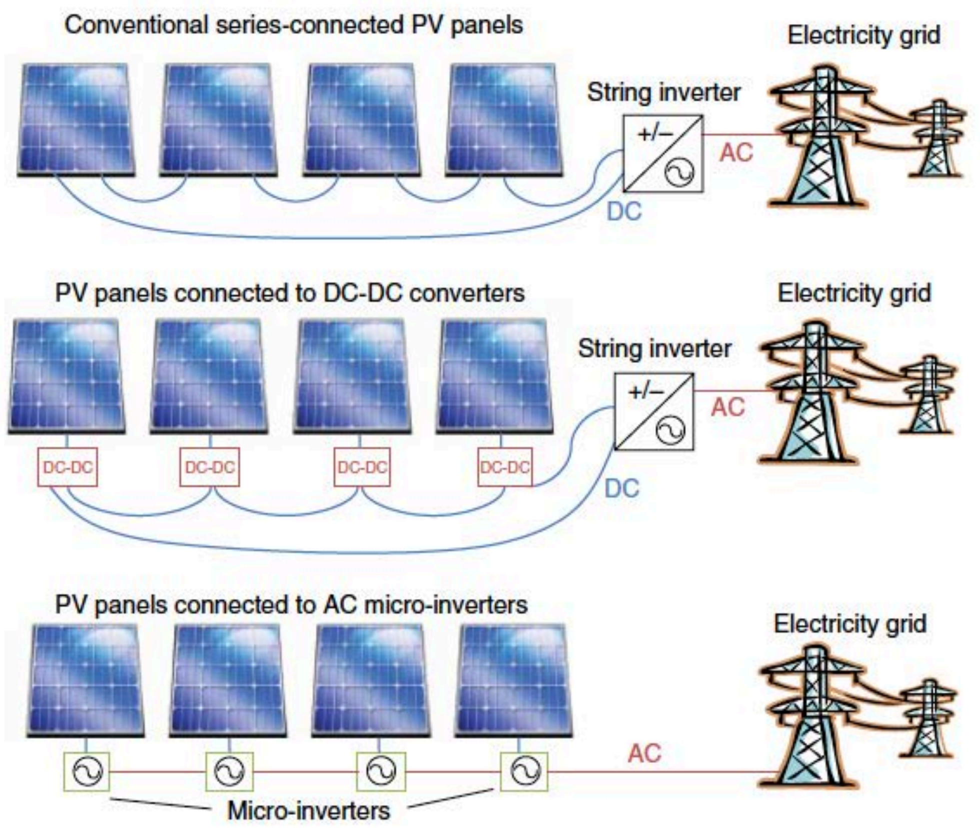

Figure 11.2.1 Schematic of conventional single-string PV system (top), DC-DC converter-equipped "Smart Modules" (middle), and AC micro-inverter-equipped PV system (bottom). (*See insert for color representation of the figure*)

An additional consideration for inverter MPPT is mismatch caused by partial shading. In the P&O strategy described above, the algorithm operates around a local maximum point,

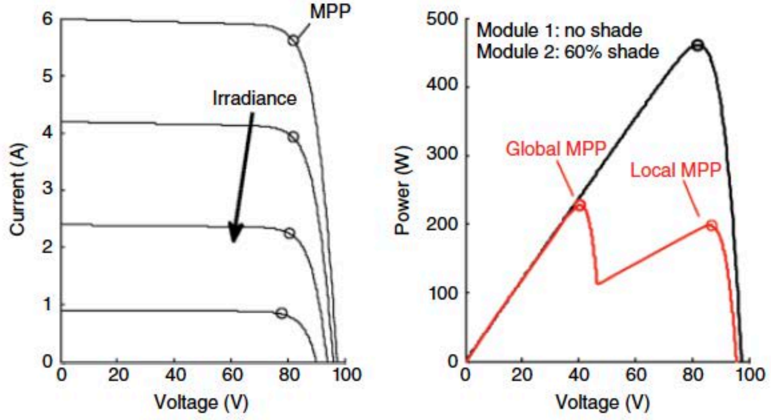

Figure 11.2.5 Comparison of MPP voltage and current with change in irradiance (left). Partial shading (right) can result in multiple local maxima, potentially affecting the MPPT operation

