Renewable Energy

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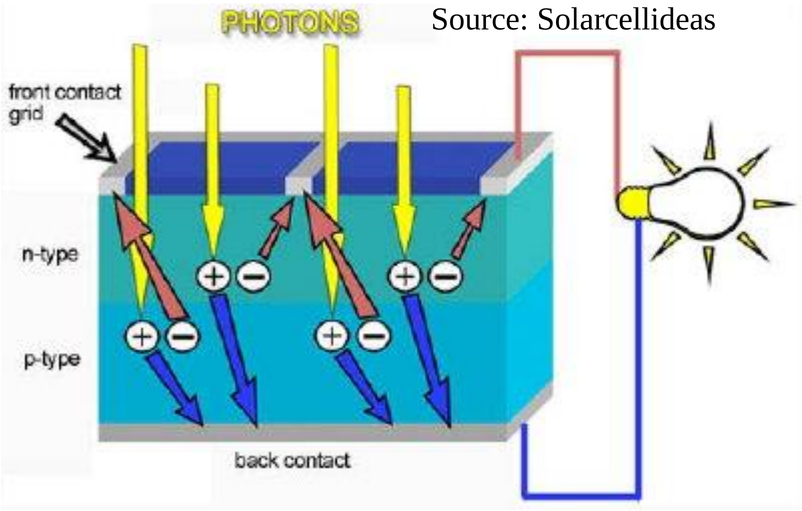
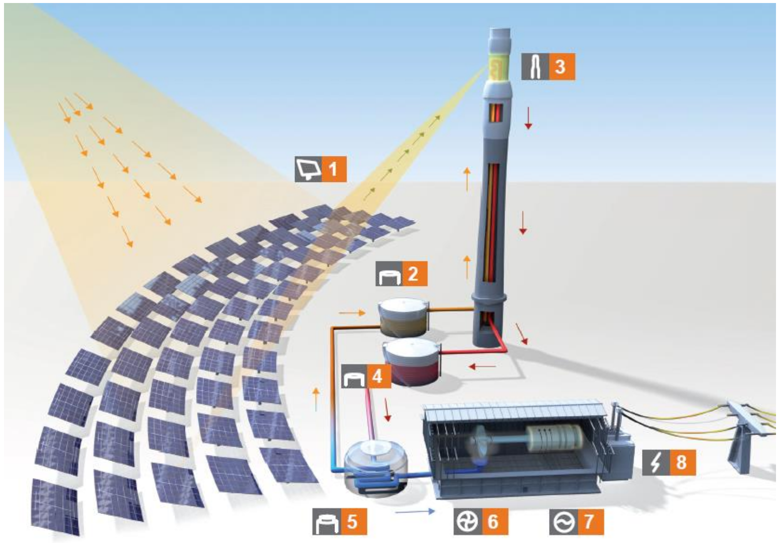
Conversion pathways

- Solar energy conversion
  - Solar to electric: photovoltaic



  - Solar to electric: solar thermal plus power cycle



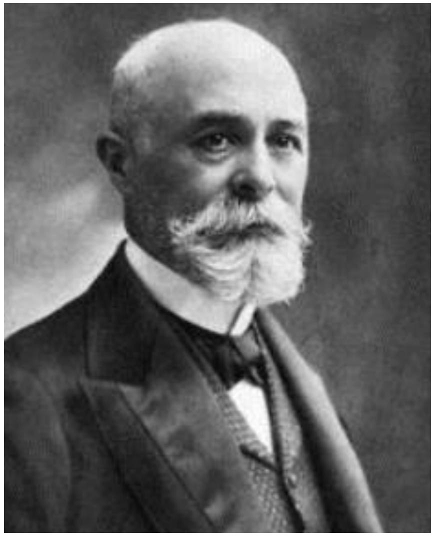
- Outline:
  - Fundamentals
    - History
    - Solar irradiation characteristics
    - Semiconductors
  - Working principle
  - Efficiency
  - PV technologies
  - Sustainability
  - Market
  - Aesthetics

Learning outcomes of todays lecture

- Solar to electricity via PV:
  - Working principle of photovoltaic cell
  - Efficiency calculation for ideal cell
    - What influences efficiency (operating conditions)
    - Materials and their influence on efficiency
  - Overview of various PV technologies
    - Current efficiencies and potential
    - Differences, advantages and disadvantages

History

- 1839: E. Becquerel discovers photovoltaic effect (at age of 19), AgCl was placed in an acidic solution while connected to Pt-electrodes, generating voltage and current, which increased with illumination



- 1883: Charles Fritts, an American inventor, described the first solar cells made from selenium wafers. Based on W. Smith and W. Adams investigations

- 1904: Photovoltaic effect is theoretically described by A. Einstein

History

- 1954: Bell Laboratories, D.M. Chapin, C.S. Fuller, and G.L. Pearson, published the results of their discovery of 4.5% efficient Si solar cells, raised to 6% only a few months later

- Early 1950 and later: market driven by space applications

- 1963: Sharp Corporations developed first useable Si cell-based modules

- 1970 and later: First use of PV technology on earth

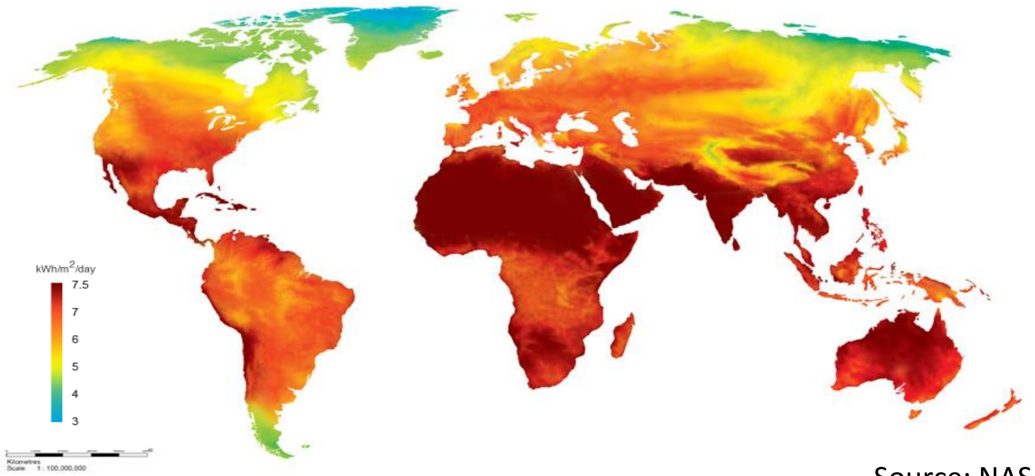
- See more:

http://www.pvresources.com/Introduction/HistoricalOverview.aspx

http://www.nrel.gov/education/pdfs/educational_resources/high_school/solar_cell_history.pdf

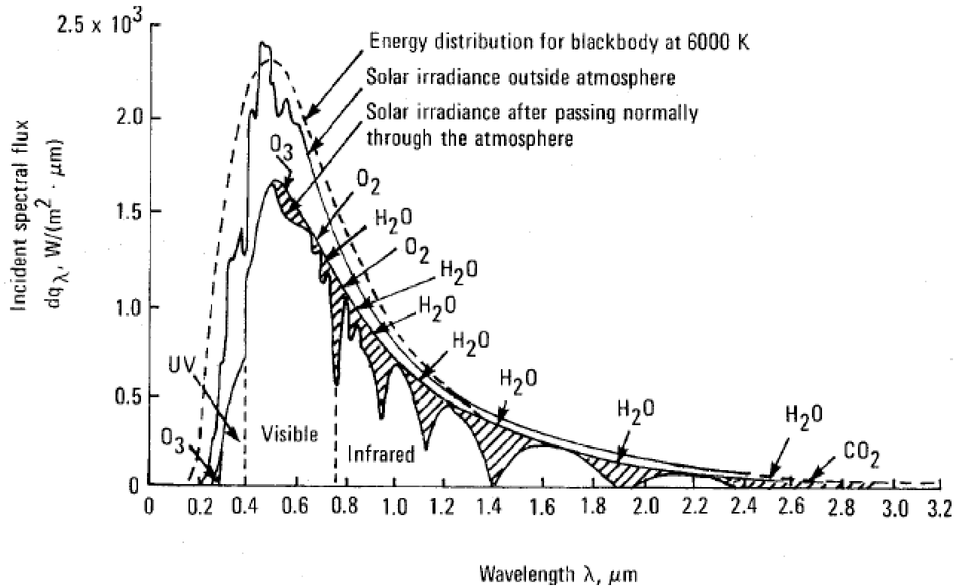
Solar irradiation characteristics

- Solar irradiation:
  - Power density [W/m²] is location, date, and time dependent:



Source: NASA

  - Spectral-dependence given by black-body radiation at 5800 K (sun) and absorption in atmosphere:



  - Energy of photon: $E_{\text{photon}} = \dfrac{hc}{\lambda}$

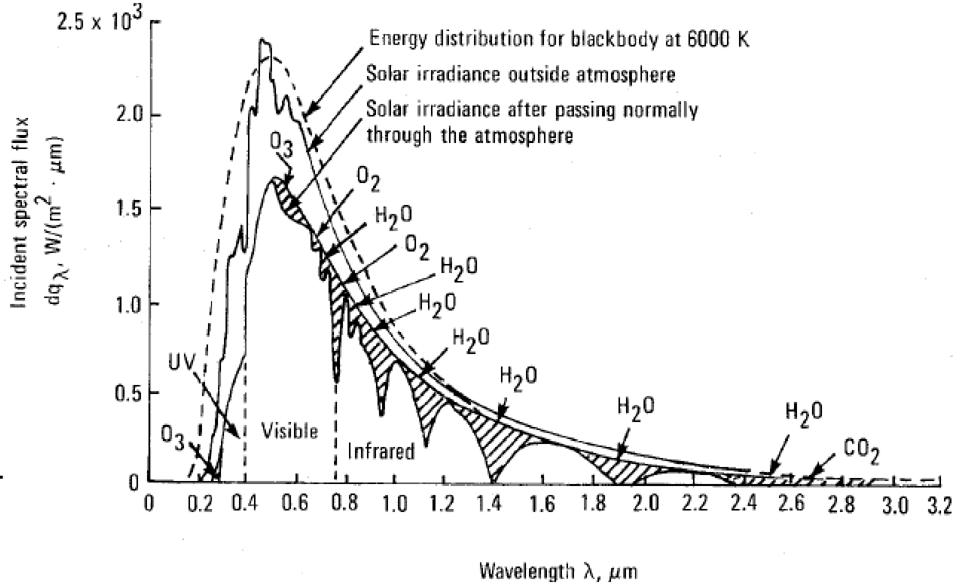
Solar irradiation characteristics

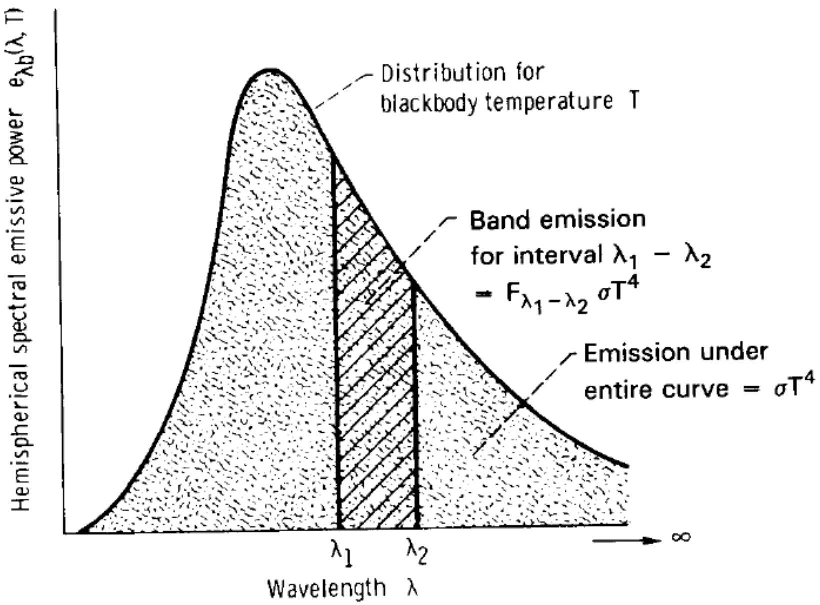
- Solar radiation:
  - Black body emissive power:

$$E_{\lambda b}(\lambda,T)=\frac{2hc_0^2}{\lambda^5\left(e^{hc_0/(k\lambda T)}-1\right)}$$

$$E_{\mathrm{b}}=\int_0^\infty E_{\lambda \mathrm{b}}\,d\lambda=\sigma T^4 \qquad \sigma=\frac{2hc_0^2\pi^5k^4}{15h^4c_0^4}$$

$$F_{\lambda_1-\lambda_2}=\frac{\int_{\lambda_1}^{\lambda_2}E_{\lambda b}\,d\lambda}{\int_0^\infty E_{\lambda b}\,d\lambda}=\frac{\int_{\lambda_1}^{\lambda_2}E_{\lambda b}\,d\lambda}{\sigma T^4}$$



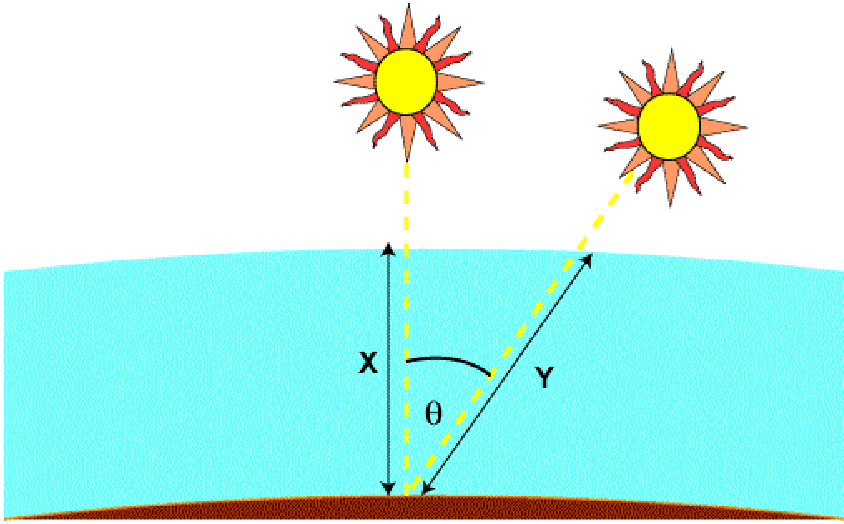


Solar irradiation characteristics

- Definitions:
  - Air mass (AM):

    AM is the path length which light travels through the atmosphere normalized to the shortest possible path length (sun is directly overhead).

