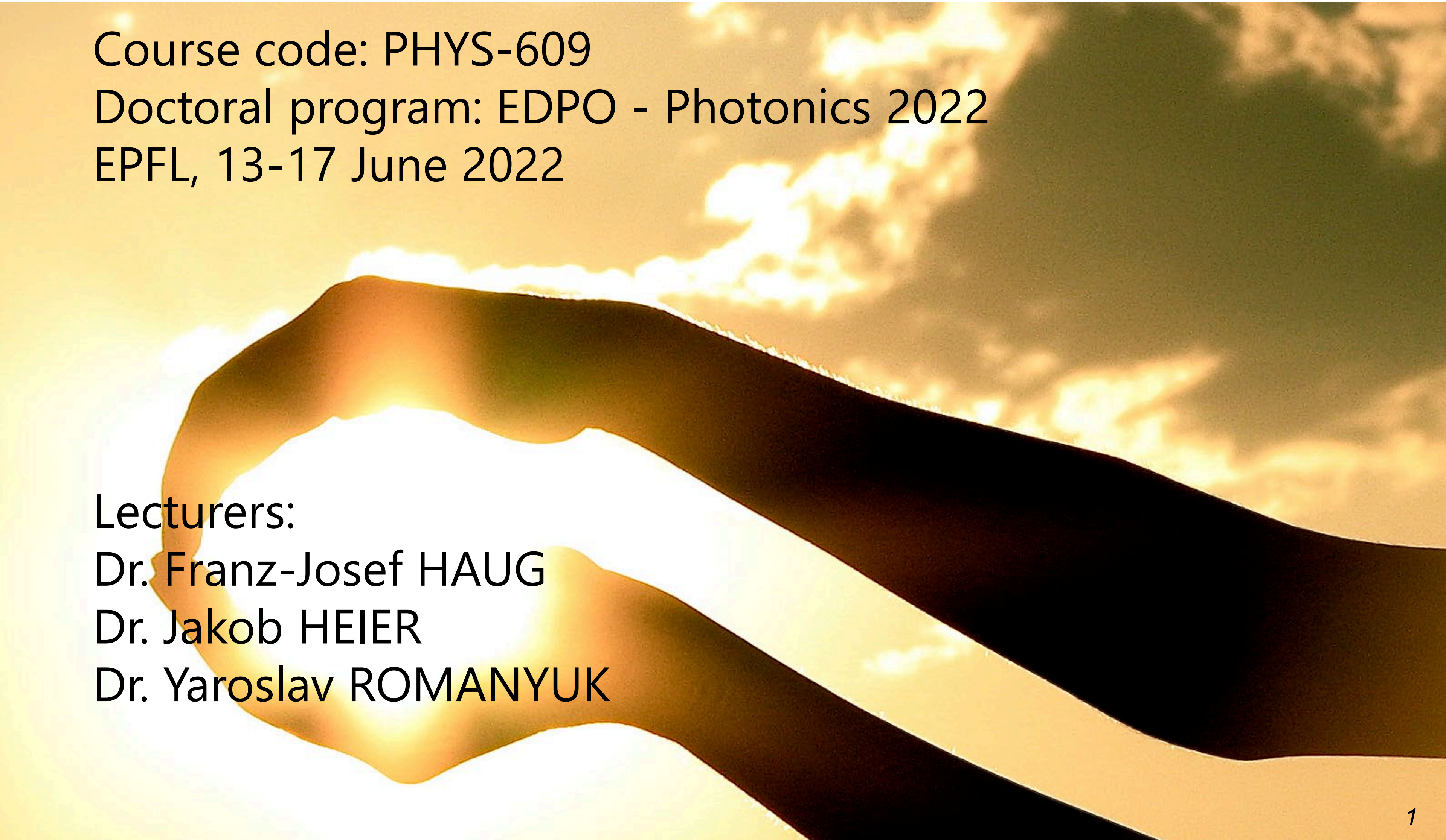
Modern photovoltaic technologies



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Part 1.1 Introduction

- Solar energy and photovoltaics
- Semiconductor physics
- Solar cell parameters
- Generations of solar cells
- PV economics

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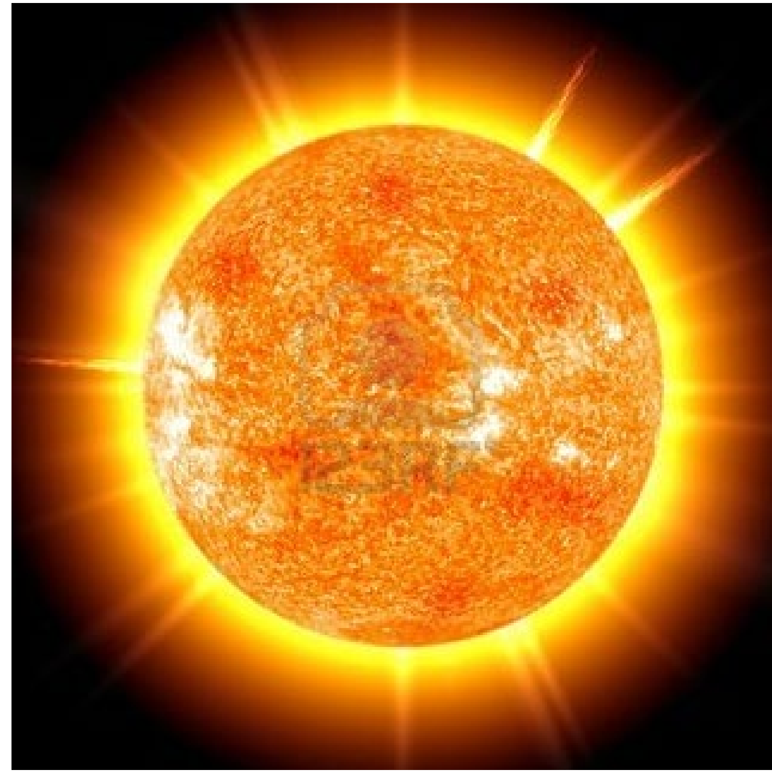
Materials Science and Technology

Solar energy and photovoltaics

Solar energy

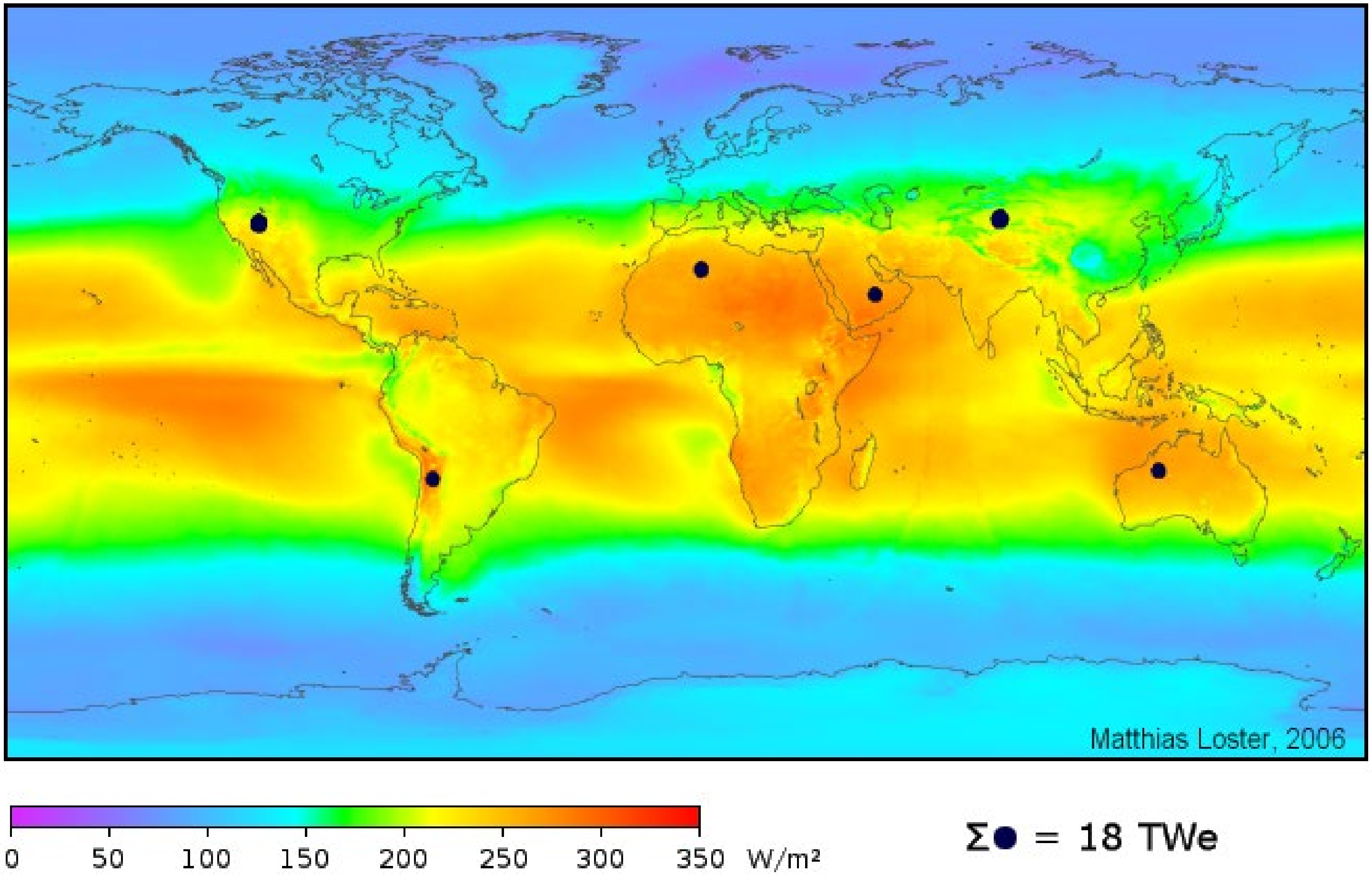


Solar energy received by the Earth within one hour

equals the world electricity consumption in one year

(26,700 TWh in 2018)

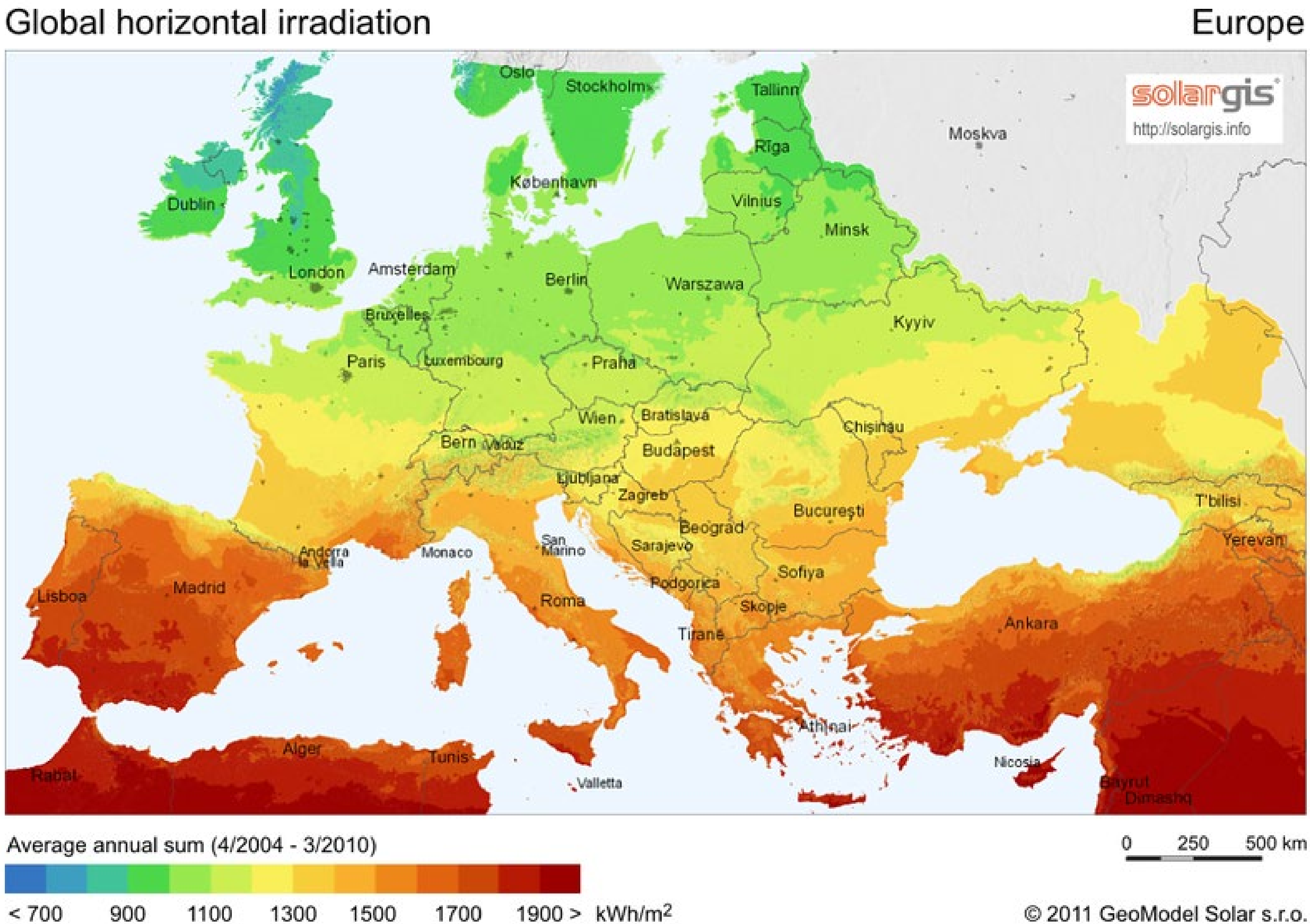
Solar irradiation



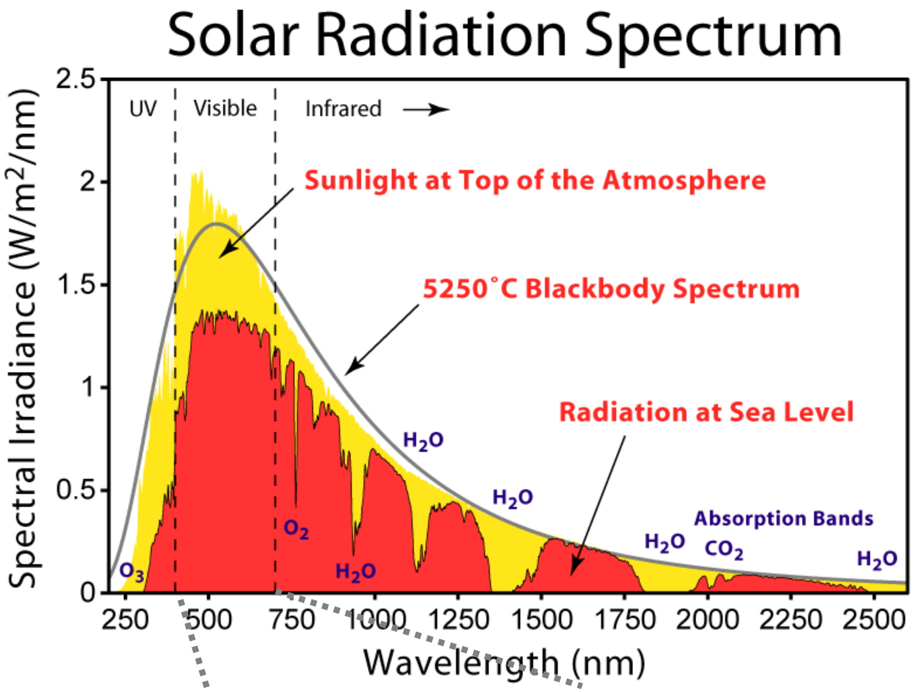
http://en.wikipedia.org/wiki/Solar_energy