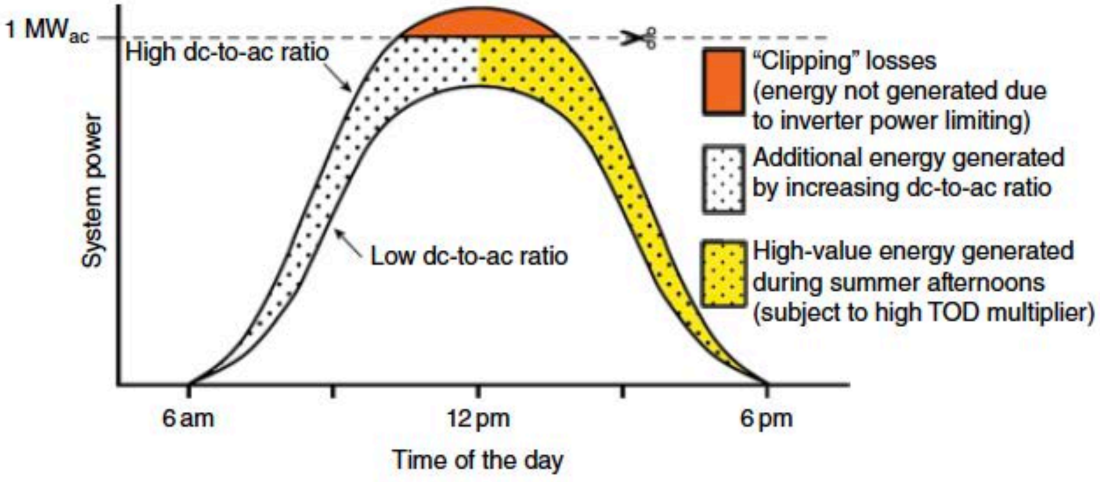

Figure 11.1.7 Impact of varying PV system DC/AC ratio. Source: *SolarPro Magazine* (2013)