    AM quantifies the reduction in the power of light as it passes through the atmosphere and is absorbed by air and dust:



$$AM = \frac{1}{\cos\theta} = \frac{Y}{X}$$

  - AM0: solar spectrum outside of the atmosphere with 1367 W/m^2
  - AMx defines both the spectrum and the power density
  - AM1.5D = only direct radiation, normalized at 900 W/m^2
  - AM1.5G = including diffuse radiation, normalized at 1000 W/m^2

Working principle

The operating principle of a solar cell relies on the **direct** conversion:

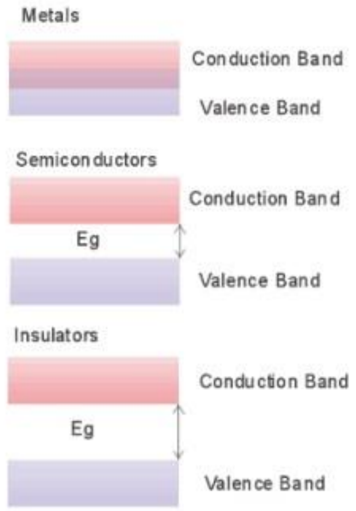
1) of incident energy of photons (solar spectrum) on a semiconductor

2) in electricity, by creation of charge carrier pairs (electrons, n^-, and holes, p^+) in the semiconductor

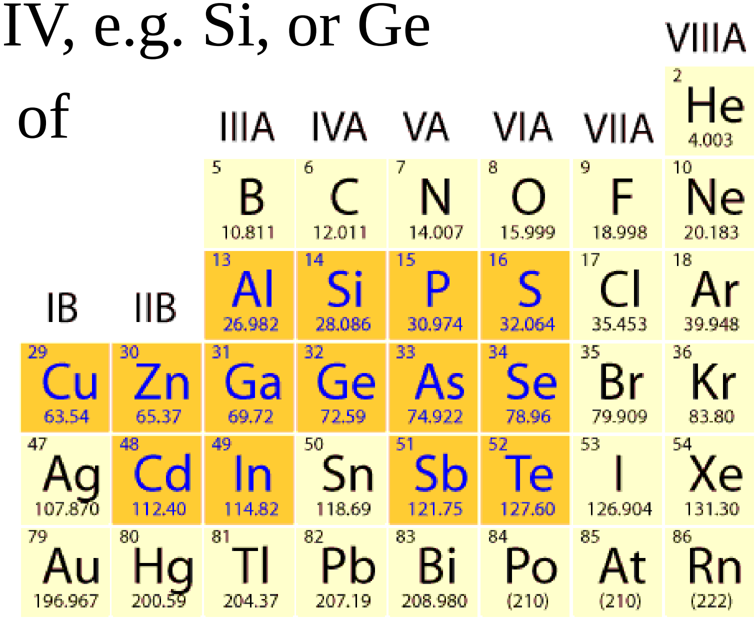
3) separation of these thanks to an internal electrical field (p-n junction)

Semiconductors

- Semiconductor:
  - Materials which have electrical conductivity between a conductor and an insulator
  - Properties dependent on state



- Three important types:
  - Elemental: elements mainly of group IV, e.g. Si, or Ge
  - Compounds: Elemental combinations of
    - Groups III-V, e.g. GaAs
    - Groups II-VI, e.g. CdTe
  - Alloys: $Si_xGe_{(1-x)}$ or $Al_xGa_{(1-x)}As$



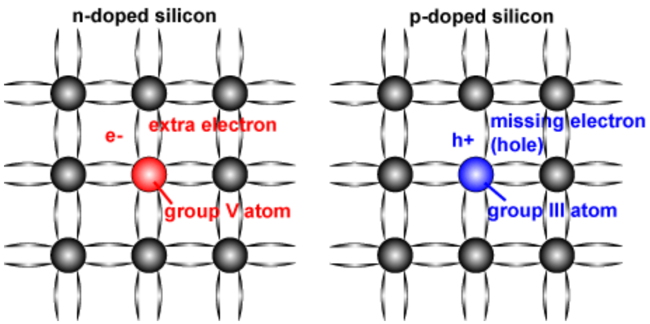
Semiconductors

- Semiconductor:
  - Excited electrons can move in conduction band, leave behind a hole; electron and hole pairs contribute to conduction
  - Intrinsic charge carrier: *f*(temperature,band gap)

    e.g. for Si (Misiakos):

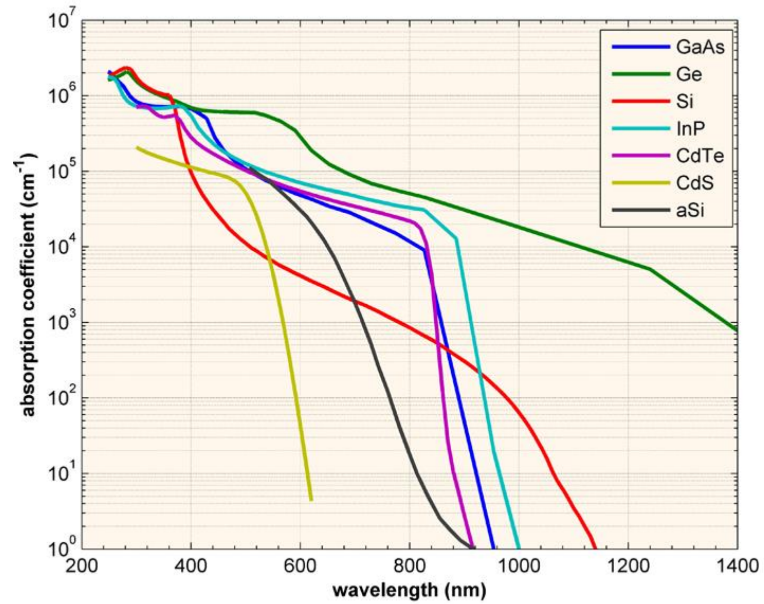
$$n_i = 5.29 \cdot 10^{19} (T/300)^{2.54} \exp\left(-6726/T\right)$$

  - Additionally, doping can be used to increase charge carriers:
    - n-doped: material with more valence electrons than base material (electrons are majority carrier)
    - p-doped: materials with less valence electrons than base material (holes are majority carrier)



Semiconductors

- Semiconductor under irradiation:
  - Electron-hole pairs are generated by solar irradiation, if the energy is larger than the band gap energy they are absorbed



  - Absorption depth is inversely proportional to absorption coefficient, according to Beer's law:

$$I = I_0 \exp(-\alpha l) \qquad I \overset{l=1/\alpha}{=} I_0 \exp(-1) \rightarrow 0.36 \cdot I_0$$

  - Generation rate (electron-hole-pairs): $\left| \frac{dI}{dl} \right| = \alpha N_0 \exp(-\alpha l)$

Photonflux [#/m^2/s] = I/E

EPFL

Semiconductors

- Semiconductor under irradiation:
  - Once an electron hole-pair is generated, they can recombine:
    - Radiative recombination
    - Shockley-Read-Hall recomb.
    - Auger recombination

$$\frac{1}{\tau}=\frac{1}{\tau_{rr}}+\frac{1}{\tau_{ar}}+\frac{1}{\tau_{srh}}=\frac{R}{\Delta n}=\frac{D}{l^2}$$

Recombination rate (R), Diffusion coef. (D), Diffusion length (l)

  - Free charge carriers randomly moving, but no net movement
  - Net movement only if «driver»:
    - Diffuse in the material according to the concentration gradient

$$J_{x,n}=qD_n\frac{dn}{dx}\qquad J_{x,p}=qD_p\frac{dp}{dx}$$

    - Drift in the material according to an electric field

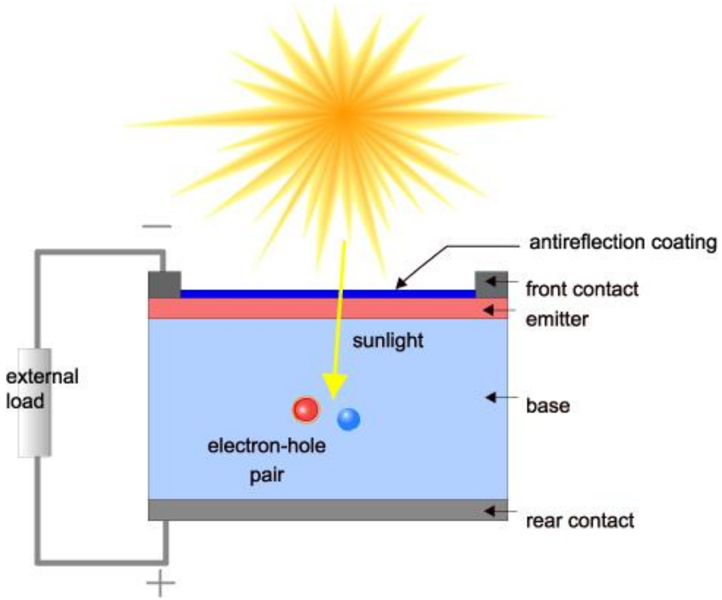
$$J_{x,n}=qn\mu_nE_x\qquad J_{x,p}=qp\mu_pE_x$$

    - Continuity equation: $\frac{dn}{dt}=\frac{1}{q}\frac{dJ_n}{dx}+G-R\qquad\frac{dp}{dt}=-\frac{1}{q}\frac{dJ_p}{dx}+G-R$
    - Plus Poisson eq. for electric field

Working principle

- A solar cell is an electronic device which directly converts sunlight into electricity.

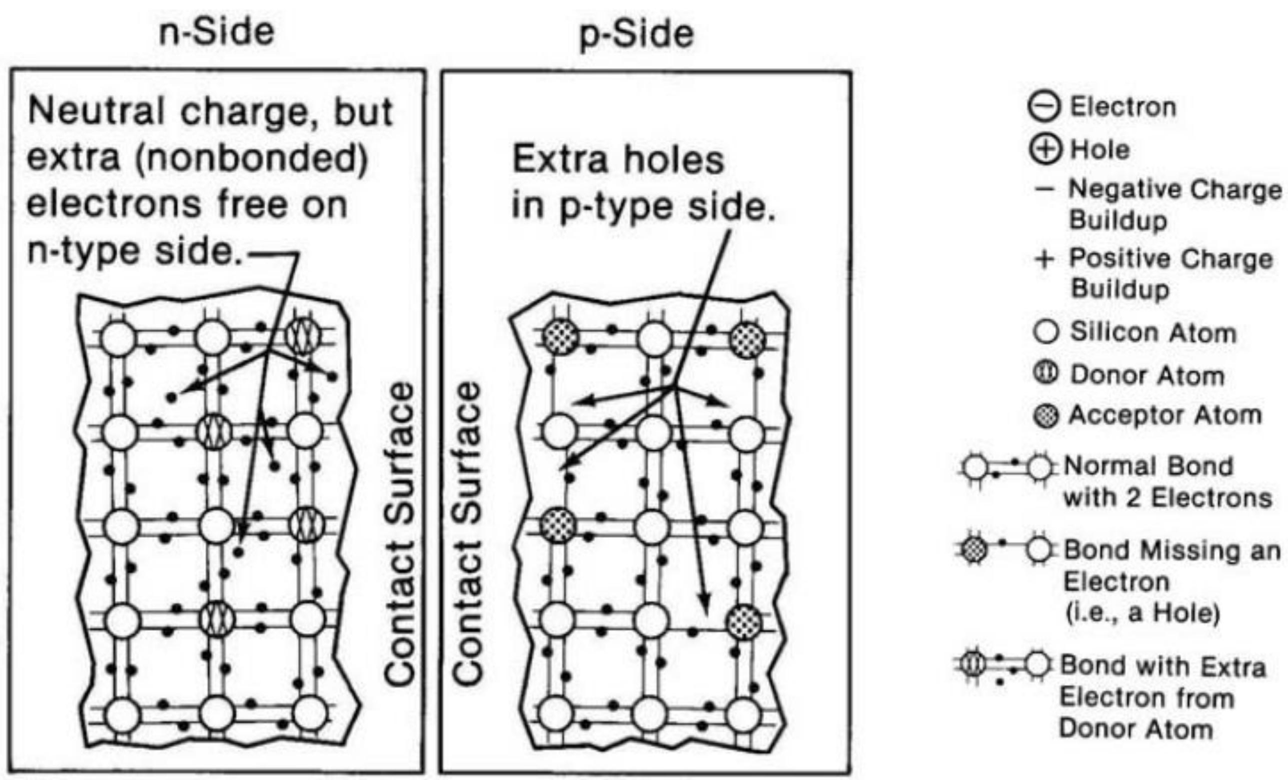
  Light shining on the solar cell produces both a current and a voltage to generate electric power.



- This process requires
  - a material in which the absorption of light raises an electron to a higher energy state
  - the movement of this higher energy electron from the solar cell into an external circuit. The electron then dissipates its energy in the external circuit and returns to the solar cell.