- 4% of existing desert area can provide PV power equivalent to the world energy consumption

Solar radiation in Europe



Solar radiation



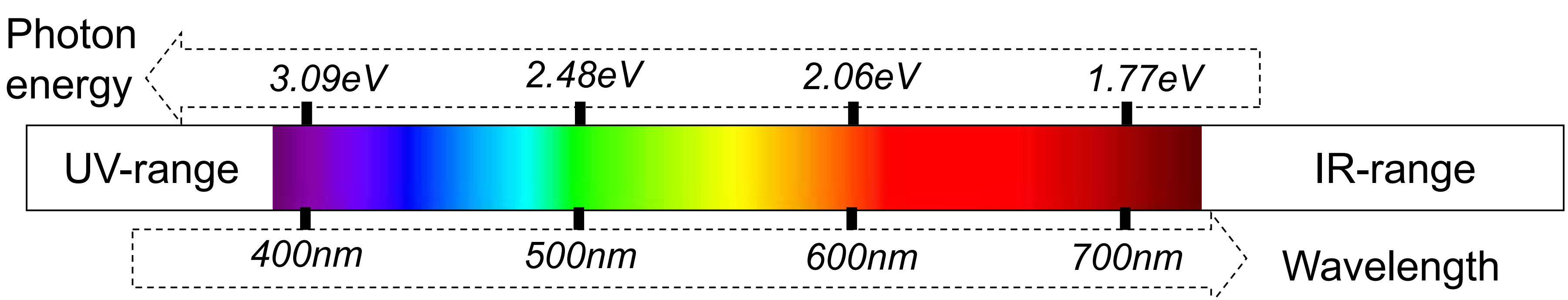
$$\text{Photon Energy} = h\upsilon = \frac{hc}{\lambda}$$

ν – frequency, λ - wavelength

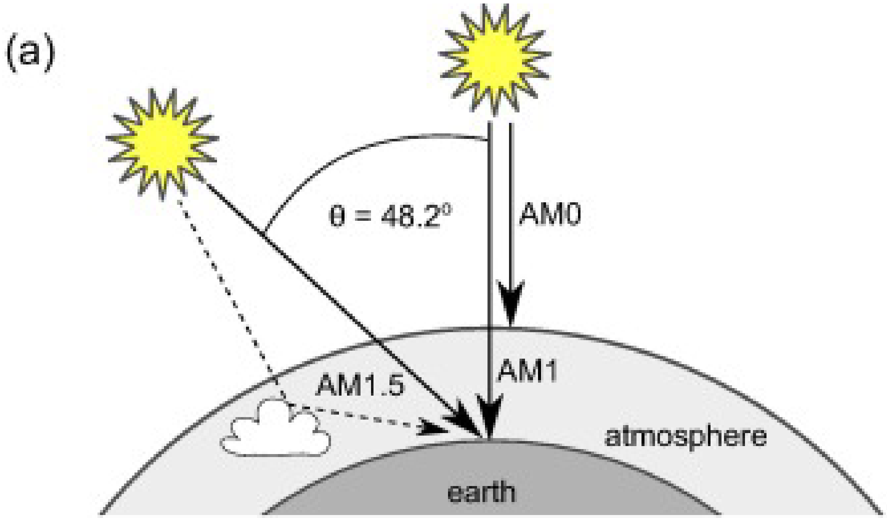
h = Planck constant = 6.6×10^{-34} J s

c = speed of light = 3×10^{8} m s^{-1}

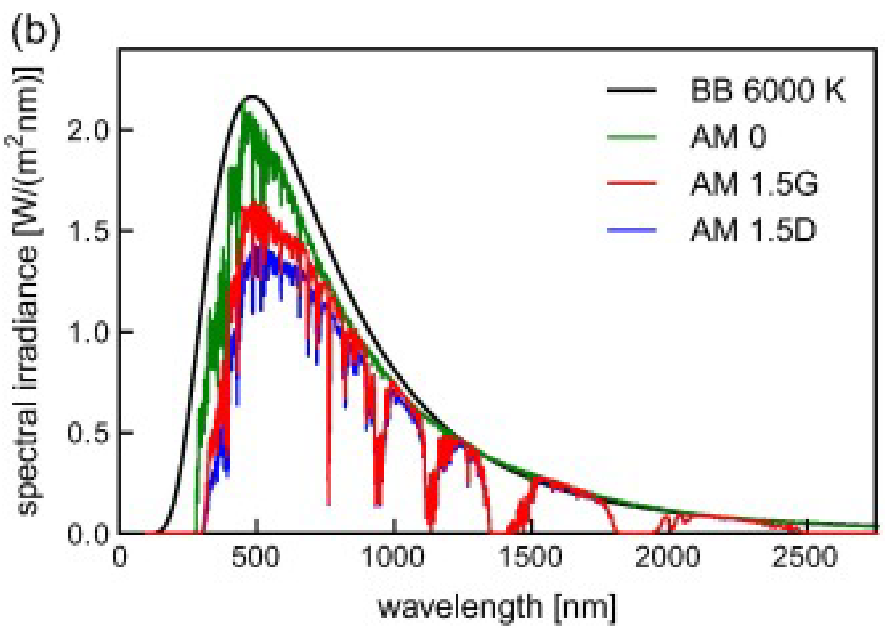
$$E_{photon}\,[\text{eV}] = \frac{1240}{\lambda[nm]}$$



Air mass (AM) coefficient



AM = 1/cos z, where z is the angle between sun and the normal



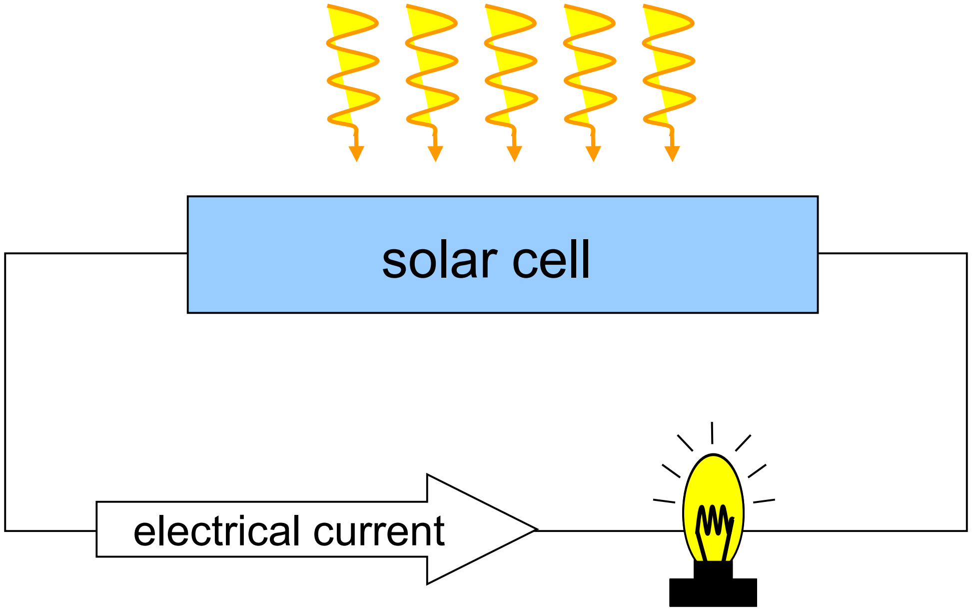
Black body: spectrum at 6000 K

AM 0 spectrum: outside Earth atmosphere

AM 1.5G (global) at zenith angle of 48.2° (realistic for central Europe)

AM 1.5D (direct only)

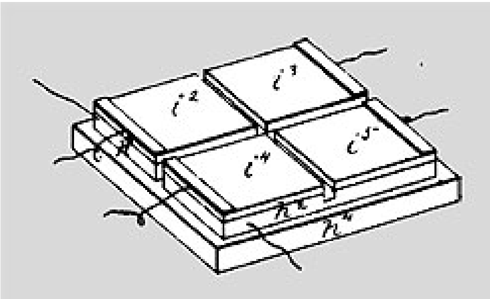
Solar cell (photovoltaic cell)



- Solar cell is a device that converts the **light energy directly into electricity** by the photovoltaic effect

- Most solar cell use **semiconductors**: Si, GaAs, $CuInSe_2$, CdTe, etc., which can be crystalline, polycrystalline, amorphous

Brief history of photovoltaics



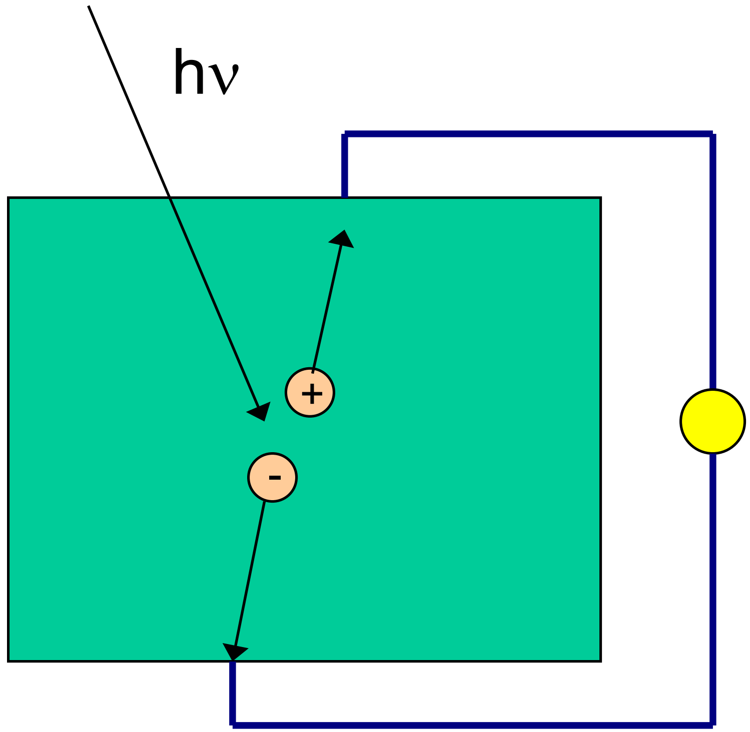
From a patent application in 1884

Vanguard 1, 1958-1964

1883	First solar cell made of selenium crystal and a layer of gold by Charles Edgar Fritts, efficiency 1%
1954	First Si cell, Bell Labs (US) efficiency 6%
1958	PV-powered satelite Vanguard 1 (US)
1973	World energy crisis
1989	1`000 rooftops in Germany
1997	100`000 rooftops in Germany
2011	Fukushima disaster,
	Swiss Energy Strategy 2050

Semiconductor physics

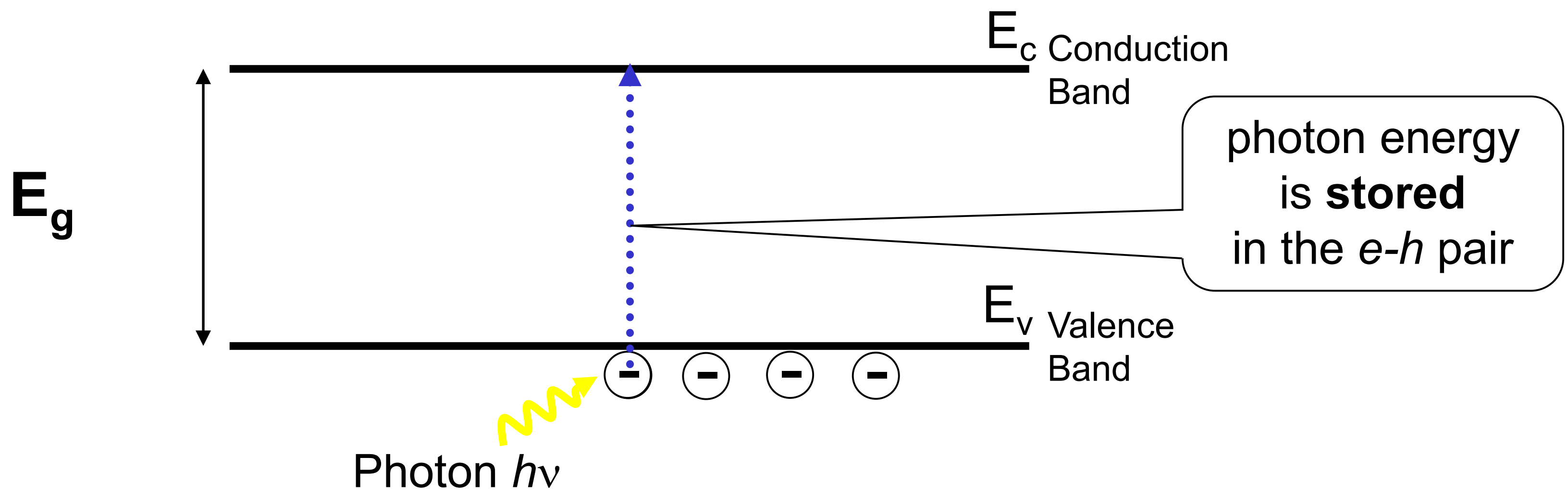
Solar cell and photovoltaic effect



1. Light absorption
2. Generation of „free“ charge carriers
3. Separation of the charges

Source: Dr. Karl Molter / FH Trier, Clemson Summer School 2011

Photogeneration



Absorption of photon ⇒ Generation of electron-hole pair

Band gap determines absorption:

$$E_{photon} \geq E_g = h\upsilon_c = \frac{hc}{\lambda_c}$$

Only photons with energy larger than band gap can generate e-h pair:

⇒ semiconductor absorbs if $l \leq l_c$

⇒ semiconductor is transparent to $l \geq l_c$

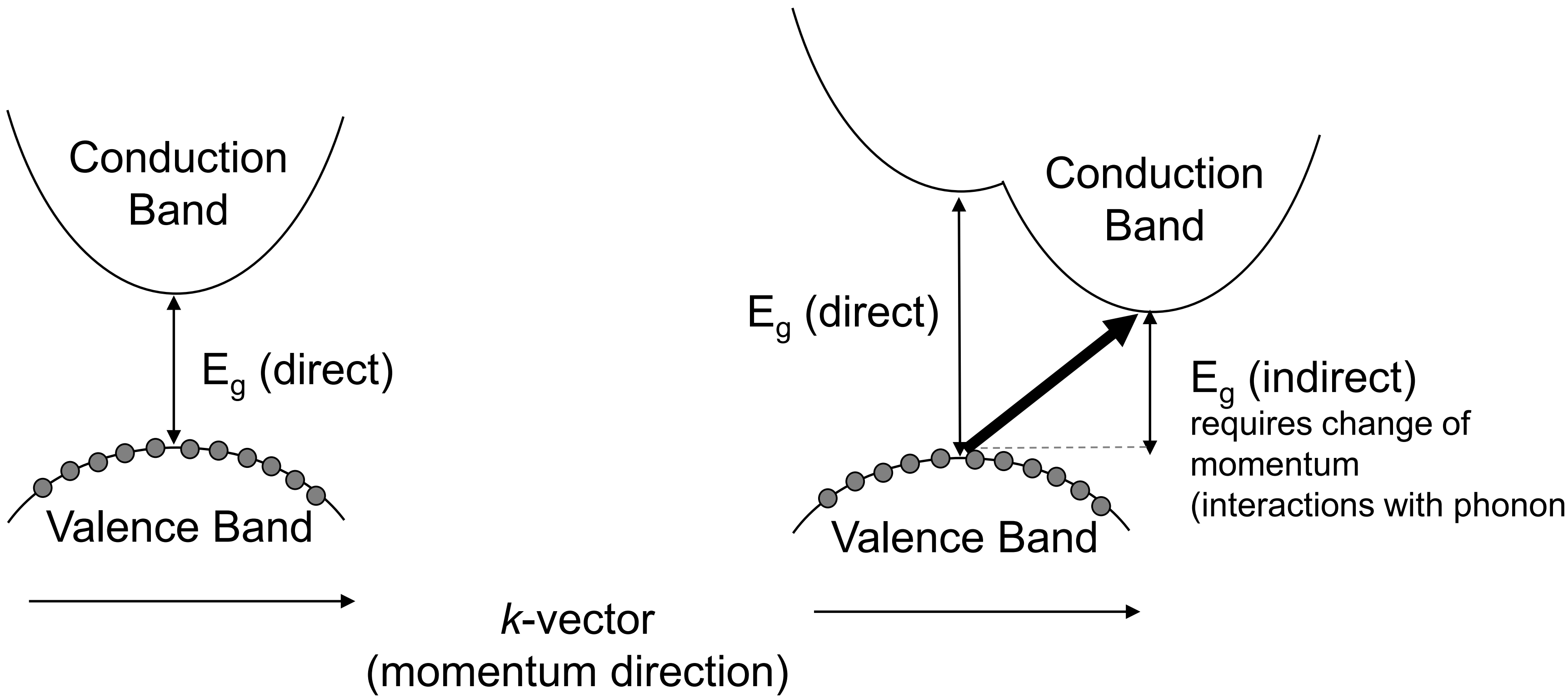
υ_c = cut off frequency

λ_c = cut off wavelength

Direct *vs* Indirect bandgap

E_g (GaAs) =1.42eV
direct gap (strong)

E_g(Si) =1.12eV
indirect gap (weak)

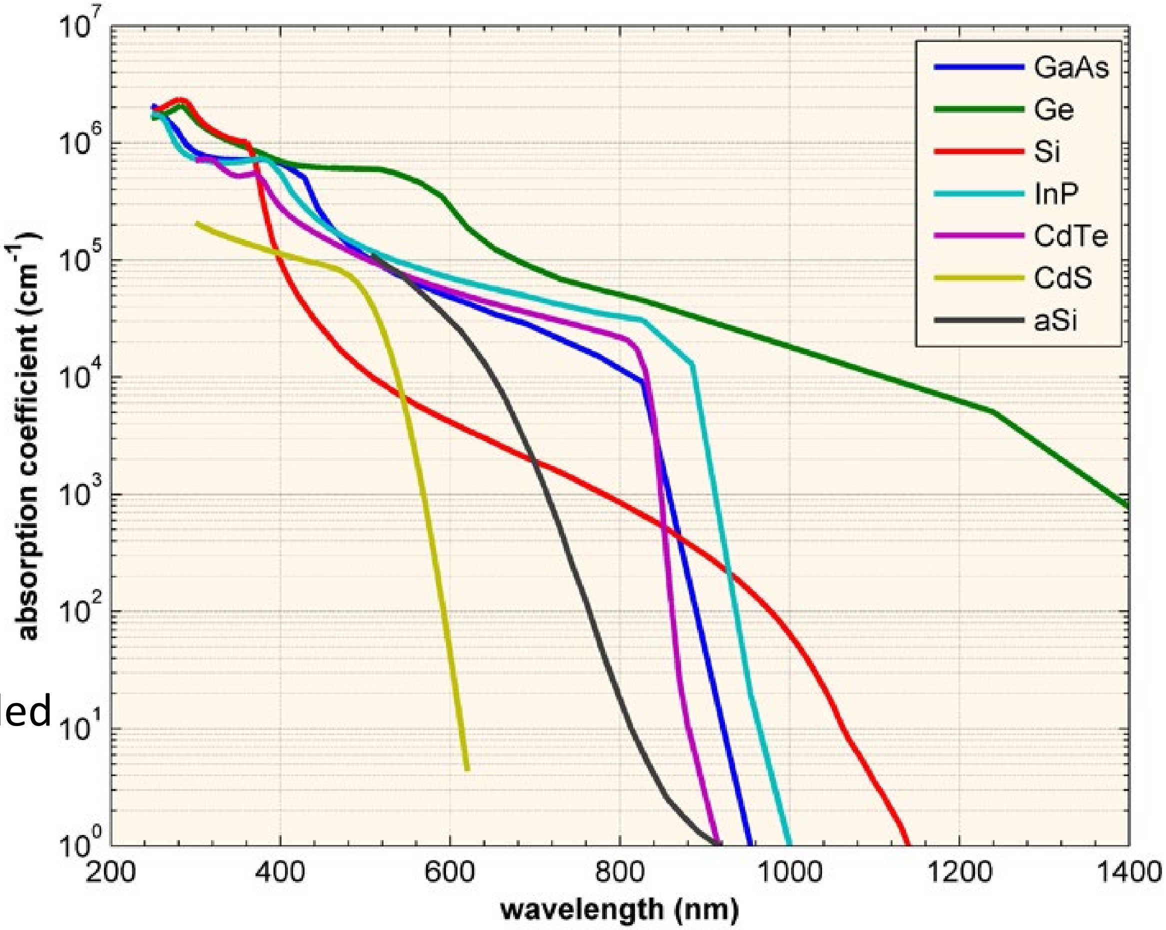


Light absorption in semiconductors

Direct bandgap
(GaAs, CdTe, a-Si):
⇒ thin layer of 1-2 μm
enough for absorption

⇕

Indirect bandgap (c-Si):
⇒ thick wafer 100 μm needed
for absorption

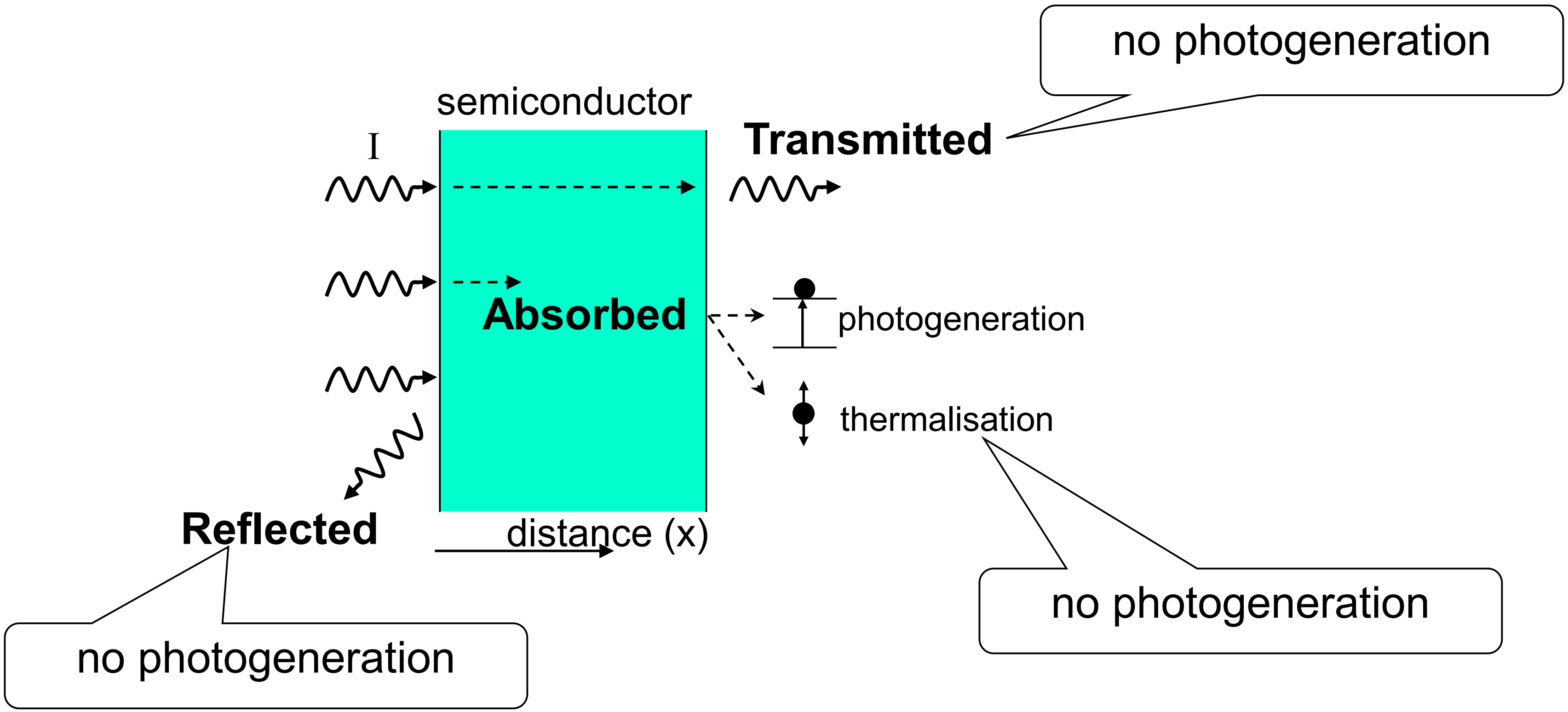


Wide bandgap (a-Si, CdTe):
⇒ better response for
«blue» photons

⇔

Low band-gap (Ge, Si):
⇒ collection of
IR photons

Optical Absorption

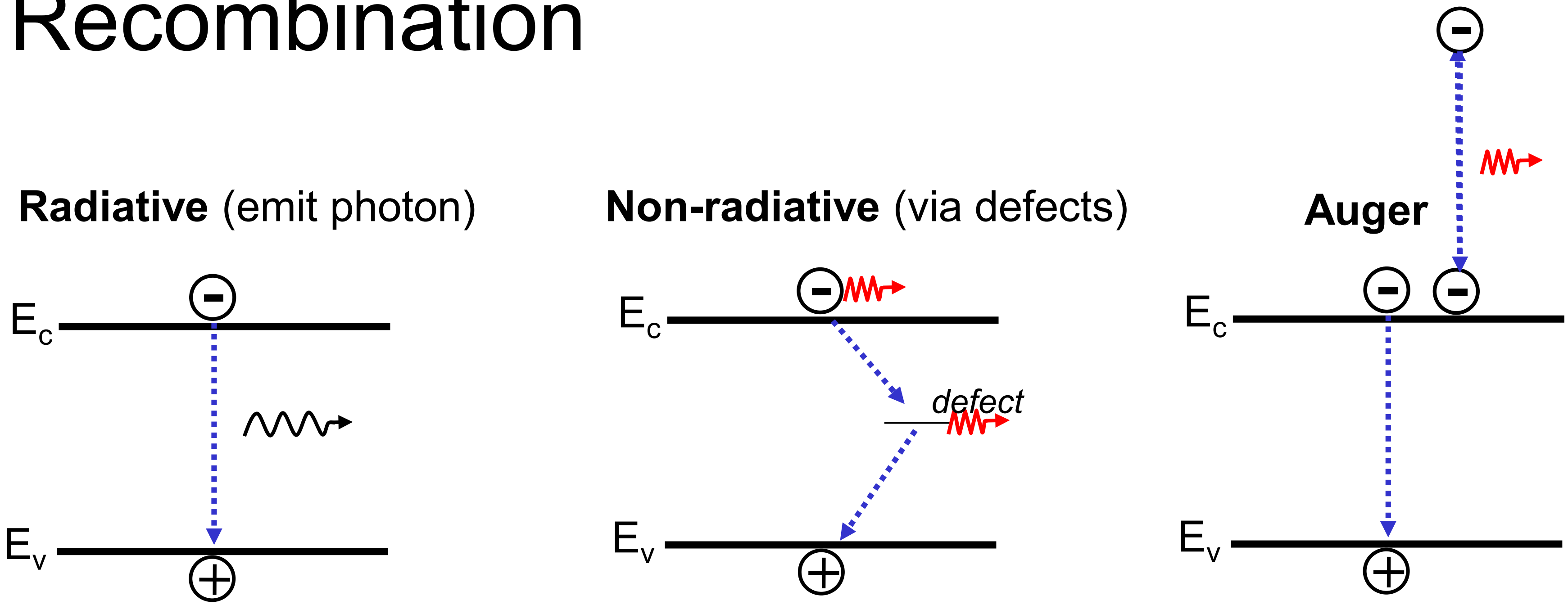


Reflection: R (%)