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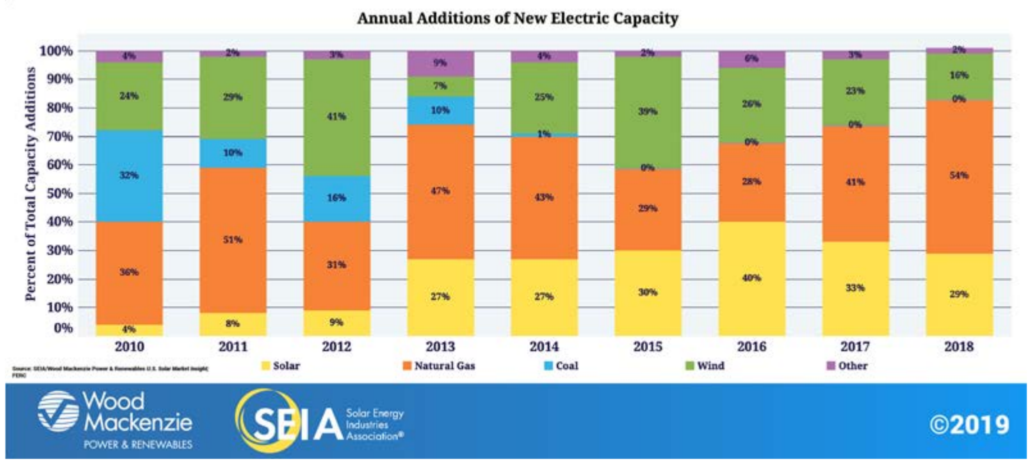
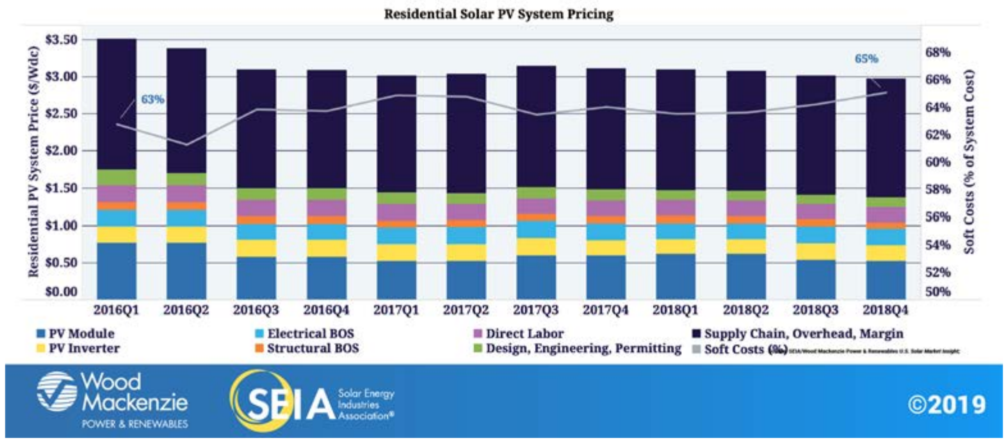
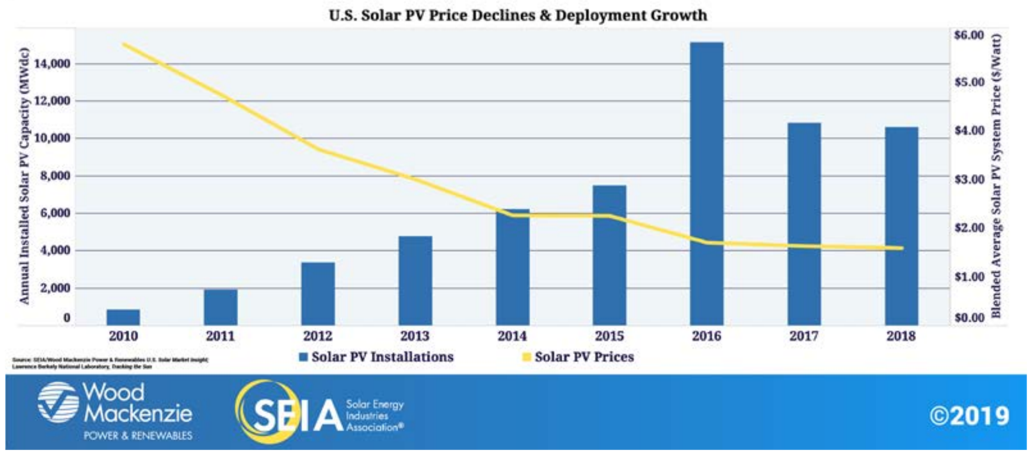
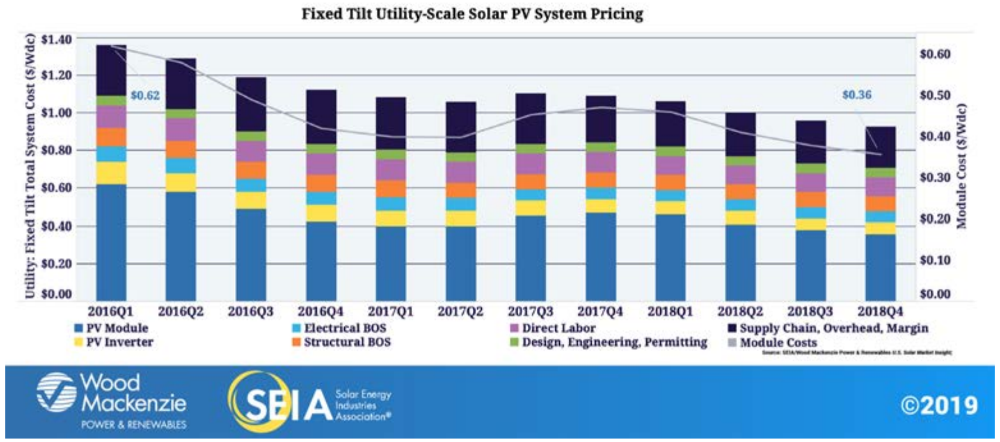
Changes in the US Electricity markets









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