Working principle

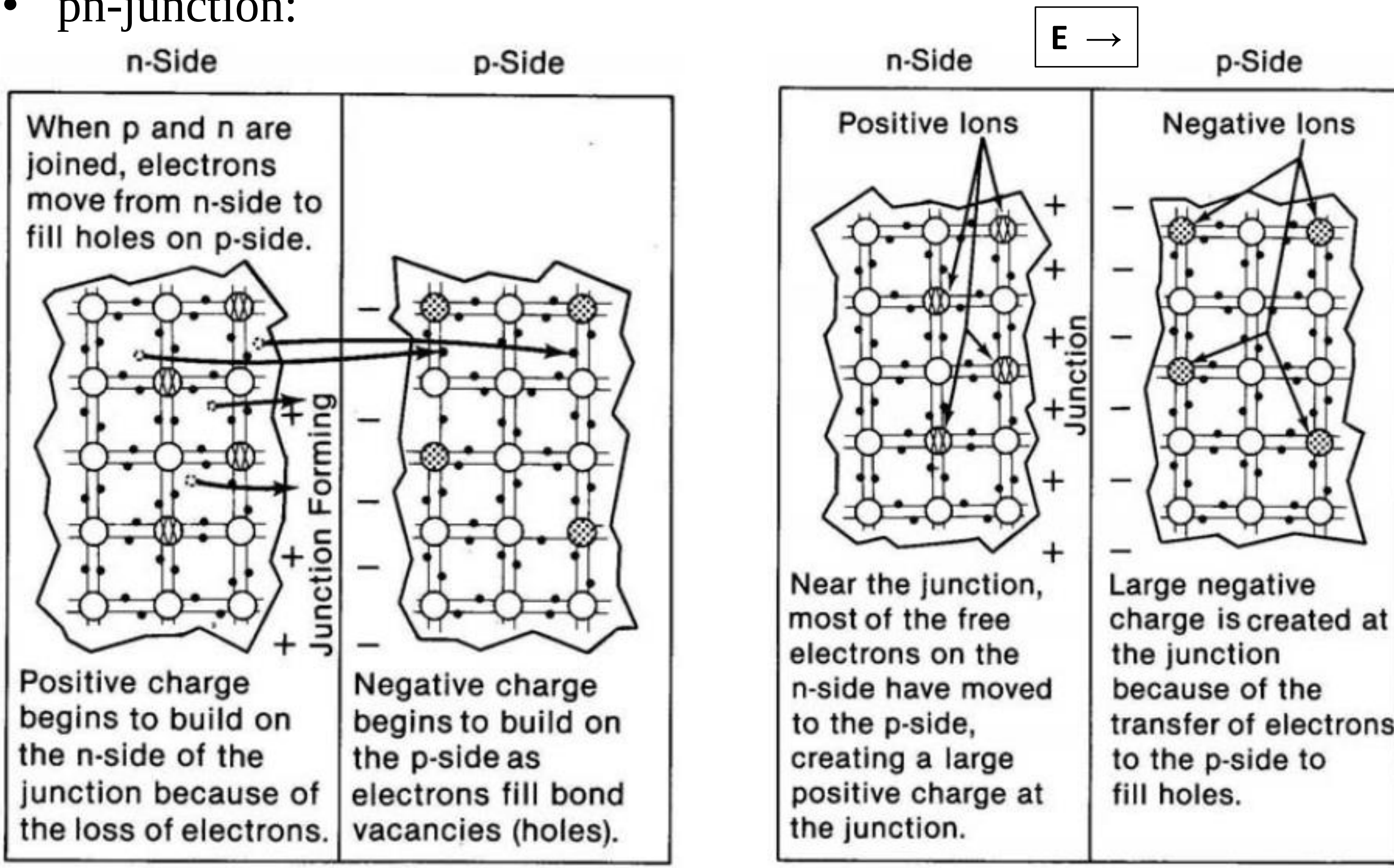
- To efficiently separate the generated electron-hole pairs before they recombine, often electric field required
- pn-junction a possible approach to generate electric field:



Basic photovoltaic principles and methods, 1981.

Working principle

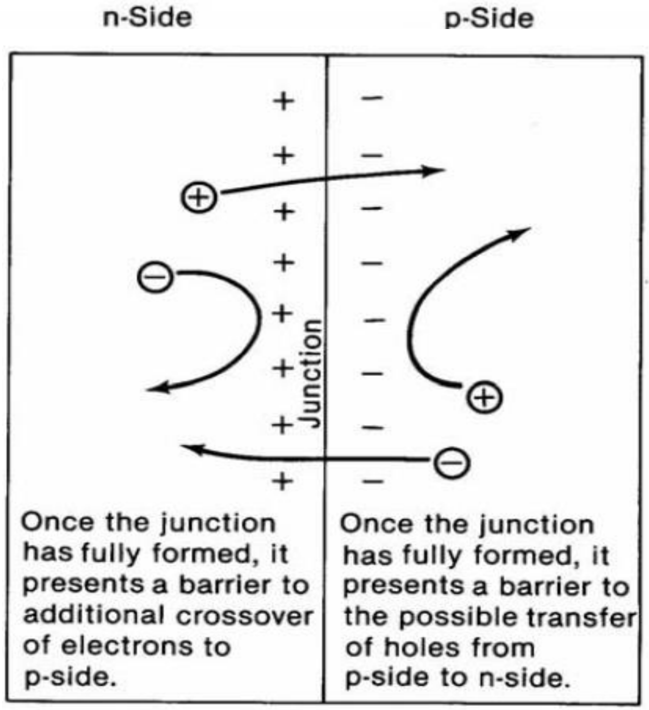
- pn-junction:



Basic photovoltaic principles and methods, 1981.

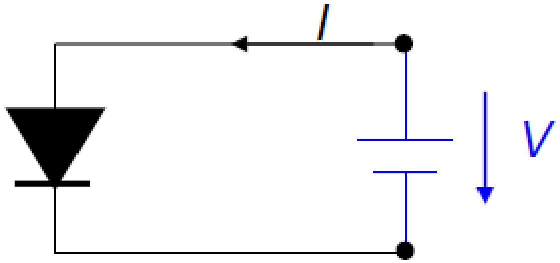
Working principle

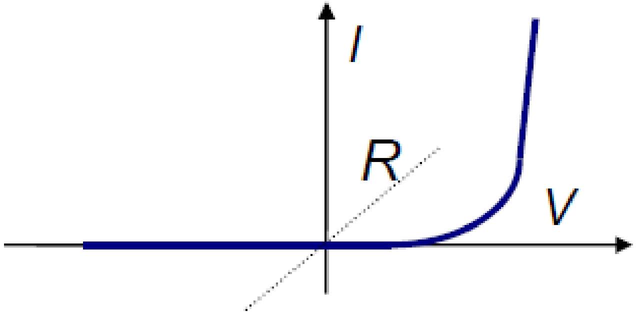
- pn-junction:
  - At equilibrium drift and diffusion currents are equal, zero net current



Basic photovoltaic principles and methods, 1981.

  - Behaves like a diode:

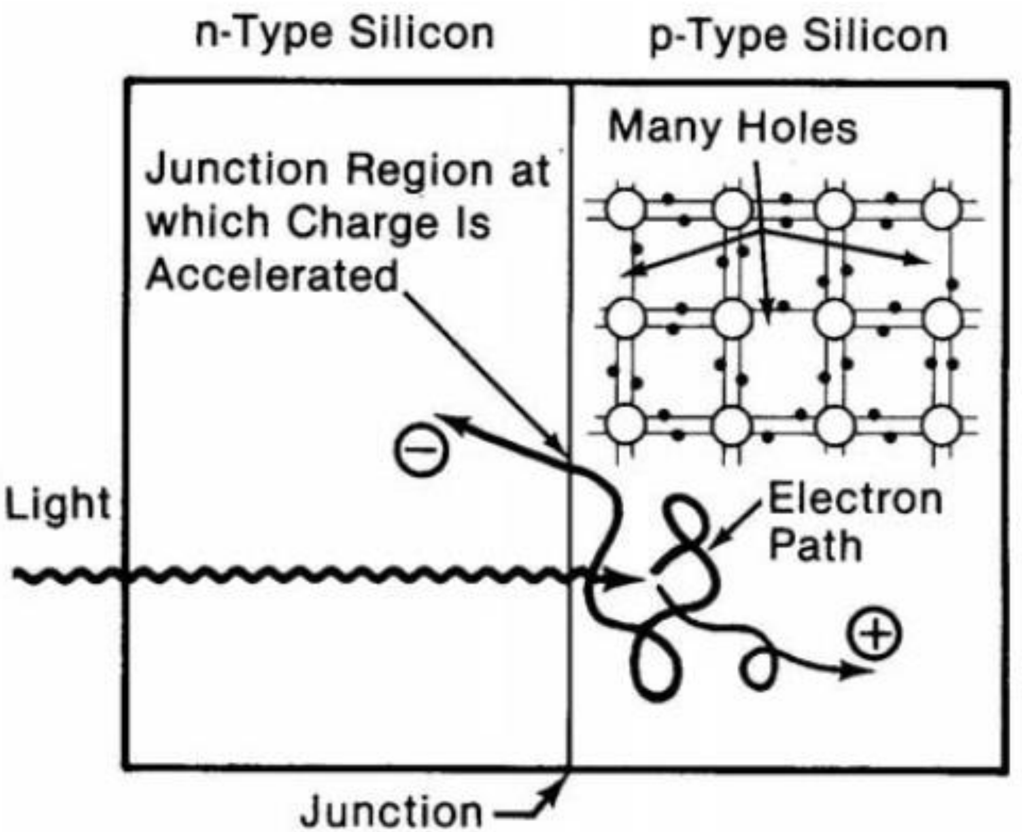




$$I = I_0\left(\exp\left(\frac{qV}{kT}\right)-1\right)$$

Working principle

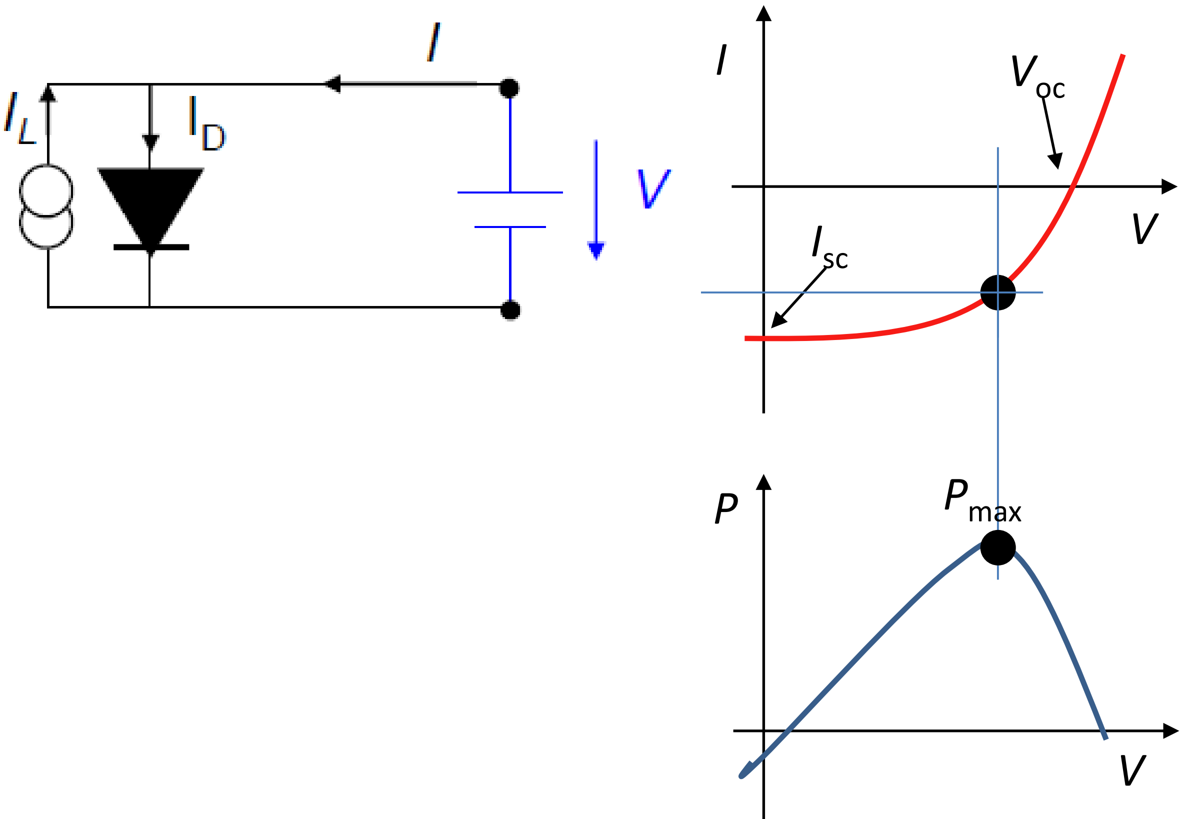
- pn-junction in a photovoltaic cell:



Basic photovoltaic principles and methods, 1981.