Transmission: T (%)

Absorption: absorption coefficient α (cm^{-1})

Recombination



Recombination mechanisms:

1. **Radiative** (emission of photons = photoluminescence)
2. **Non-radiative** (Shockley-Read-Hall or SRH)
3. **Auger** (energy transfer to another electron)

Undesirable in solar cells (applies to 2 and 3)

Carrier lifetime and diffusion length

$$\tau = \frac{\Delta n}{R}$$

τ – lifetime
Δn – excess minority carrier concentration
R – recombination rate

$$\frac{1}{\tau_{bulk}} = \frac{1}{\tau_{Band}} + \frac{1}{\tau_{Auger}} + \frac{1}{\tau_{SRH}}$$

τ_{bulk} – bulk lifetime
τ_{Band} – radiative band-to-band lifetime
τ_{Auger} – Auger recombination lifetime
τ_{SRH} – defect recombination lifetime

- **Lifetime is an indicator of the efficiency of a solar cell - the key consideration in choosing materials for solar cells.**

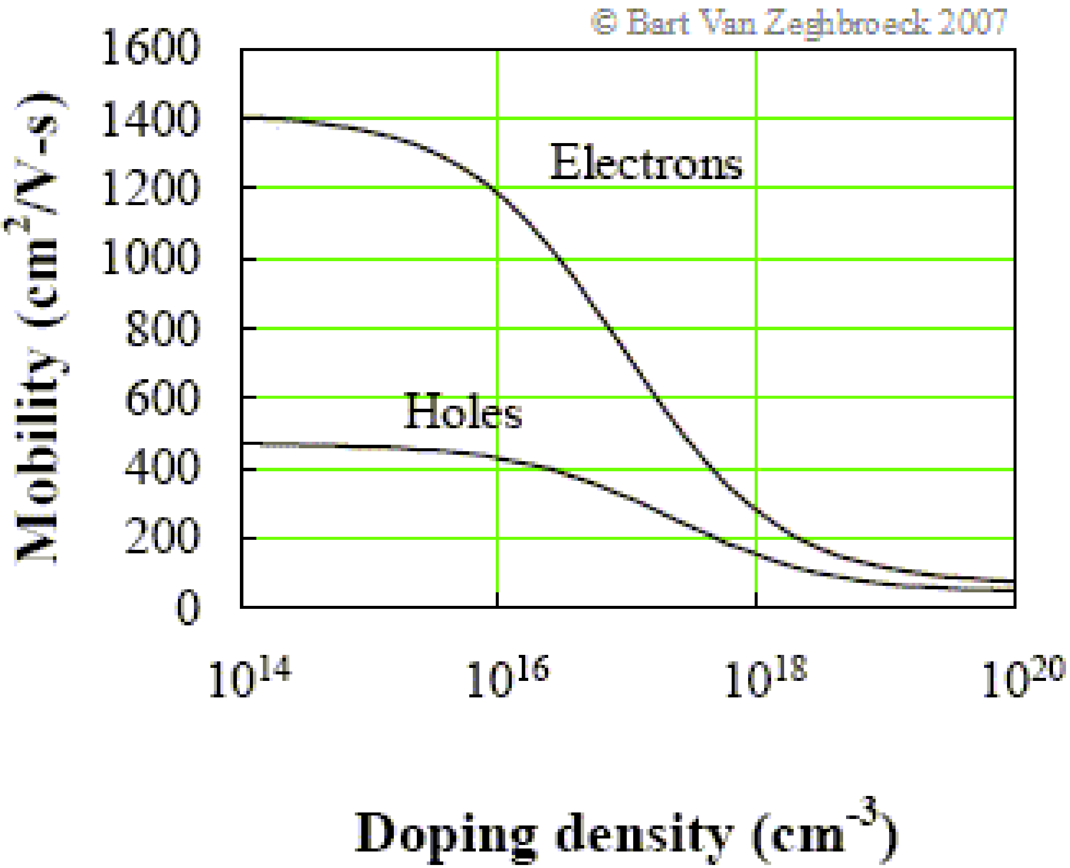
$$L = \sqrt{D\tau}$$

L – diffusion length (m)
D – diffusivity bulk lifetime (m^2/s)
τ – carrier lifetime (s)

Carrier mobility

$$\mu = \frac{v_d}{E}$$

μ – carrier mobility ($m^2/(Vs)$)
υ_d – drift velocity (m/s)
E – applied electric field (V/m)



Charge carriers in semiconductors

Electron (n) & hole (p) concentration in semiconductor:

equal amount of holes & electrons in intrinsic semiconductors

$$n = p = n_i$$

$$np = n_i^2 = N_c N_v e^{\frac{-E_g}{kT}}$$

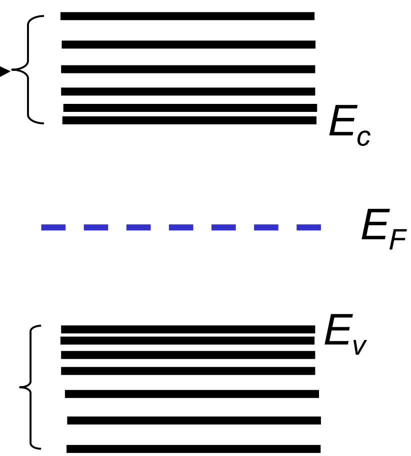
N_c and N_v are the *effective densities of states*

k is Boltzmanns constant (1.38×10^{-23} J K^{-1})

Carrier concentrations in equilibrium related to the band edges:

$$n = N_c e^{-(\frac{E_c - E_f}{kT})}$$

$$p = N_v e^{-(\frac{E_f - E_v}{kT})}$$

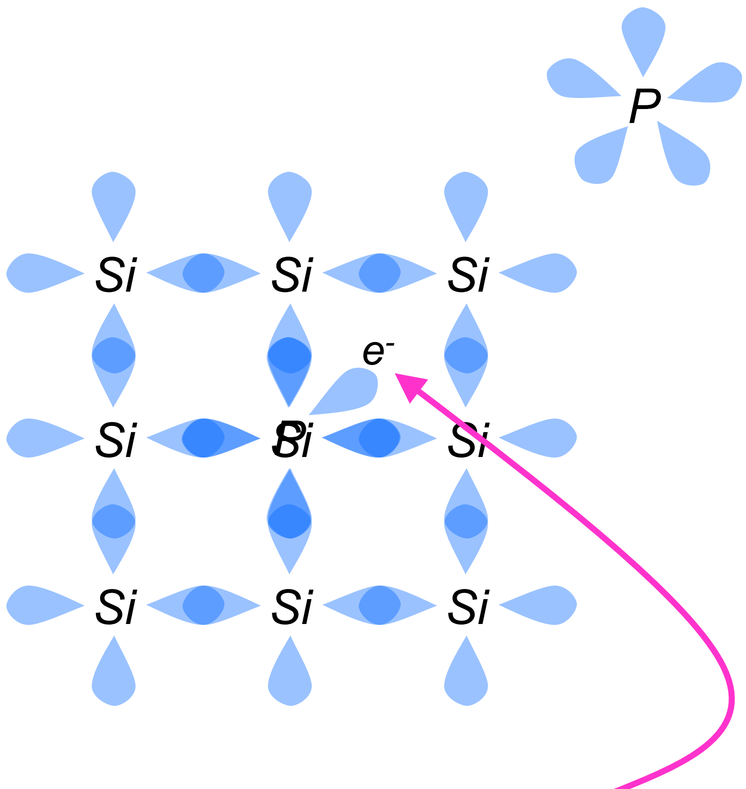


Fermi level: probability to find an electron at this energy level is 50%

located at midgap in instrinsic semiconductors

Doping of semiconductors (e.g. Silicon)

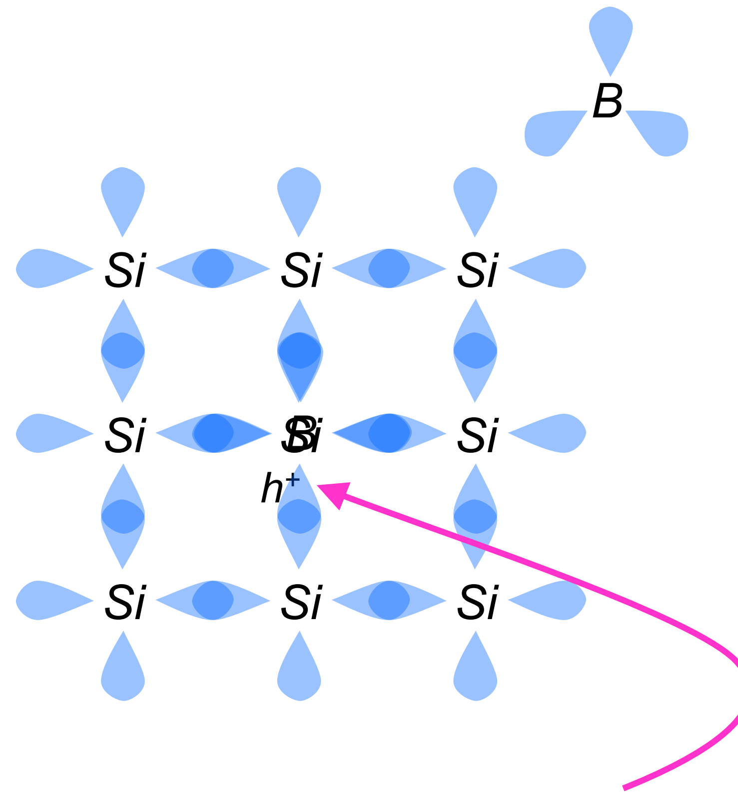
Phosphorus (P)
5 outer electrons vs Si’s 4



One electron per donor atom

⇒ **n-type doping**

Boron (B)
3 outer electrons vs Si’s 4



One hole per acceptor atom

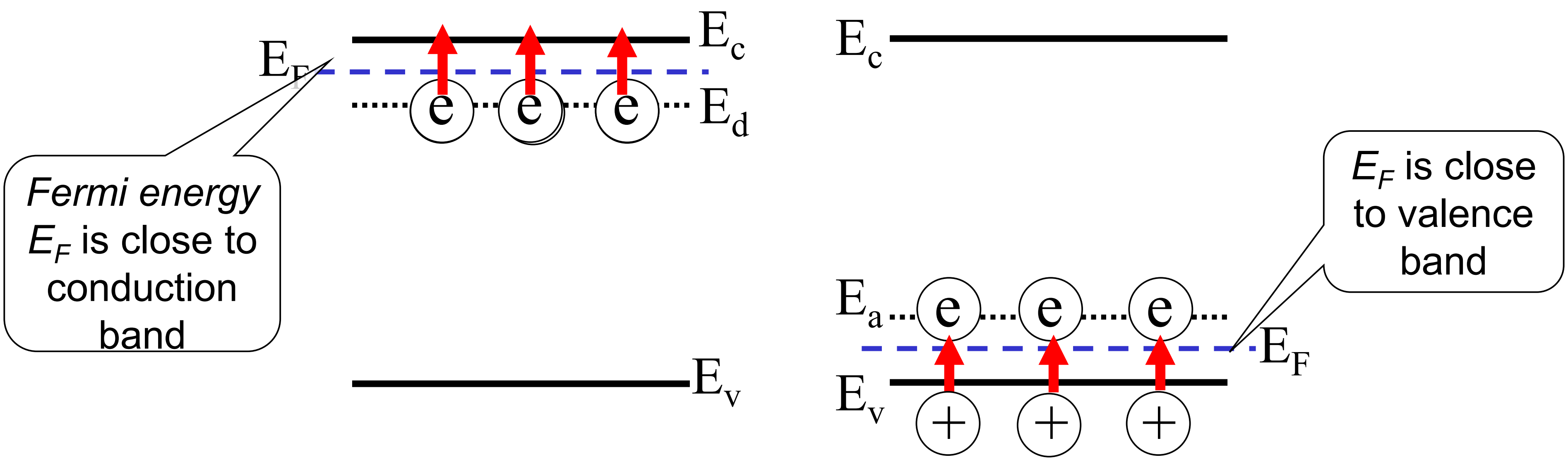
⇒ **p-type doping**

Doping of Semiconductors

- Undoped (intrinsic) semiconductors have low conductivity because the concentration of free (mobile) charge carriers is very low.
- Doping with impurities can add free (mobile) electrons or holes:

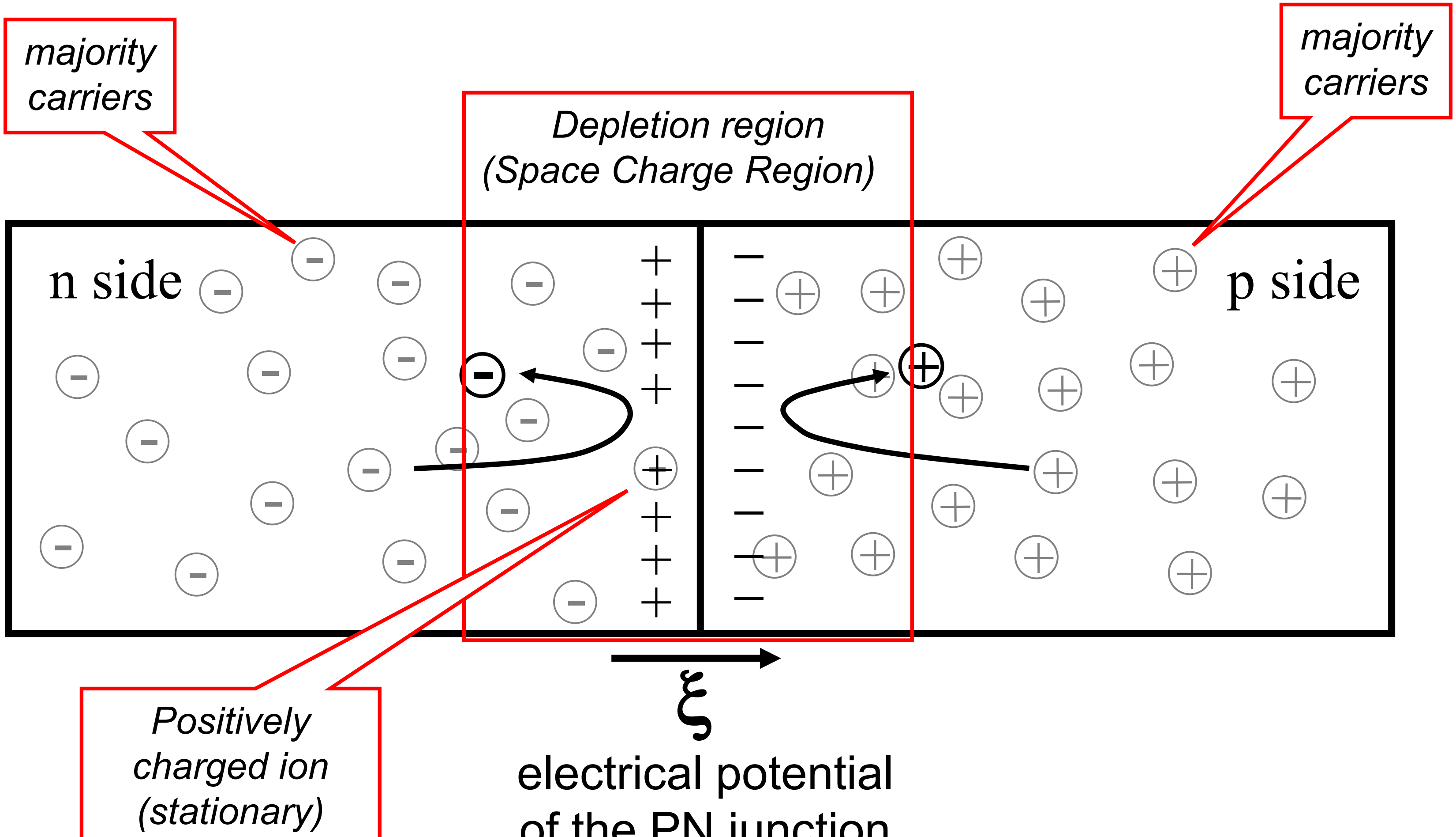
Donors ⇒ donate electrons | **Acceptors** ⇒ accept electrons

n-type | **p-type**



thermal energy (~kT) is sufficient to "activate" the carriers

The PN Junction (1)



electrical potential of the PN junction in equilibrium

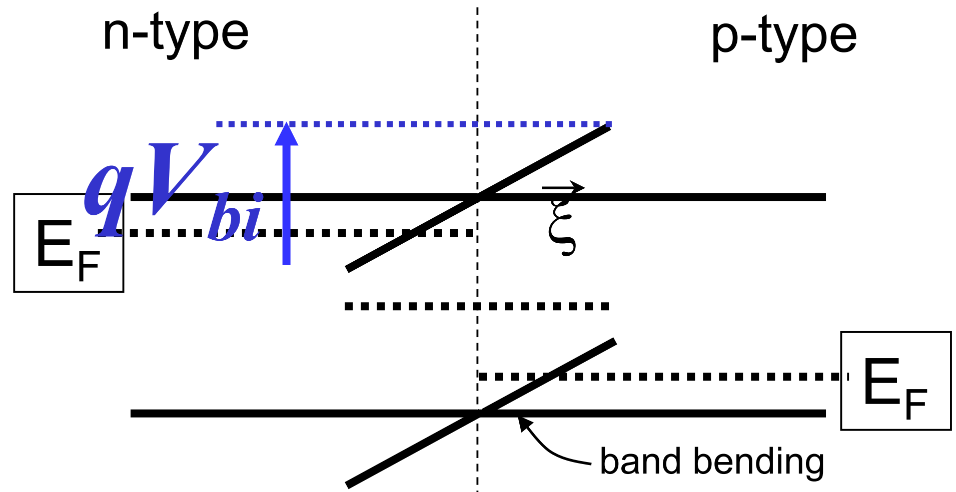
P-N junction provides charge separation

Built-in Voltage & Depletion Width

Built in voltage V_{bi}

$$qV_{bi} \approx kT \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

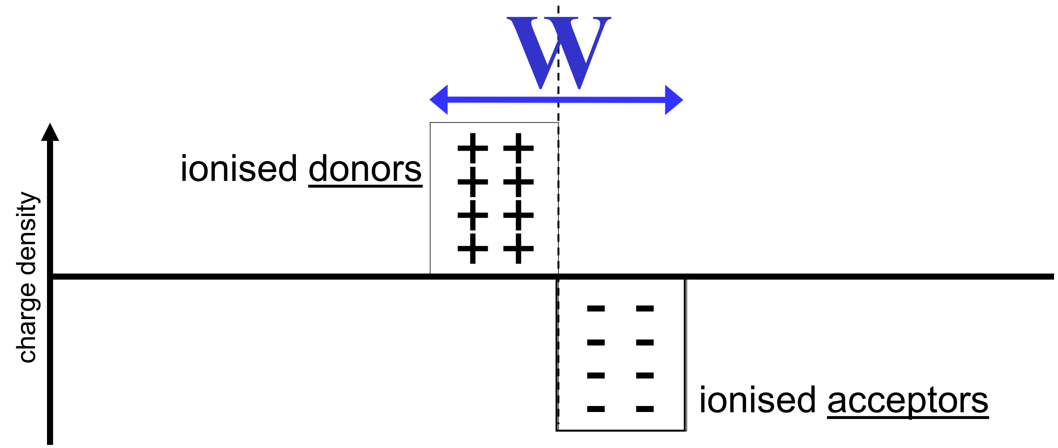
N_a, N_d – concentration of acceptors (donors)
n_i – intrinsic carrier concentration



Depletion width *W*

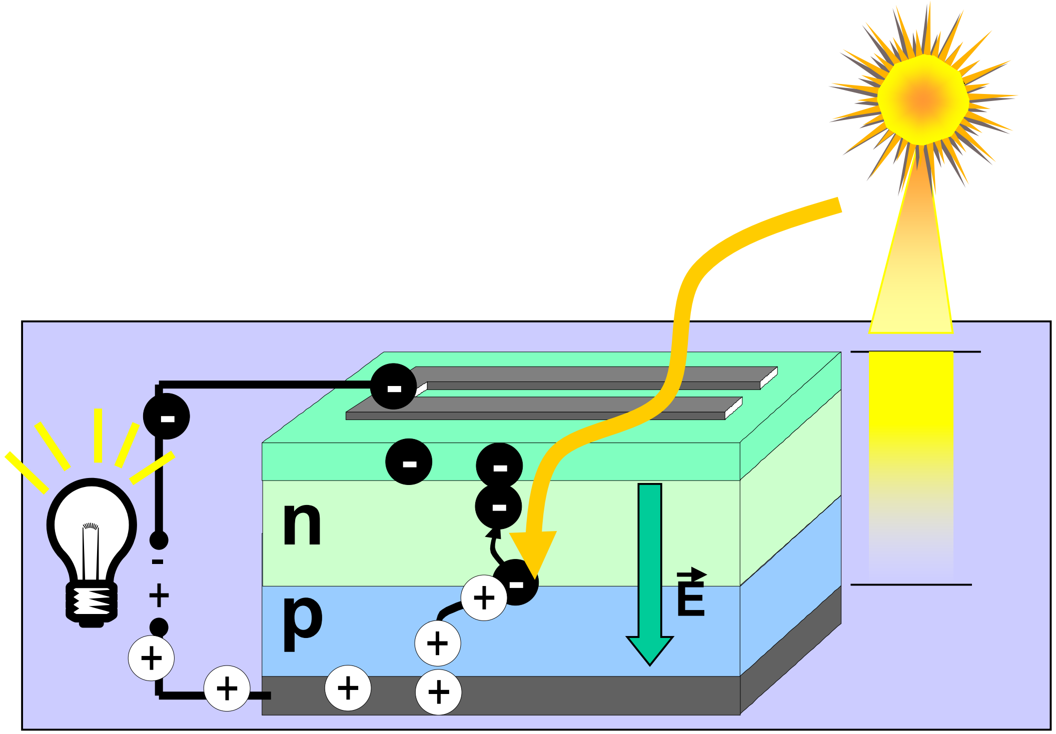
$$W = \sqrt{\frac{2\varepsilon}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)V_{bi}}$$

ε – dielectric constant



Solar cell parameters

Operation of p-n junction solar cell

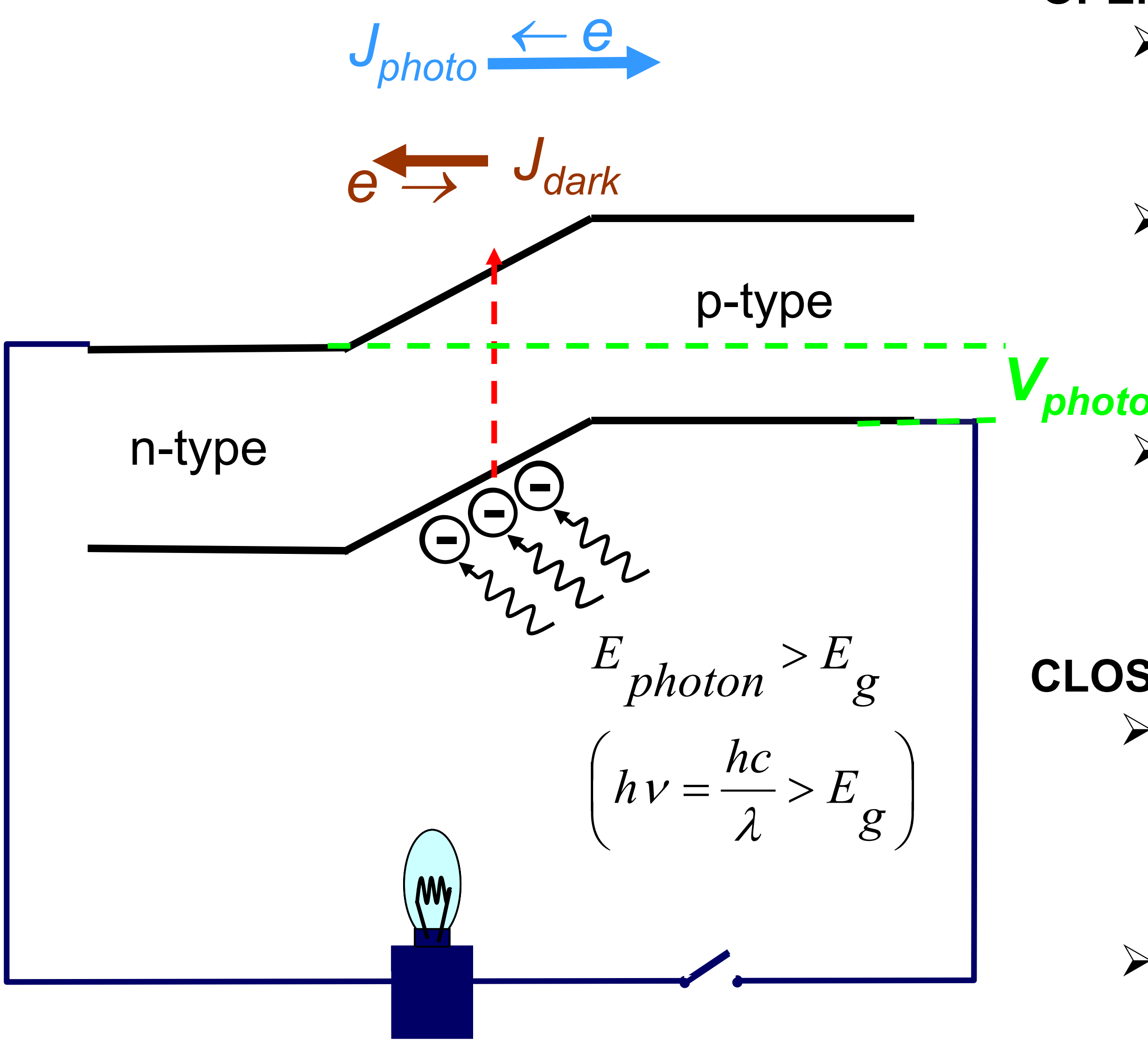


1. Light absorption

2. Generation of free mobile carriers

3. Separation of the free carriers

P-N junction under illumination



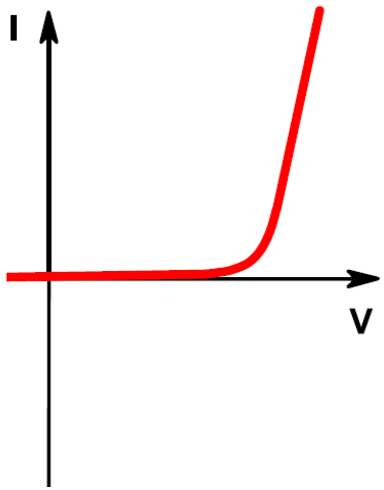
OPEN CIRCUIT:

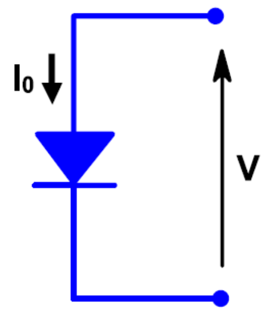
- Opposite charges build up on the contacts
- photovoltage V_{photo} is produced (maximum is open circuit voltage V_{oc})
- Dark curent (J_{dark}) equilibrates new photogenerated

CLOSED CIRCUIT:

- Charges flow via external circuit as photocurrent J_{photo}
- J_{photo} flows in the opposite direction to J_{dark}