Working principle

- pn-junction in a photovoltaic cell:
  - Light induced current



$$I = -I_L + I_D$$
$$= -I_L + I_0\left(\exp\left(\frac{qV}{kT}\right) - 1\right)$$

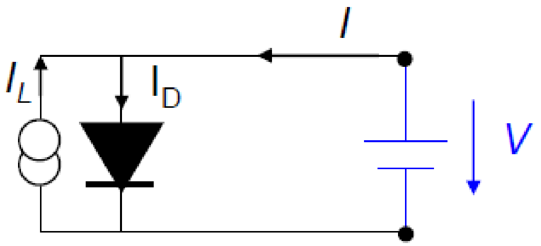
Power: $I \cdot V$

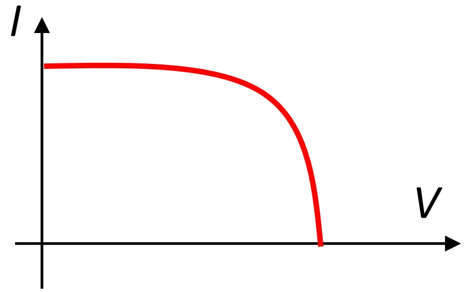
Maximum power: $I_{pmax} \cdot V_{pmax}$

Fill factor: FF= $I_{pmax} \cdot V_{pmax} / (I_{sc} \cdot V_{oc})$

Working principle

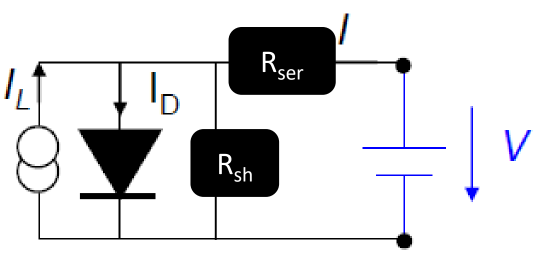
- pn-junction in a photovoltaic cell:
  - Ideal diode

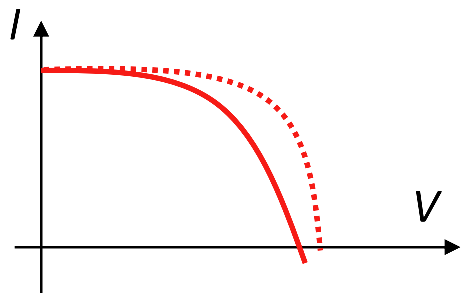




$$I = I_L - I_0\left(\exp\left(\frac{qV}{kT}\right) - 1\right)$$

  - Realistic: parasitic resistances

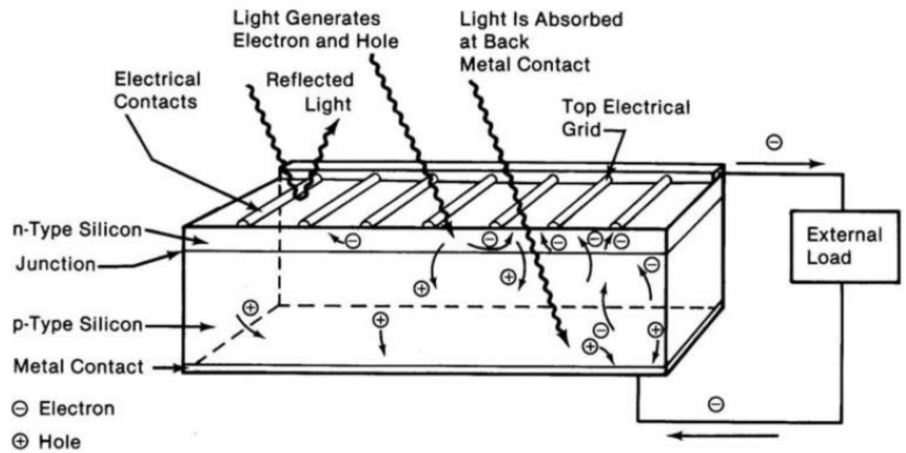




$$I = I_L - I_0\left(\exp\left(\frac{qV + qiR_{ser}}{kT}\right) - 1\right) - \frac{V + iR_{ser}}{R_{sh}}$$

Working principle

- pn-junction in a photovoltaic cell and charge collection:
  - Charge collection:

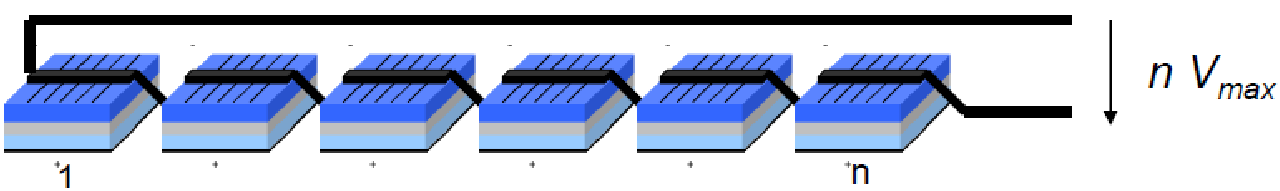


Basic photovoltaic principles and methods, 1981.

  - Voltage and current depend on material

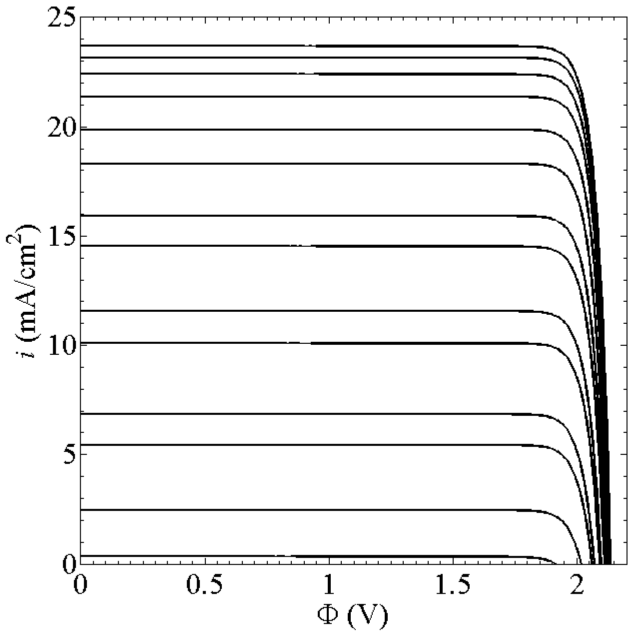
    e.g. crystalline Si V=0.6 V, i=35 mA/m^2

    - High voltage: in series
    - High current: large area



Working principle

- PV cell:
  - Characteristics changes with irradiation, temperature, and age



  - Maximum power point tracker (MPPT):
    high efficiency DC to DC converter that presents an optimal electrical load to a solar panel or array, produces a voltage suitable for the load (e.g. a battery system or an a DC/AC converter).
  - Most common use "perturb and observe" algorithm

Working principle

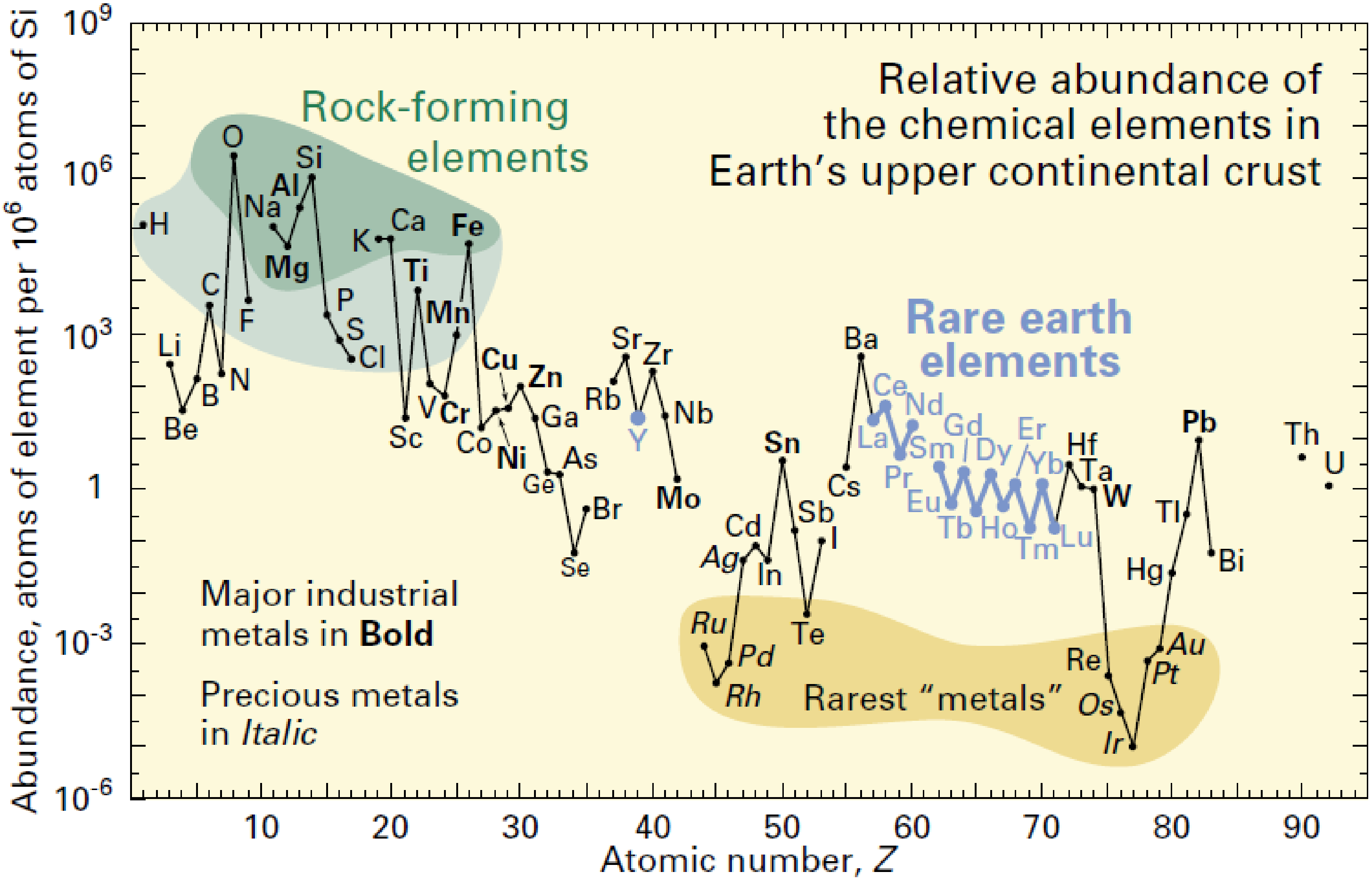
- PV cell:
  - For grid usage, use inverter (electrical device that converts DC to AC current).
  - For PV inverters usually include an MPPT tracker and additional functions such as voltage/frequency stability, fault ride through capability, anti-islanding

SMA, «Sunny boy», 3kW

Solaron PV inverters, 500 kW, installed at a 35 MW PV plant, near Coalinga, CA

Efficiency

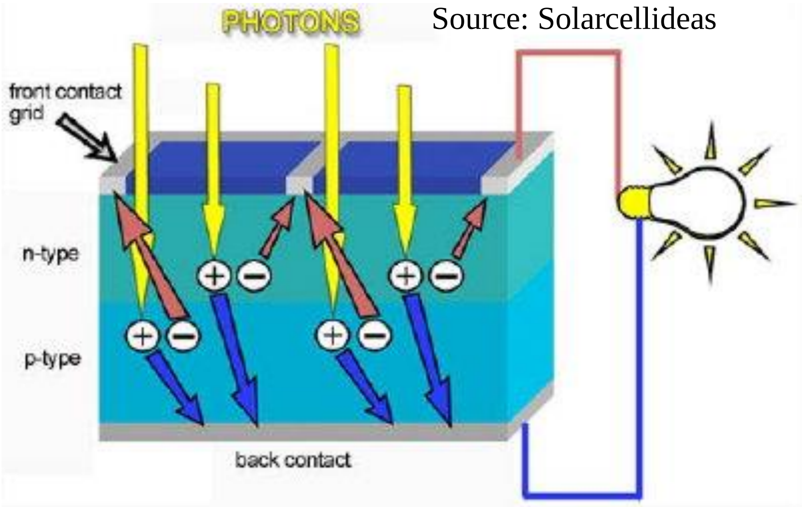
- PV material choice: availability



US Geological Survey, Fact Sheet 2002

Efficiency

- PV material choice:



Source: Solarcellideas

$$E_{\text{photon}} = \frac{hc}{\lambda} \qquad E_{\text{gap}} = \frac{hc}{\lambda_{\text{gap}}}$$

$c = 3\times10^{8}$ m/s
$h = 6.63\times10^{-34}$ J s
1 eV = 1.6×10^{-19} J

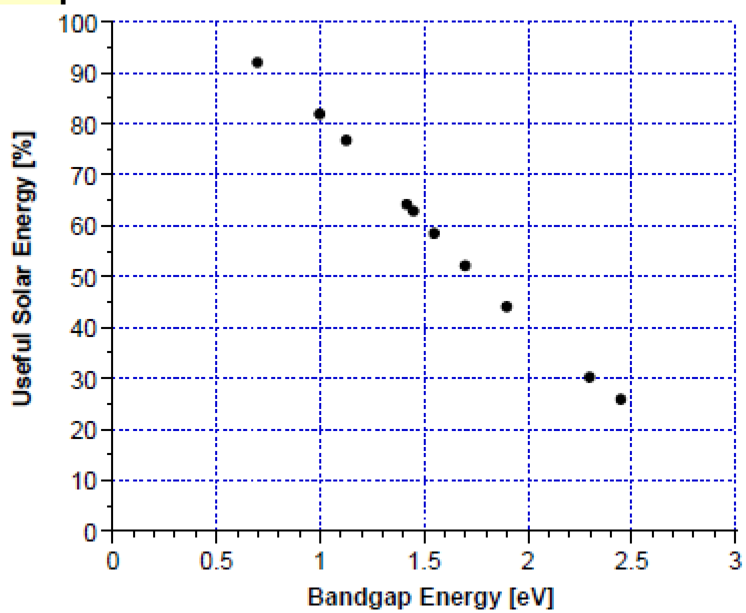
Material	E_G in eV	
Ge	0.7	→ λ_G = 1.78 μm
$CuInSe_2$	1	
Si	1.13	→ λ_G = 1.13 μm
GaAs	1.42	
CdTe	1.45	
AlSb	1.55	
$CuGaSe_2$	1.7	
a Si (amorph)	1.7	
$Al_{0.85}Ga_{0.15}As$	1.9	
GaP	2.3	
CdS	2.45	→ λ_G = 0.51 μm