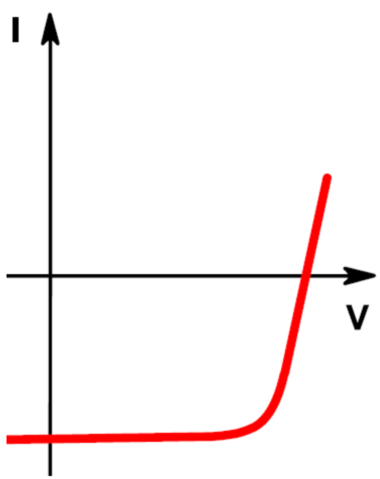
Effect of light on I-V curve

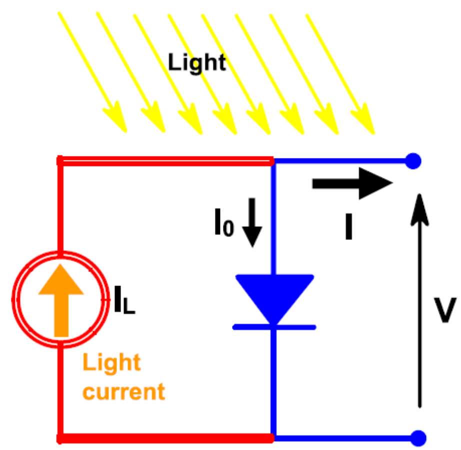




Without illumination, a solar cell acts like a diode

=> I-V curve is identical



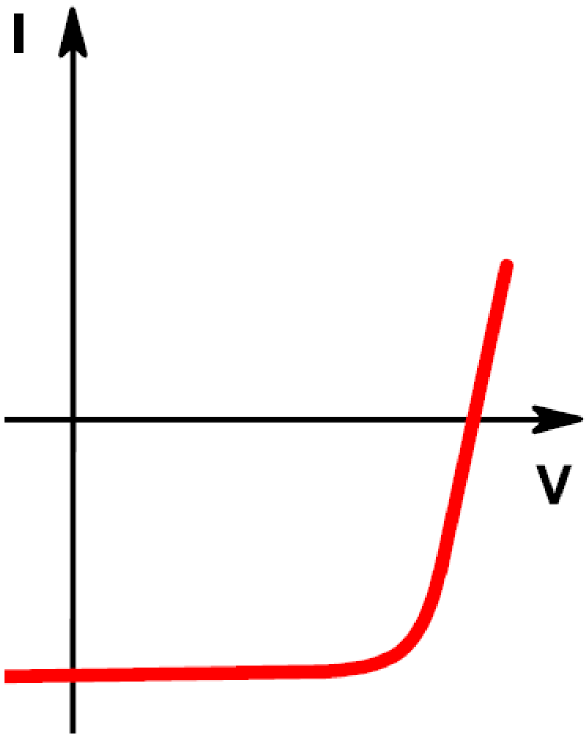


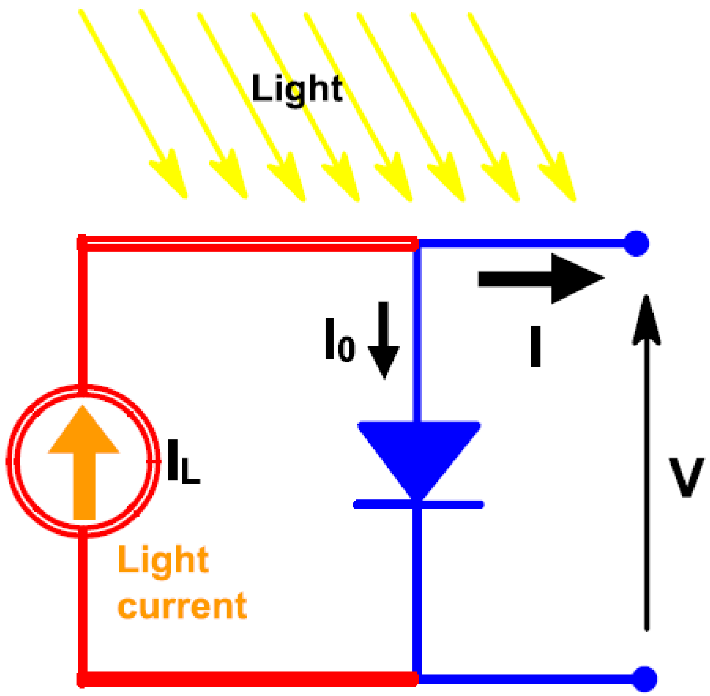
Under illumination, solar cell produces photocurrent

=> I-V curve shifts down by the value of light current

Image: www.pveducation.org

Current equation

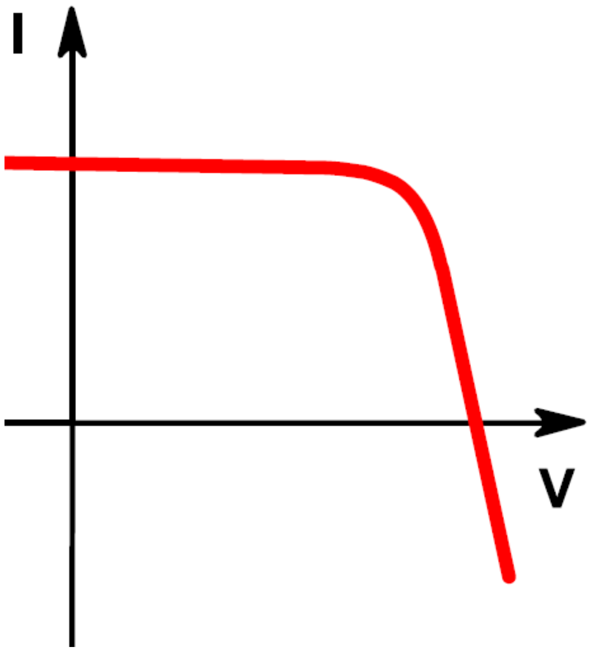


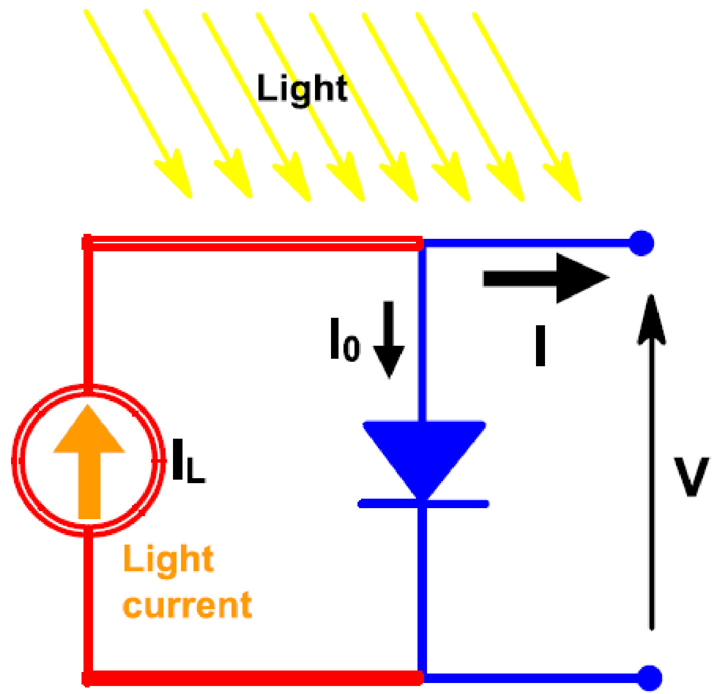


$$I = I_0(\exp(\frac{qV}{kT}) - 1) - I_L$$

Light-induced current (photocurrent) is proportional to the incident light intensity

Current equation (mirrored form)

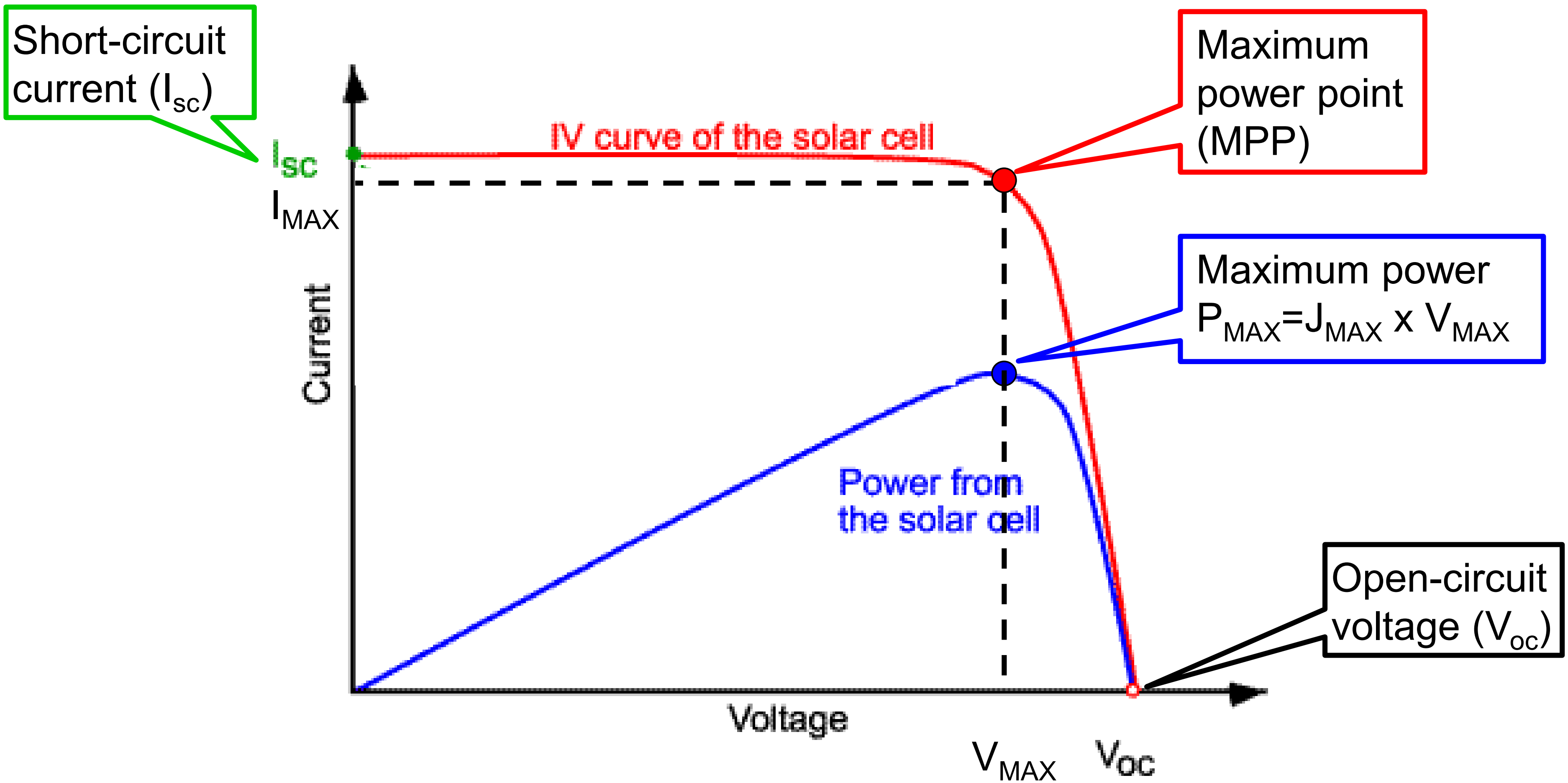




Since the cell is generating power, the convention is to invert the current axis

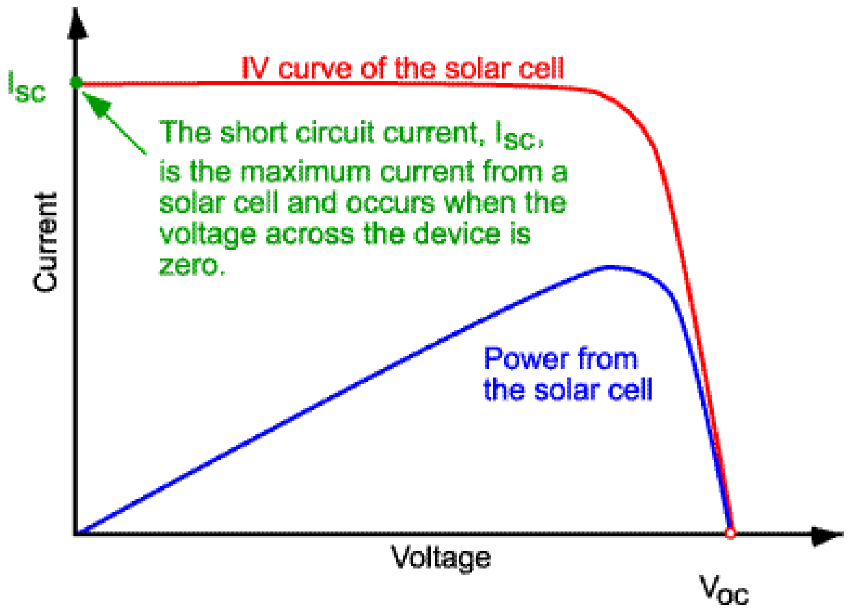
$$I = I_L - I_0(\exp(\frac{qV}{kT}) - 1)$$

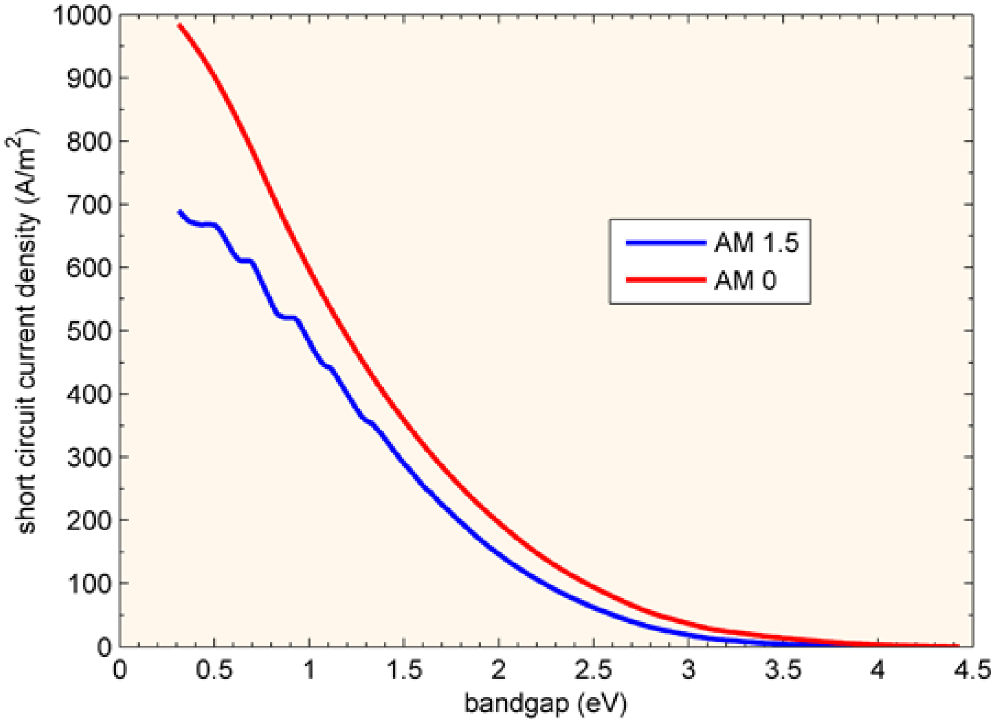
I-V curve & power curve



- I-V curves are measured under **standard test conditions** in order to compare various technologies: light intensity 1000 W/m^2, light spectrum AM1.5, and cell temperature T=25°C

Short circuit current I_{sc}





- Short circuit current Isc is the current when voltage across the device is zero
- I_{SC} is essentially the light-induced current if we neglect series resistance ($I_{sc} = I_L$)
- To remove the dependence on the solar cell area, it is more common to use the **short-circuit current density** (J_{sc} in mA/cm^2) rather than absolute current

Open circuit voltage V_{oc}

START HERE (the diode equation) →

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

At V_{oc} $I=0$

$$\Rightarrow 0 = I_L - I_0\left(\exp\left(\frac{qV_{oc}}{kT}\right)-1\right)$$

$$\frac{I_L}{I_0}+1 = \exp\left(\frac{qV_{oc}}{kT}\right)$$

$$V_{oc} = \frac{kT}{q}\ln\left(\frac{I_L}{I_0}+1\right)$$

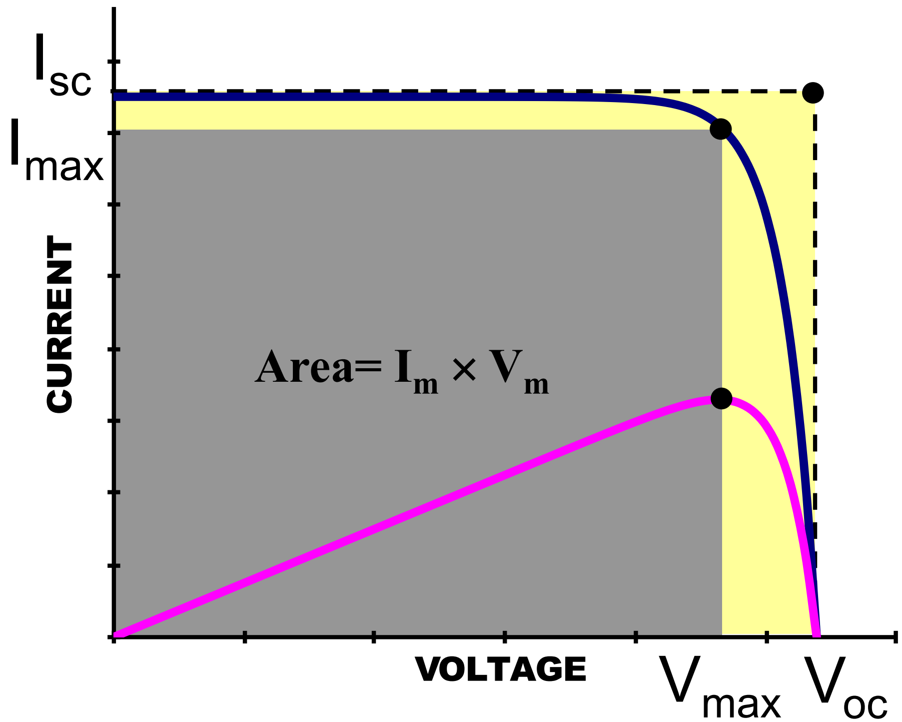
I_L~A I_0~10^{-9}A

$\Rightarrow I_L >> I_0$

$\Rightarrow I_L / I_0 >> 1$

$$V_{oc} \approx \frac{kT}{q}\ln\left(\frac{I_L}{I_0}\right)$$

Fill Factor FF



Maximum theoretical power

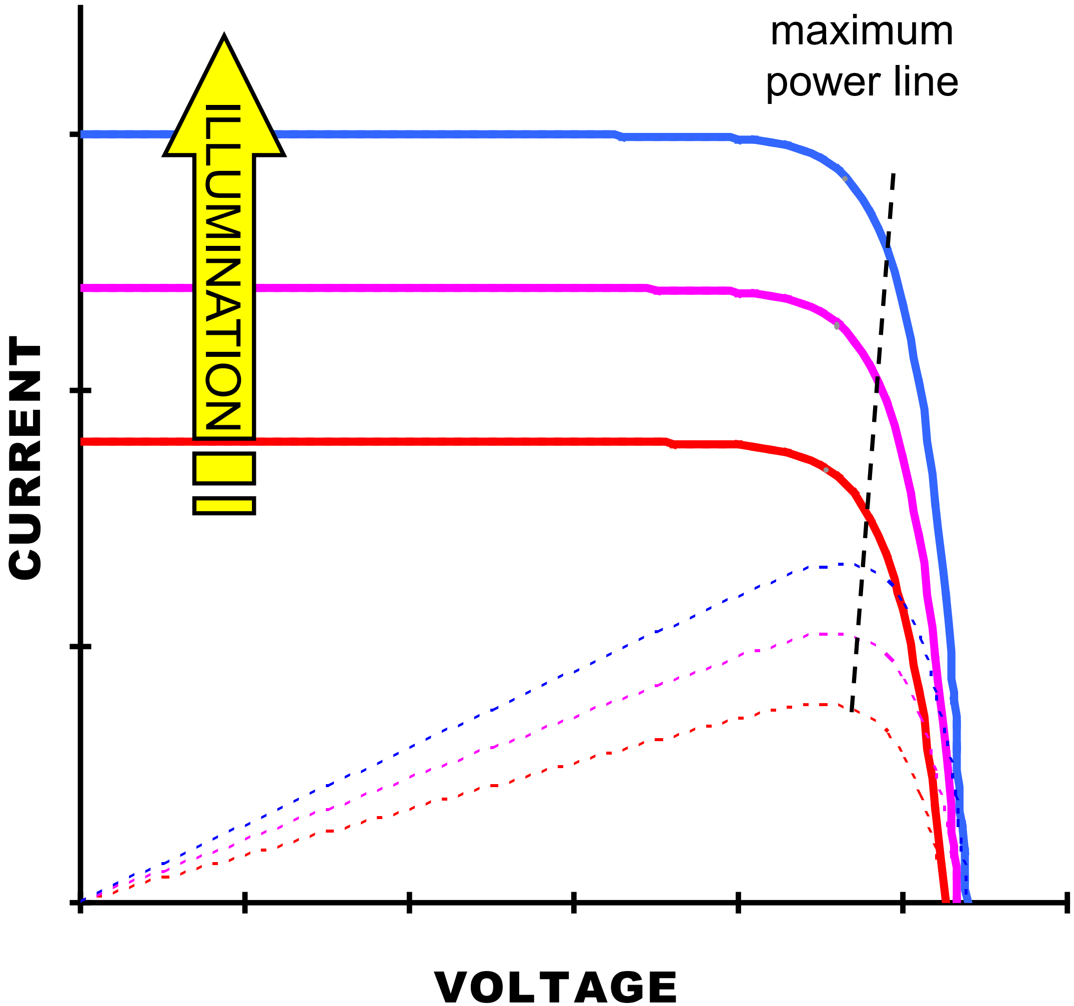
$$P_m = I_{sc} V_{oc}$$

Maximum power point (MPP)

$$P_{MPP} = I_{\max} V_{\max}$$

$$FF = \frac{\text{area } I_{max} \times V_{max}}{\text{area } I_{sc} \times V_{oc}}$$

Effect of illumination



Light intensity increases:

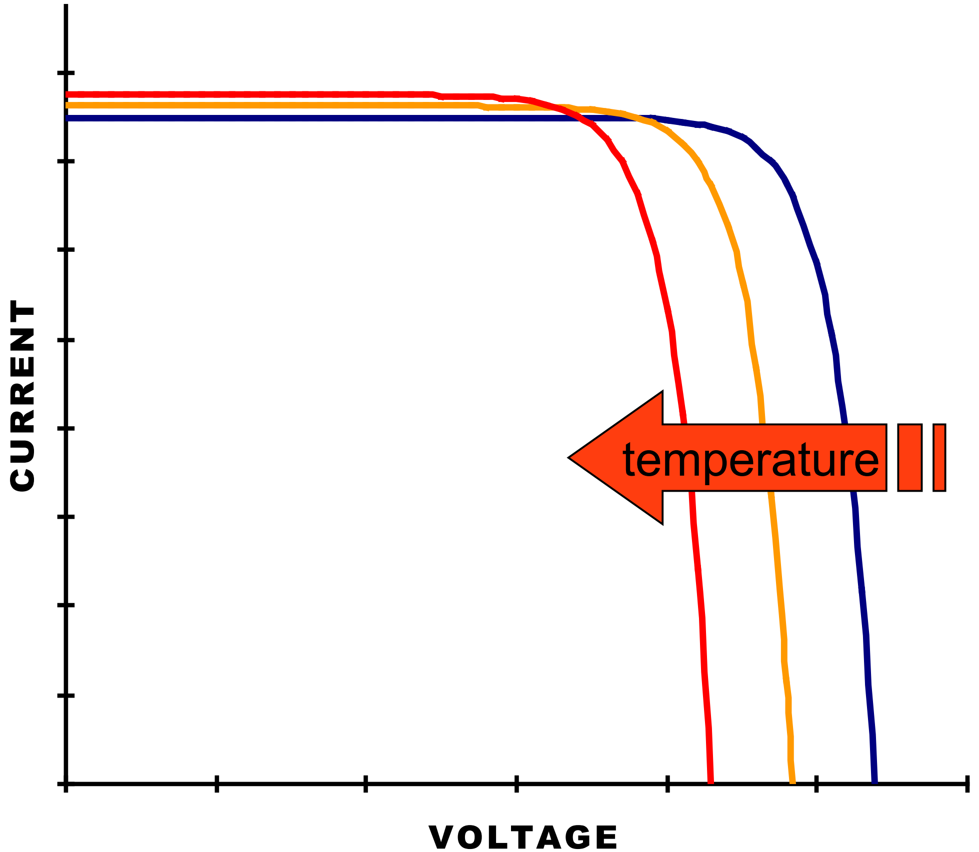
⇒ Jsc increases proportionally

⇒ Voc goes up

⇒ overall η increases (used in concentrated PV)

$$V_{oc} \approx \frac{kT}{q} \ln\left(\frac{I_L}{I_0}\right)$$

Effect of temperature



Temperature increases:

⇒ band gap E_g is reduced

⇒ the current density goes up
⇒ but the voltage goes down
⇒ overall η decreases.

For Si cell: $$\frac{dJ_{sc}}{dT} \approx 0.1 A m^{-2} K^{-1}$$

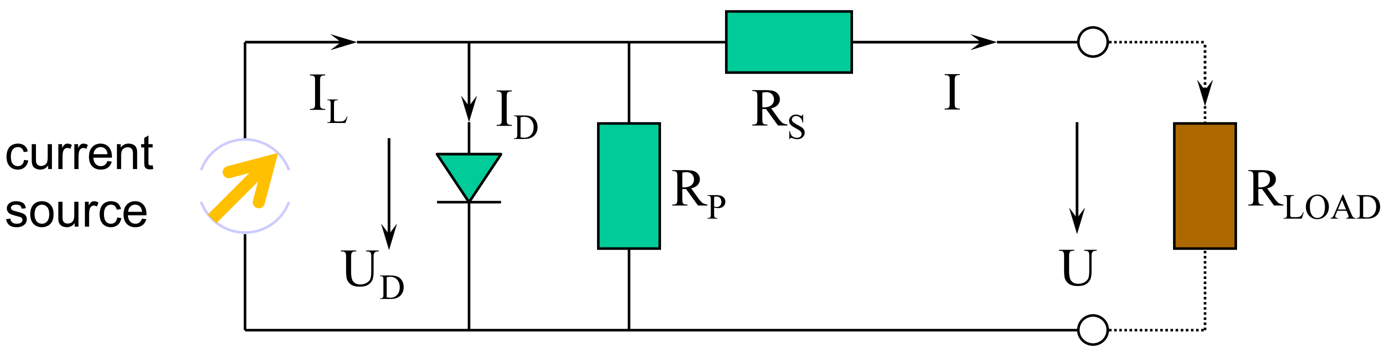
$$\frac{dV_{oc}}{dT} \approx -2.2 mV K^{-1}$$

$$\frac{d\eta}{dT} \approx -0.5\% K^{-1}$$

Solar cell characteristics

- Short-circuit current density J_{SC}:
  - proportional to irradiation
  - Typical 30-40 mA cm^{-2}
  - Increases by 0.07% per Kelvin
- Open-circuit voltage V_{OC}:
  - This is the voltage along the internal diode
  - Typical values 0.6…0.7 V depending on semiconductor
  - decreases by 0.4% per Kelvin
- Power (MPP, Maximum Power Point)
  - Power decreases by 0.4% per Kelvin
- The nominal power of a cell is measured at standard test conditions (STC):
  G_0 = 1000 W/m^2, T_{cell} = 25°C, AM 1.5G spectrum

Equivalent circuit of a real solar cell



I_L: Light-induced current of the solar-cell

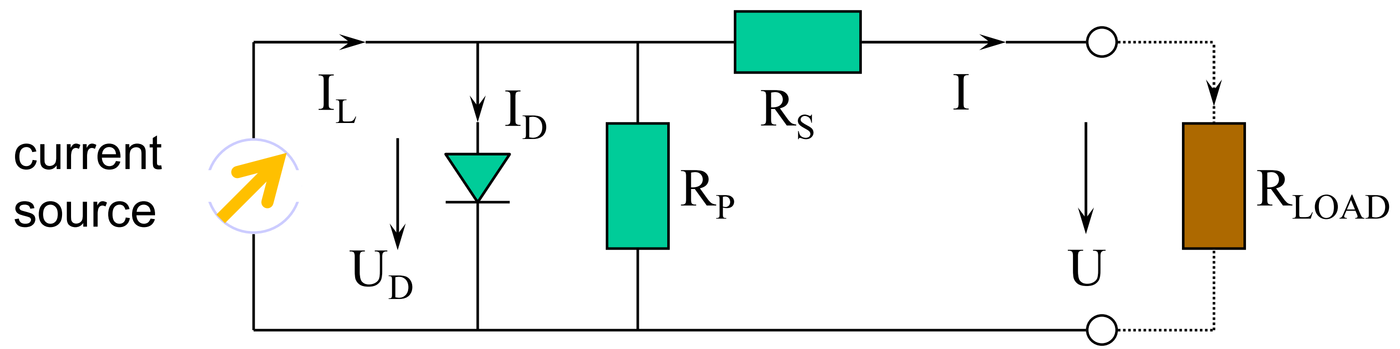
I_D / U_D: dark current and voltage of the internal p-n diode