Efficiency

- PV: simple efficiency calculations

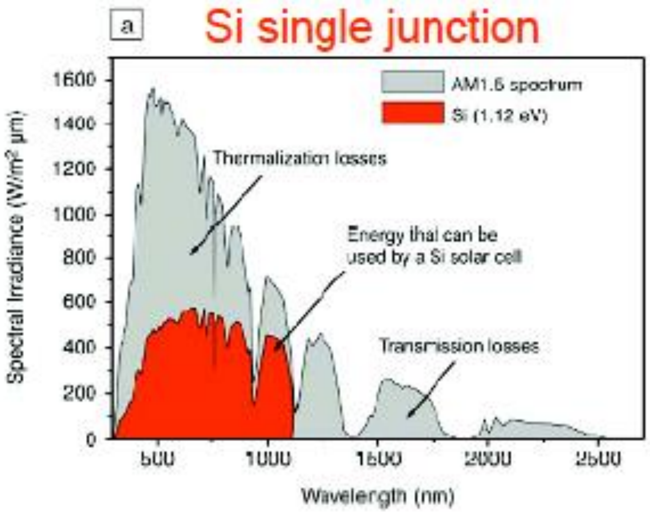
$F_{0-\lambda T}$

Material	E_G	λ_G	useful	not useful
	[eV]	[mm]	[%]	[%]
Ge	0.7	1.78	91.94	8.06
CuInSe2	1	1.24	81.84	18.16
Si	1.13	1.10	76.62	23.38
GaAs	1.42	0.88	64.12	35.88
CdTe	1.45	0.86	62.81	37.19
AlSb	1.55	0.80	58.45	41.55
CuGaSe2	1.7	0.73	52.05	47.95
a Si	1.7	0.73	52.05	47.95
AlGaAs	1.9	0.65	43.98	56.02
GaP	2.3	0.54	30.12	69.88
CdS	2.45	0.51	25.80	74.20



Efficiency

- PV: simple efficiency calculations
  - But for wavelengths smaller than band gap wavelength, not all energy useful for charge generation



  - Consequently, efficiency is given by:

$$\eta = \frac{\int_0^{\lambda_g} \frac{E_g}{E} e_{\lambda b} d\lambda}{\int_0^{\infty} e_{\lambda b} d\lambda} = \frac{1}{\sigma T^4} \int_0^{\lambda_g} \frac{E_g}{E} e_{\lambda b} d\lambda \approx \frac{1}{\sigma T^4} \sum_{i=1}^{N} \int_{\lambda_i}^{\lambda_{i+1}} \frac{E_g}{E_{\lambda_{m,i}}} e_{\lambda b} d\lambda = \sum_{i=1}^{N} \frac{E_g}{E_{\lambda_{m,i}}} F_{\lambda_i - \lambda_{i+1}}$$

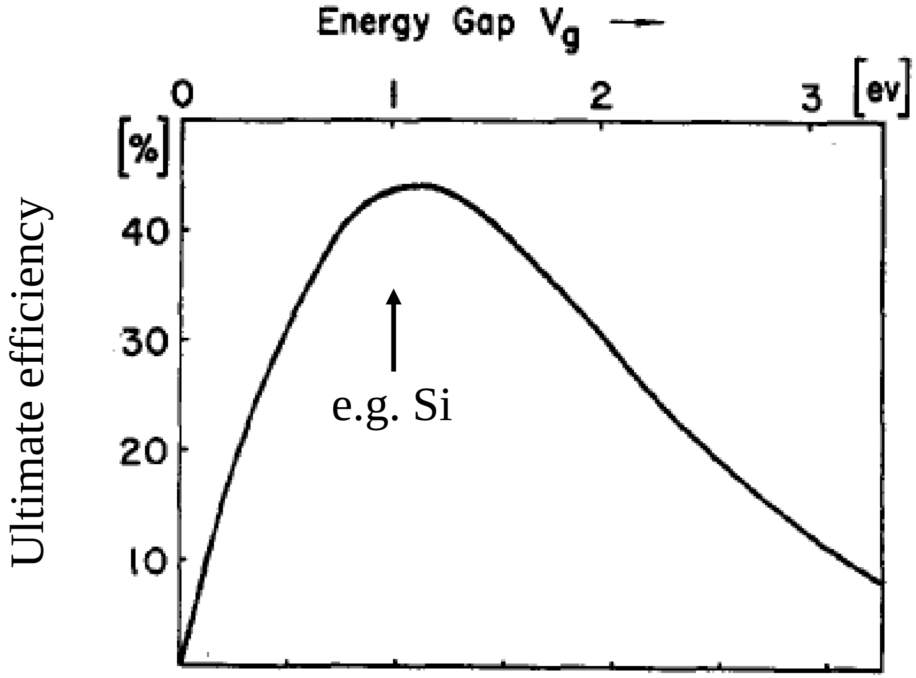
Mean wavelength in *i*-th band

Efficiency

- PV: simple efficiency calculations – Example Si, E_g=1.1 eV

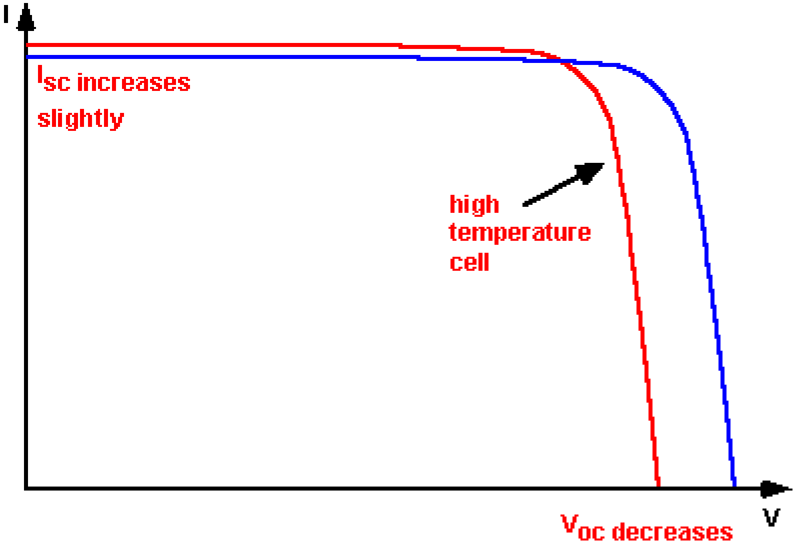
Efficiency

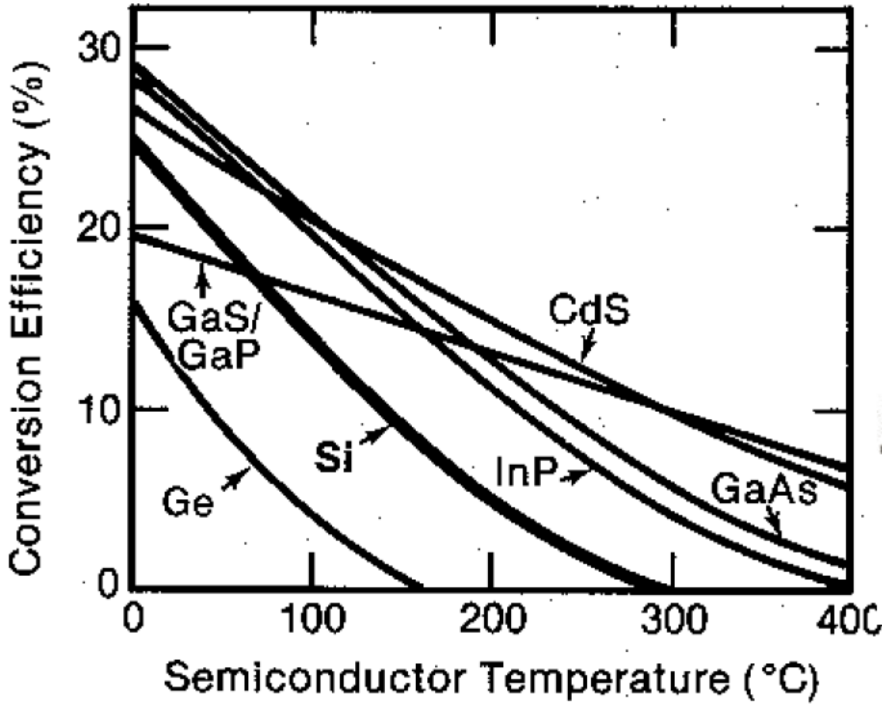
- PV theoretical efficiencies
  - Theoretical efficiency limit by Shockley and Queisser, 1961



Efficiency

- Efficiency:
  - Temperature dependence:
    - Decrease in band gap energy
    - Slight increase in I_{sc}
    - But decrease in V_{oc}





Basic photovoltaic principles and methods, 1981.

Efficiency

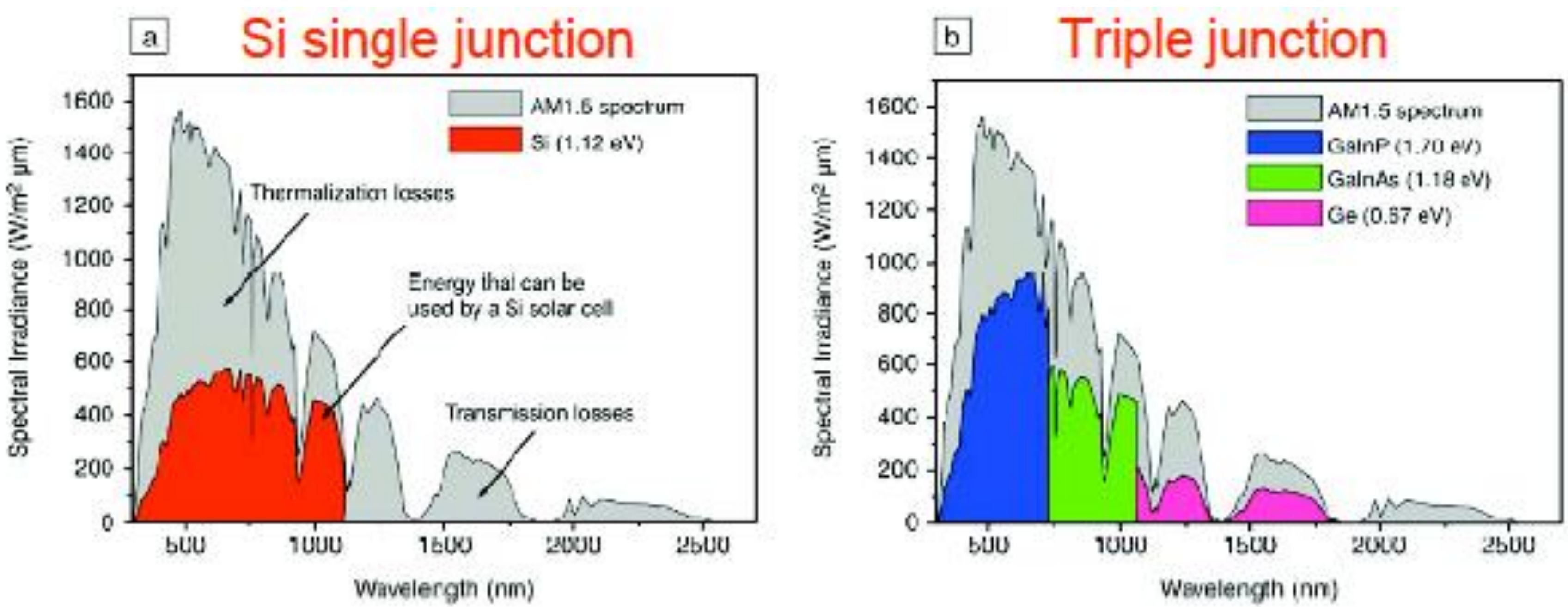
- Efficiency:
  - Concentration dependent:
    - I_{sc} linearly increases with concentration (no effect on efficiency)
    - V_{oc} increases logarithmically

Efficiency

- Efficiency:
  - Realistically also to consider:
    - Surface reflection
    - Opacity of current collectors
    - Limited thickness
    - Limited minority carrier lifetime
    - Material quality (e.g. crystal boundaries)
    - Series resistance of cell
    - Shunt resistance of cell
    - Irradiation condition (spectral changes, directional changes)

Efficiency

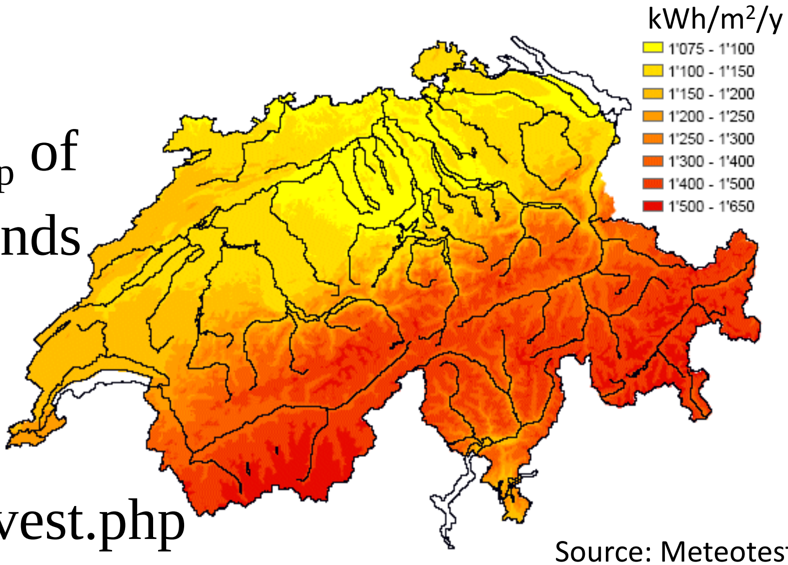
- PV cell with higher efficiency:
  - Multi-layers with different materials:



  - In series, connected with tunnel junctions: try to be current matching!

Efficiency

- Measurement of efficiency:
  - Standard test conditions (*STC*), Module at 25°C, spectrum AM1.5G (global), light intensity 1000 W/m²
  - Efficiency: $\eta = \left. \frac{P_{\max}}{P_{in}} \right|_{STC}$
  - Modules are sold according to W or W_p (=W peak), with respect to 1000 W/m² (AM1.5G)
  - Rule of thumb: in CH or Germany 1 W_p of modules give 1 kWh per year (corresponds roughly to 1000 hours of full sun, i.e. 1x1000 = 1kWh)
  - http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php



Source: Meteotest

Technologies

- Photovoltaics: Technologies and market

Market

Crystalline silicon
Mono and multicrystalline

Status: main market share

Thin films
CIGS, CdTe, Thin film silicon

Status: stabilised market share

Concentrator technologies
Mostly III-V based

Status: trying entering the market, many start-ups

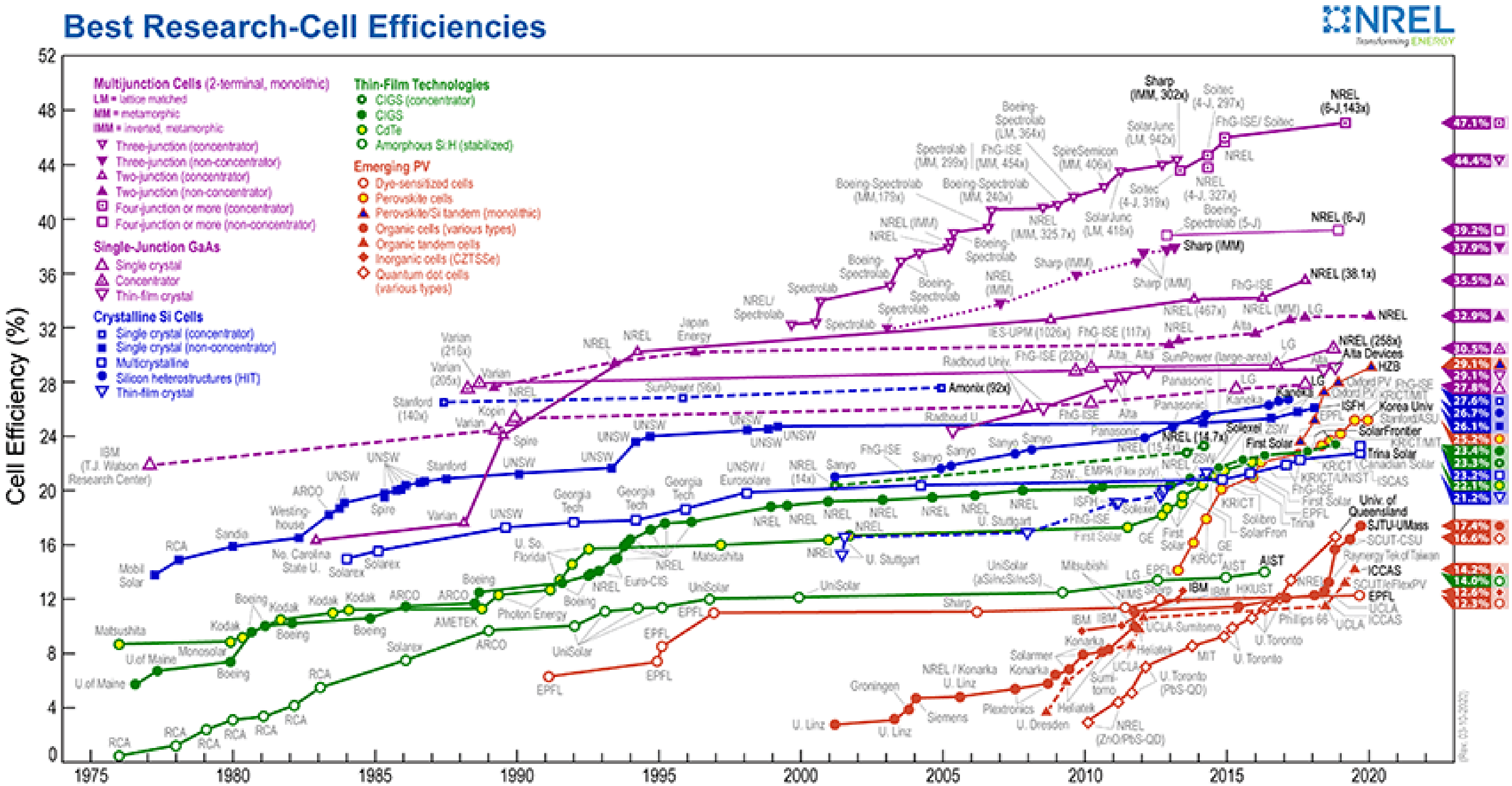
Emerging technologies
Nano inorganic
Organic-Polymer
Dye sensitized and variation
Status: niche application

Novel PV concepts
Quantum dots, intermediate band,…
Status: attempt of demonstration

Ballif, PV-lab, EPFL

Technologies

- Efficiencies of various technologies



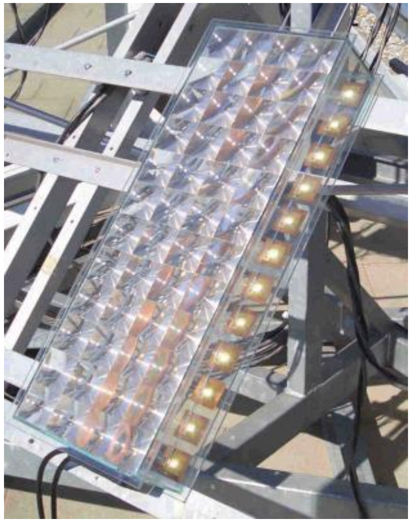
https://www.nrel.gov/pv/cell-efficiency.html

Technologies

- Efficiencies of various technologies:
  - Crystalline (Si: mono and poly):
    - Efficiency: 14-21%
    - Potential: 20-25%

- Thin film (CdTe, CIGS a-Si / μc-Si):
    - Efficiency: 14-16%
    - Potential: 16-20%

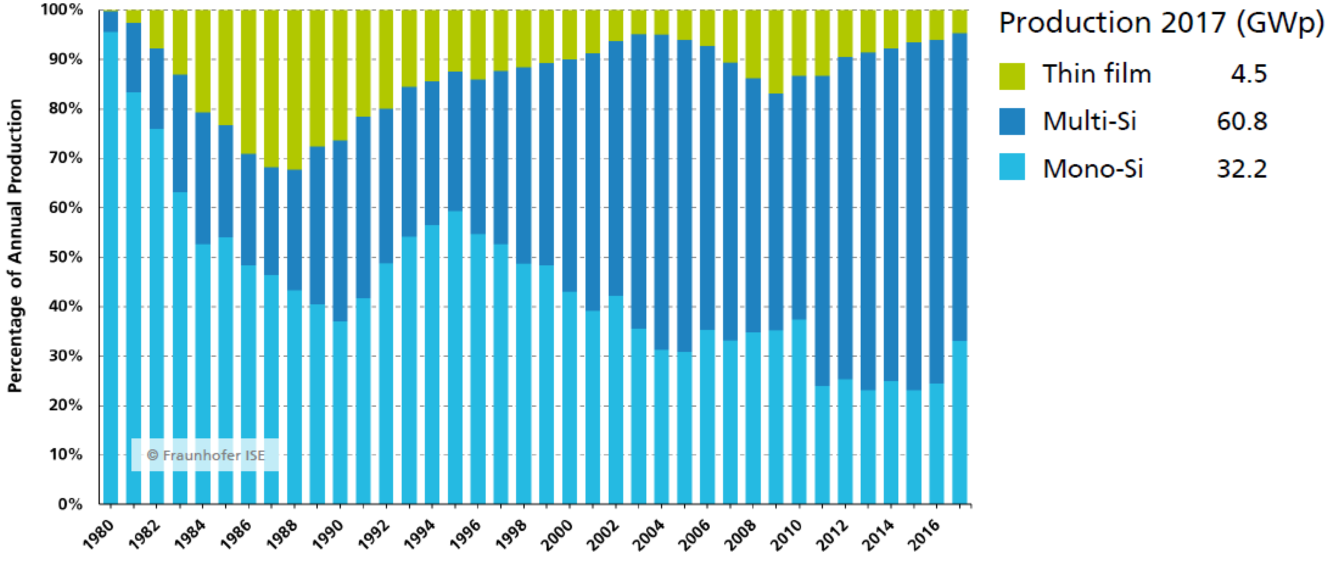
  - Concentrated (III-V-based):
    - Efficiency: 25-30%
    - Potential: 30-50%



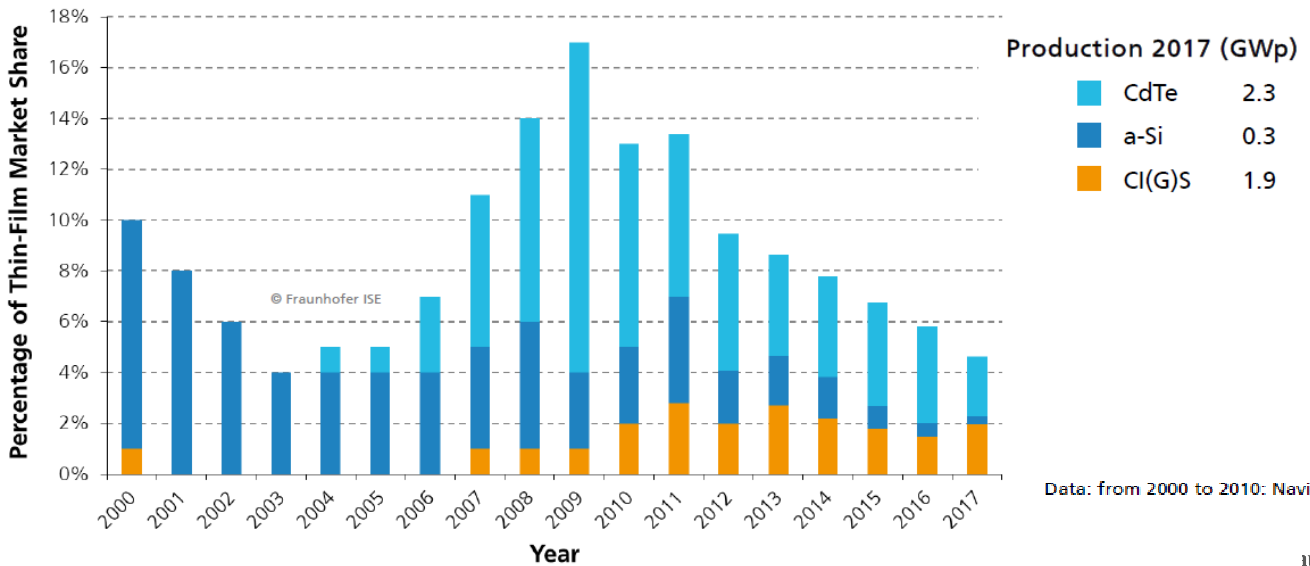
EPFL

Technologies

- Market shares:



Data: from 2000 to 2010: Navigant; from 2011: IHS (Mono-/Multi- proportion from cell production). Graph: PSE GmbH 2018



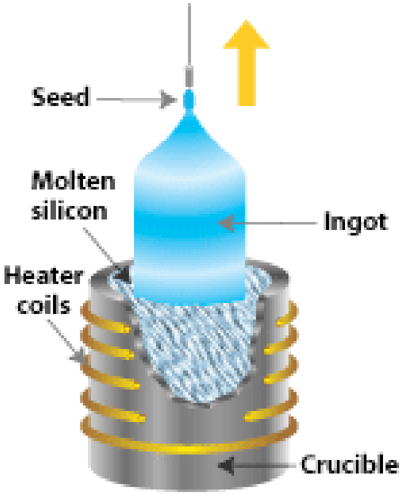
Data: from 2000 to 2010: Navigant; from 2011: IHS. Graph: PSE GmbH 2018

Technologies

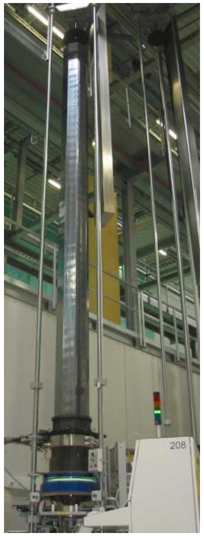
- Crystalline Silicon: Manufacturing
  - Get the raw material (SiO_2)
  - Produce high quality material by carbothermal reduction: $SiO_2+C \rightarrow Si+CO_2$, 98.7% pure, 1-3 CHF/kg
    and Siemens process:
    $Si+HCl \rightarrow SiHCl_3+H_2$, and distillation, 2ppb impurity
    $2SiHCl_3 \rightarrow Si+2HCl+SiCl_4$, «solar grade», 0.1ppb impurity, 15 CHF/kg
  - Dopping of the material (often p-doping)
  - If monocristalline quality needed: Czochralski process or edge-defined film-fed growth
  - Sawing

Technologies

- Cristalline Si: Manufacturing
  - Czochralski process

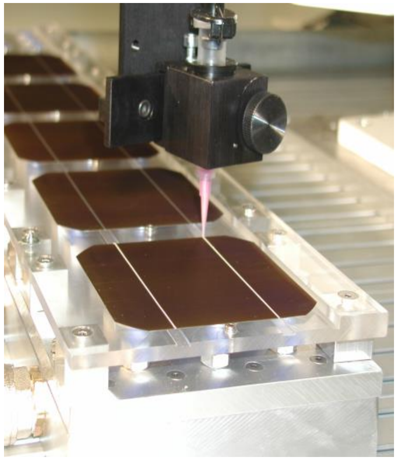


  - Edge-defined film-fed growth (RWE Schott Solar, 2005)



Technologies

- Crystalline Silicon: Manufacturing
  - Chemical surface attacking with hot HF or NaOH texturing of surface (20µm) to reduce surface reflection (40% reflection reduced to about 15%)
  - Doping (n-doping): diffusion of phosphorous into surface
  - „printing" of the contacts and „electron connector" grid (often in a single assembly line, automatic)
  - Printing of back contacts (Al, Ag, …)
  - Potential additional antireflection coating on front
  - Assembling of panel, sealing and transportation

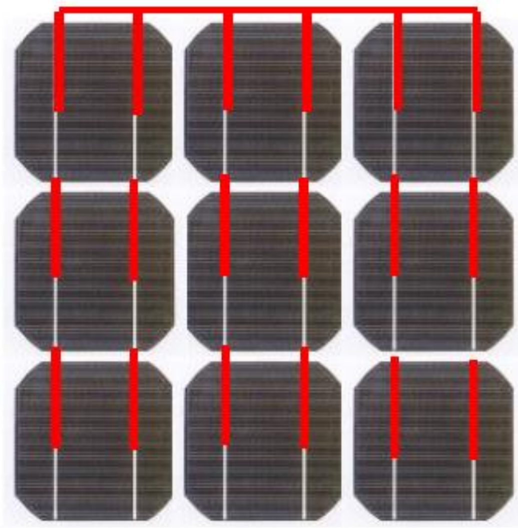


Technologies

- Photovoltaics:
  - Crystalline silicon:

    Processing of wafers

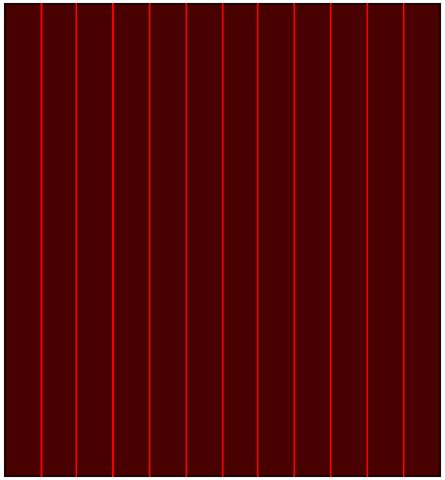
    Series connection of individual solar cells



  - Thin film:

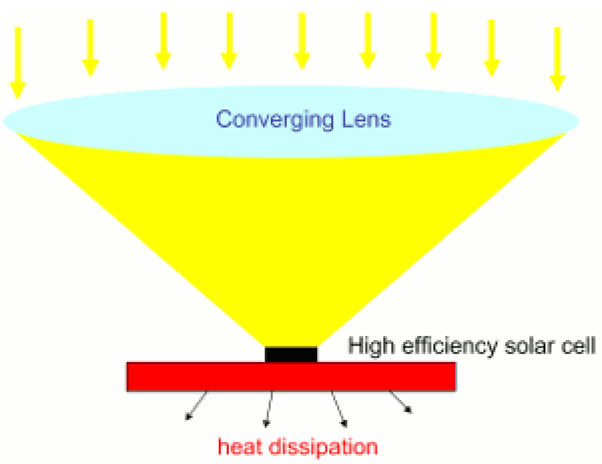
    Depositions on large area substrate

    “monolithic series integration” of the cells (typically by lasering)



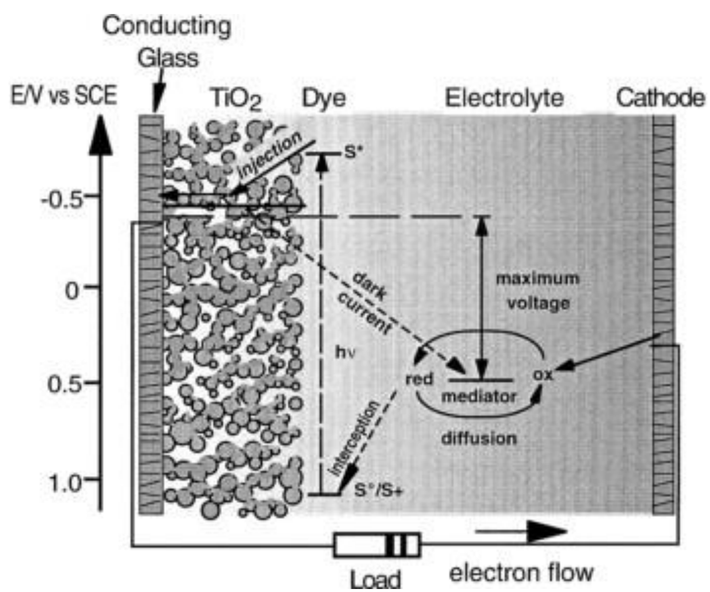
Technologies

- Concentrated PV:
  - Expensive solar cells can be cut and light concentrated
  - Good heat management required
    (because of V_{oc} and FF decrease with temperature)
  - The more you concentrate, the lower the acceptance angle

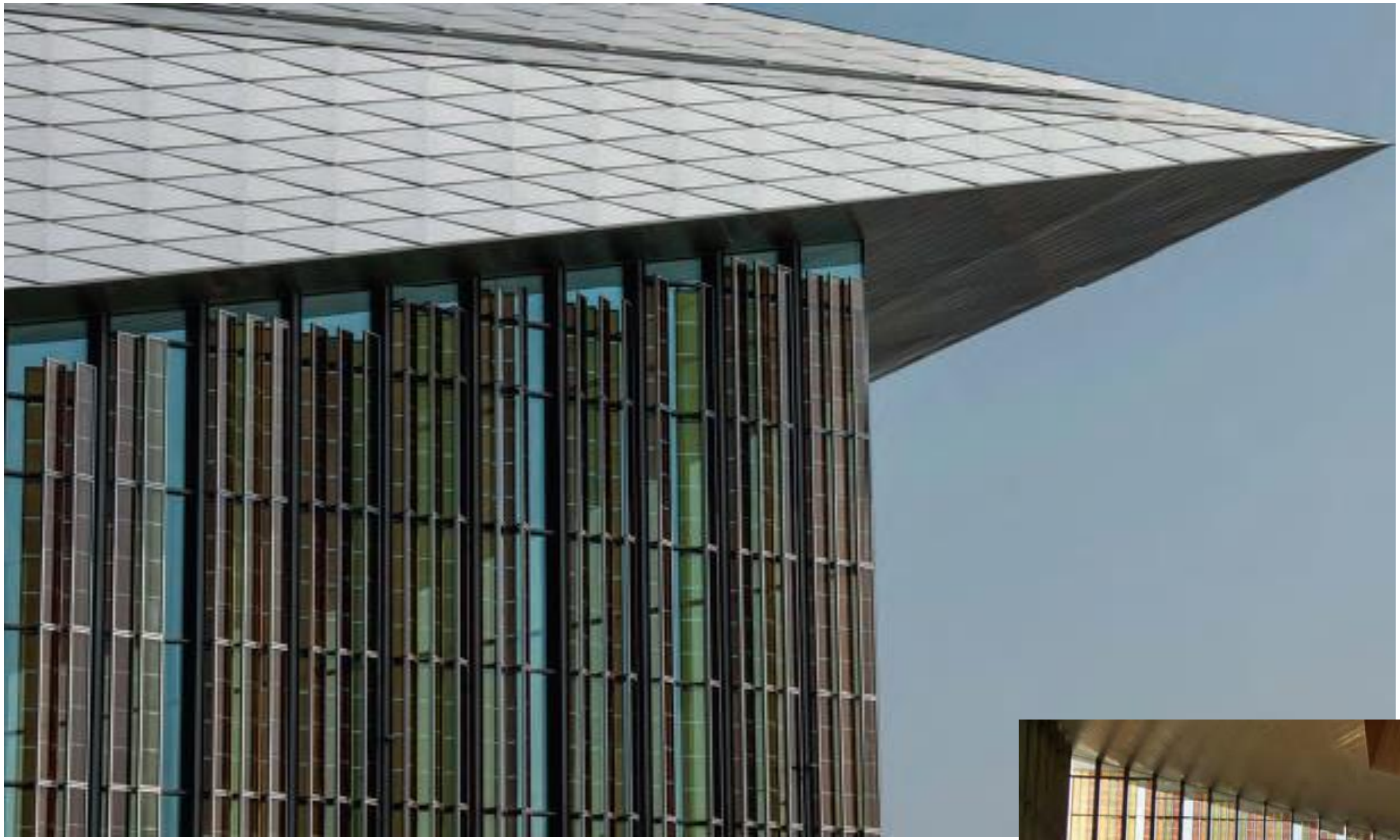


Technologies

- Organic solar cells, e.g. dye sensitized solar cells
  - Based on excitation of electron from a dye attached to a titania nanoparticles network, and fast transfer of electron to titania
  - Electron conduction through electrolyte solution
- Based on Brian O'Regan and Michael Grätzel, 1991, A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO2 films, *Nature* **353** (6346): 737–740.

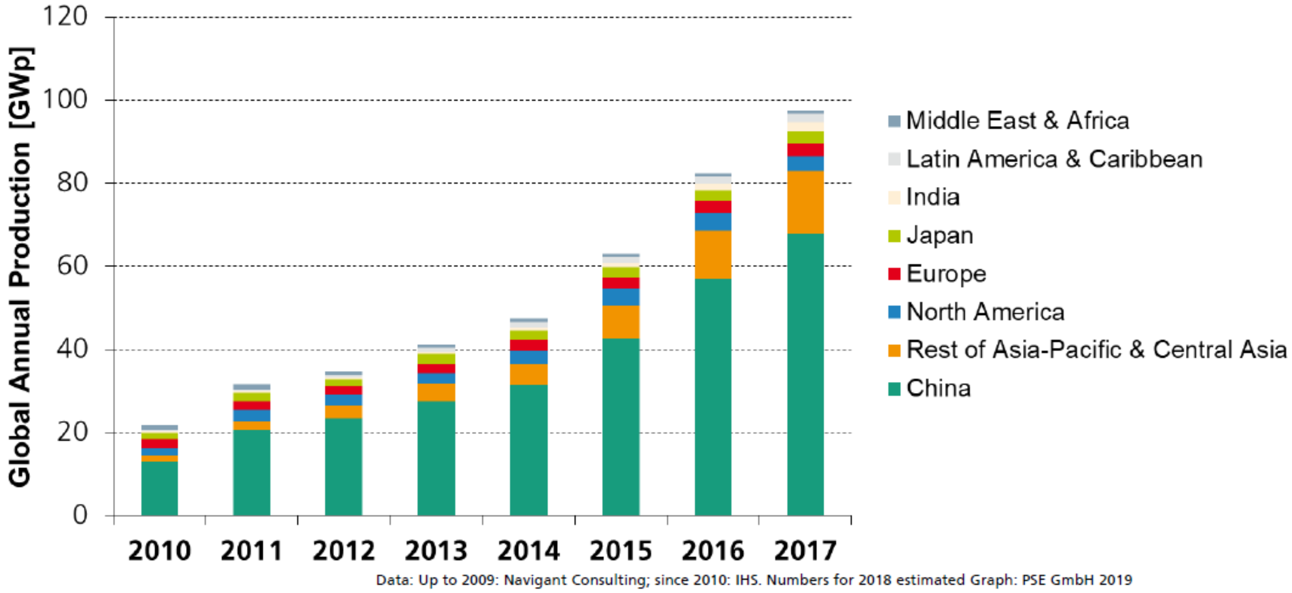


Technologies

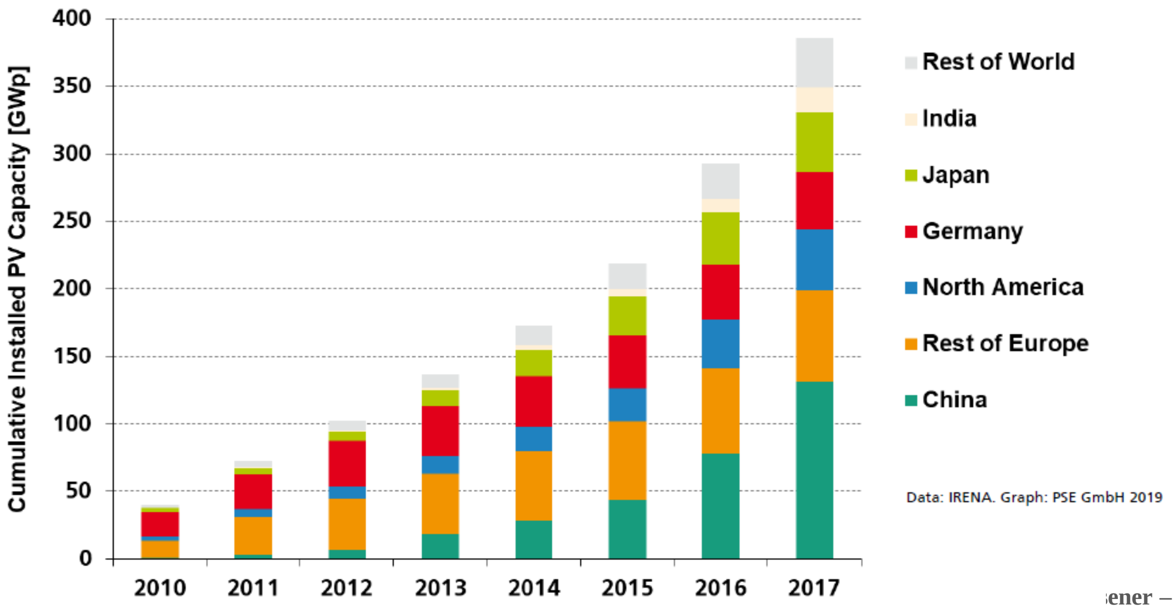


Production and Installation

- Production



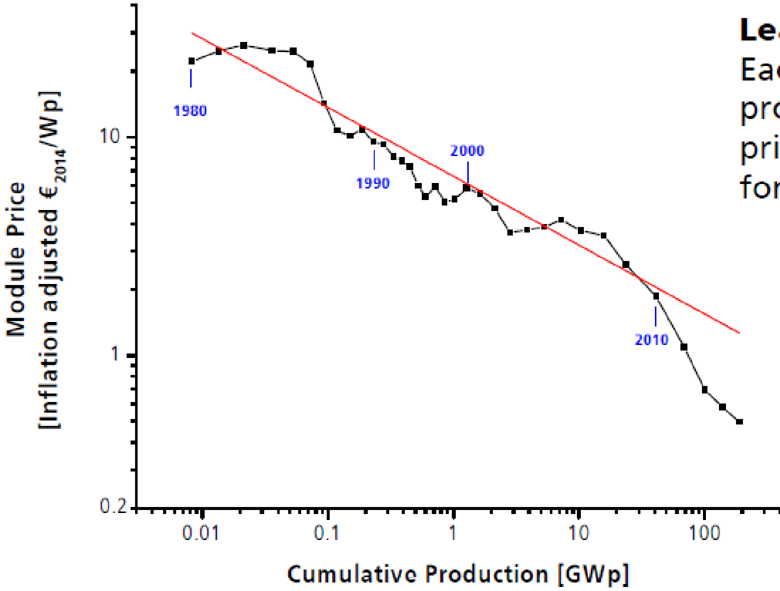
- Installation



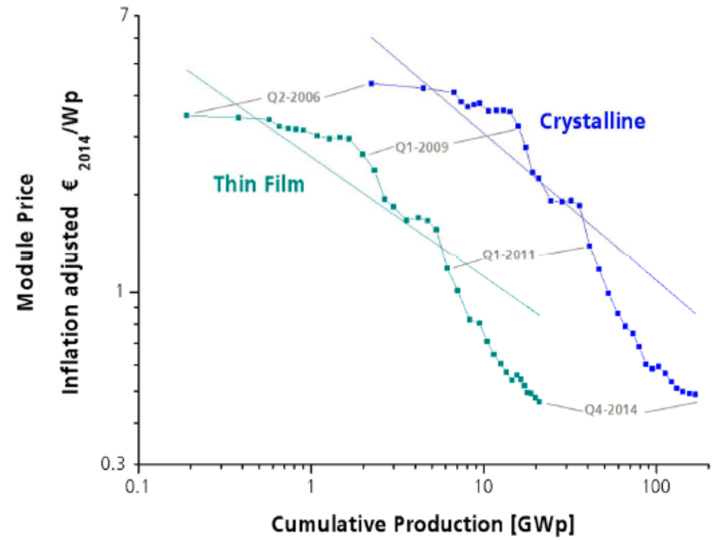
Cost

- Photovoltaics: Learning curve

Includes all commercially available technologies:



Learning Rate:
Each time the cumulative production doubled, the price went down by 19.6% for the last 34 years.

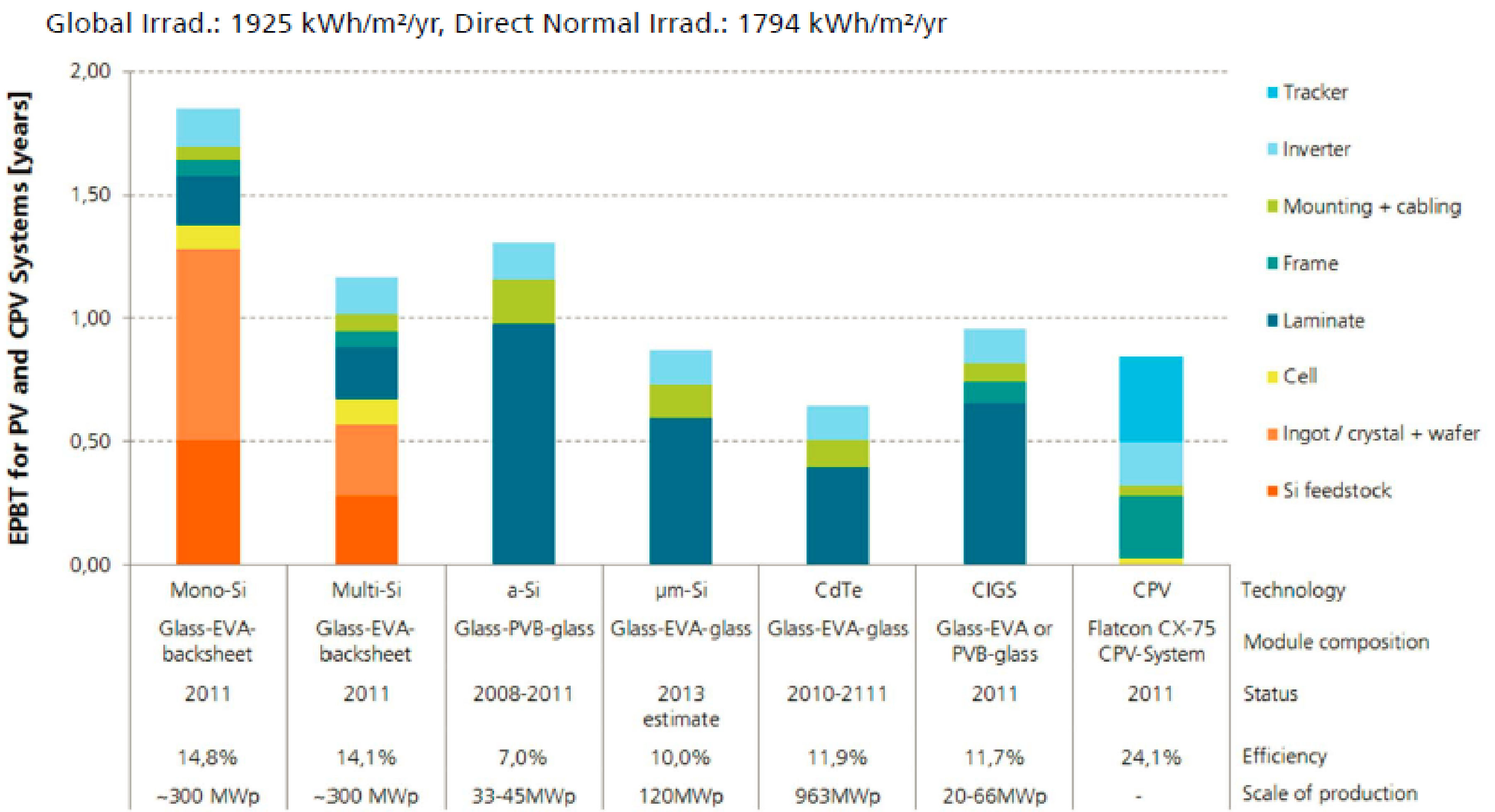


Data: from 1980 to 2010 estimation from different sources : Strategies Unlimited, Navigant Consulting, EUPD, pvXchange; from 2011 to 2014: IHS. Graph: PSE AG 2016

- Price for a Si-based module: ~ 1 €/W_p, ~ 150 €/ m^2

Sustainability

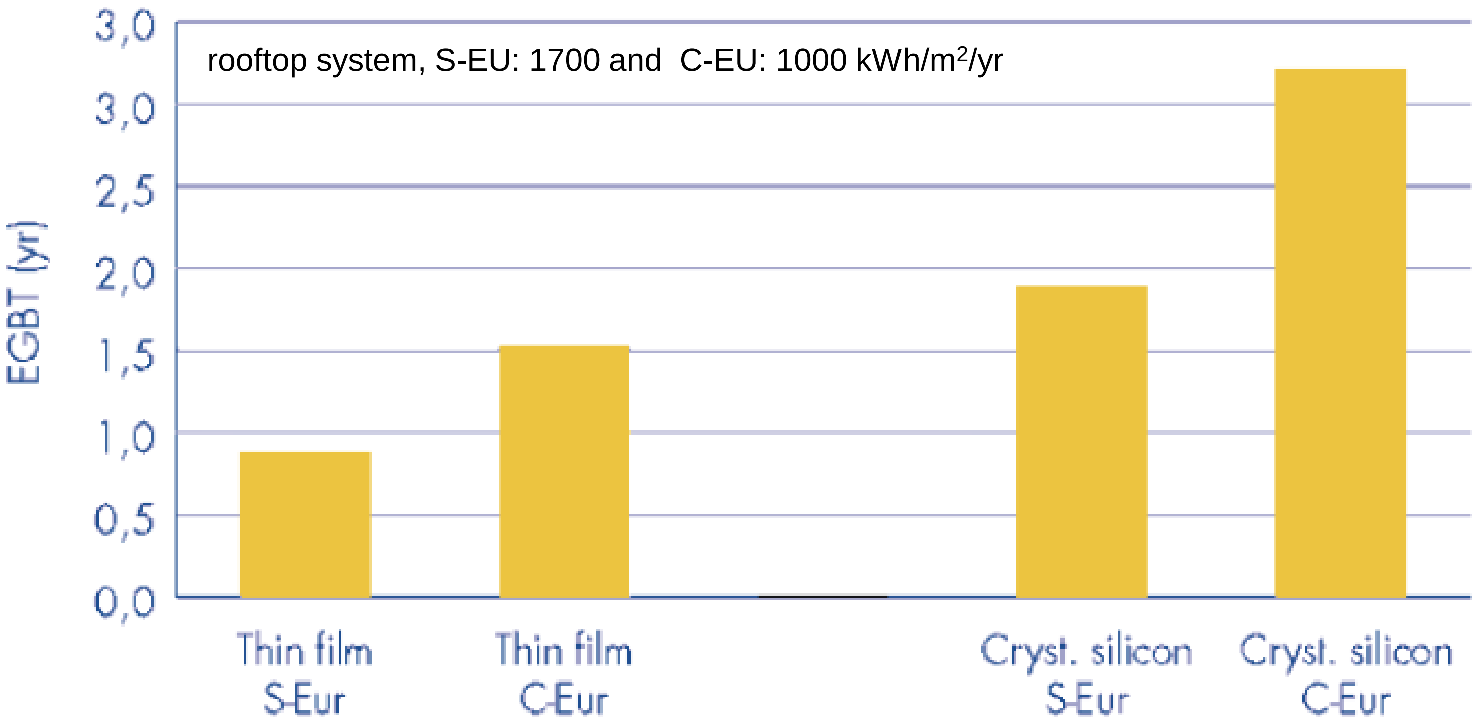
- Photovoltaics: Life cycle assessment - Technology



Data: M.J. de Wild-Scholten 2013; CPV data: "Environmental Sustainability of Concentrator PV Systems: Preliminary LCA Results of the Apollon Project" 5th World Conference on PV Energy Conversion. Valencia, Spain, 6-10 September 2010. Graph: PSE AG 2014

Sustainability

- Photovoltaics: Life cycle assessment - Location



Fthenakis et al., Environmental Science and Technology, 2008

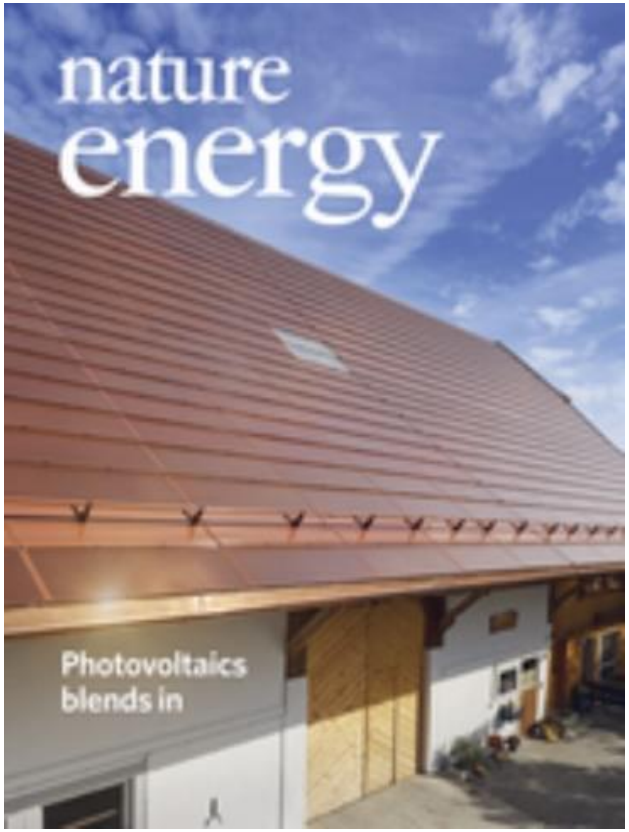
Aesthetics

- Photovoltaics: early modules

- Fully integrated today:

Aesthetics

- Photovoltaics: various colors



- Covered by prints

Learning outcomes of todays lecture

- Solar to electricity via PV:
  - Working principle of photovoltaic cell
  - Efficiency calculation for ideal cell
    - What influences efficiency (operating conditions)
    - Materials and their influence on efficiency
  - Overview of various PV technologies
    - Current efficiencies and potential
    - Differences, advantages and disadvantages

Literature

- Web:
  - pveducation.org

- Books:
  - A. Goetzberger, *Sonnenergie: Photovoltaik*, Teubner, Stuttgart (1997)
  - Da Rosa: Fundamentals of Renewable Energy Processes, Elsevier, 2005.