R_P: parallel (shunt) resistor due to inhomogeneity of the surface and current loss at the solar-cell edges

R_S: serial resistor due to resistance of the bulk and contacts

R_{LOAD}: load resistance

Full current equation

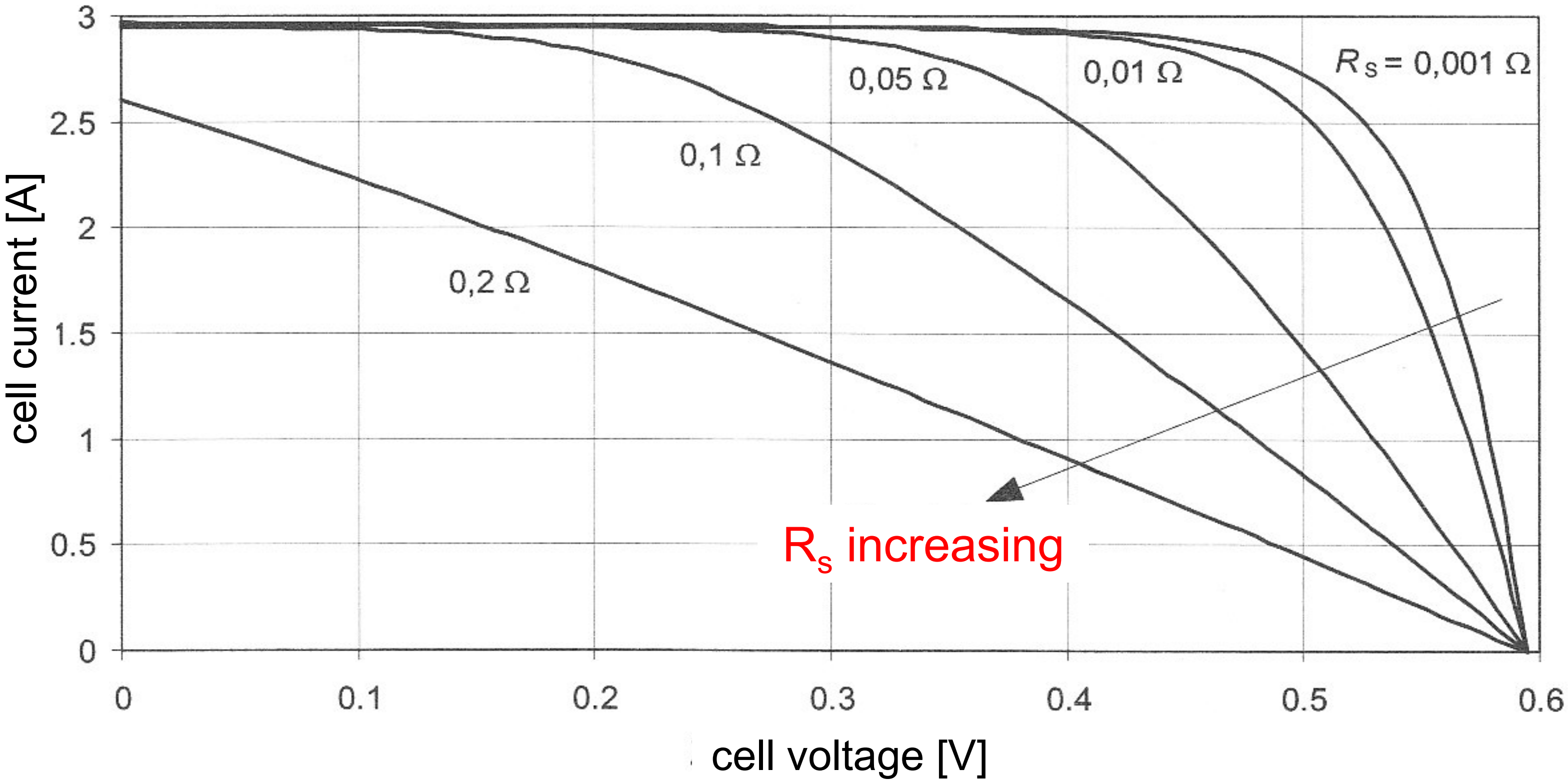


$$I = I_L - I_0 \left\{ \exp\left(\frac{q\left(V + IR_s\right)}{nkT} \right) - 1 \right\} - \frac{V + IR_s}{R_p}$$

diode ideality factor
n = 1….2

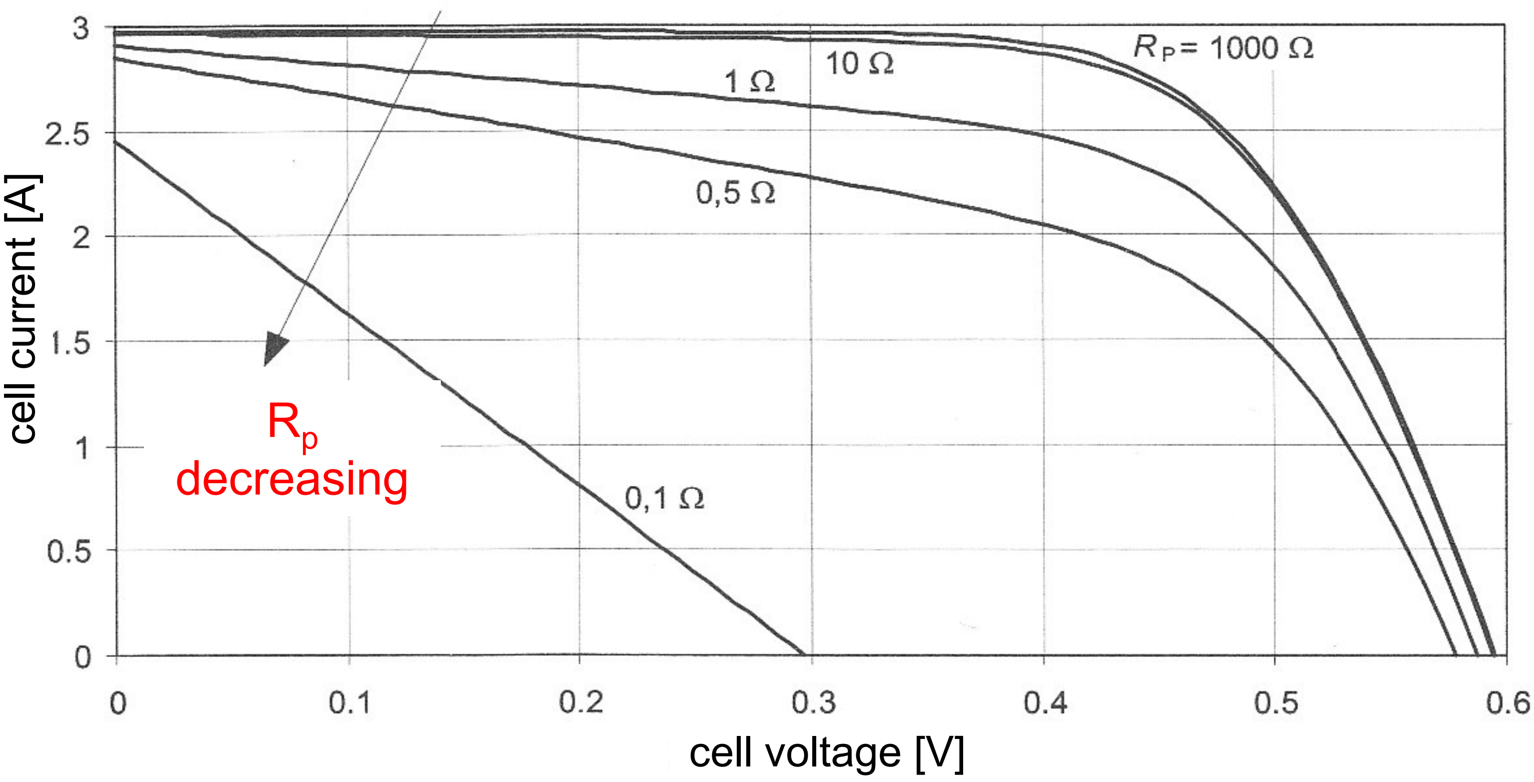
Effect of series resistance R_s

$$I = I_L - I_0\left\{\exp\left(\frac{q(V+IR_s)}{nkT}\right)-1\right\}-\frac{V+IR_s}{R_p}$$



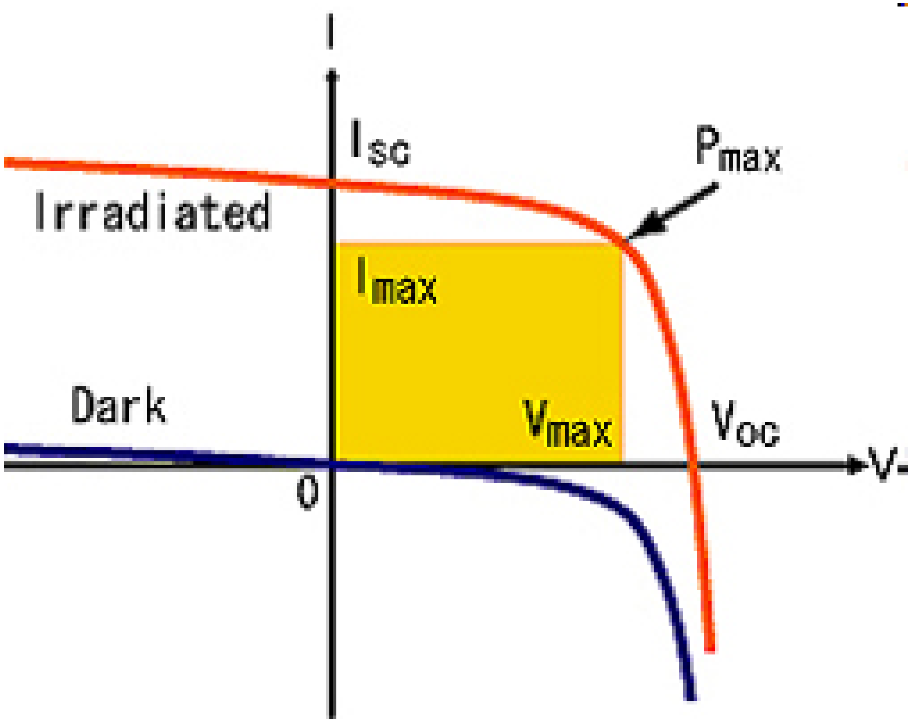
Effect of parallel resistance R_p

$$I = I_L - I_0\left\{\exp\left(\frac{q(V+IR_s)}{nkT}\right)-1\right\}-\frac{V+IR_s}{R_p}$$



Solar cell efficiency

Efficiency: the ratio of the generated power to the power of incident light

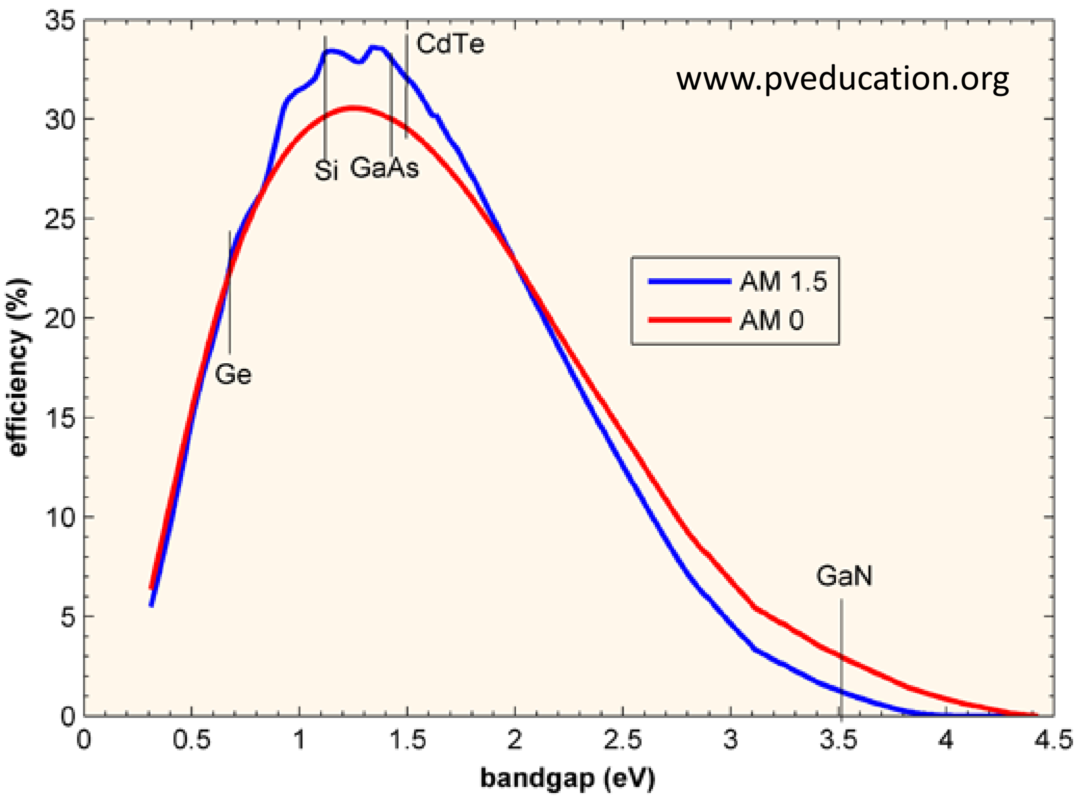


$$\eta = \frac{P_{electrical}}{P_{light}} = \frac{V_{MAX} \times I_{MAX}}{P_{IN}}$$

Standard conditions:
Light intensity P_{IN} = 1000 W/m^2
AM1.5G spectrum
Temperature 25°C

$$FF = \frac{I_m V_m}{I_{sc} V_{oc}} \quad => \quad I_{max} V_{max} = I_{sc} V_{oc} FF \quad \Rightarrow \quad \eta = \frac{I_{sc} V_{oc} FF}{P_{in}}$$

Shockley-Queisser limit



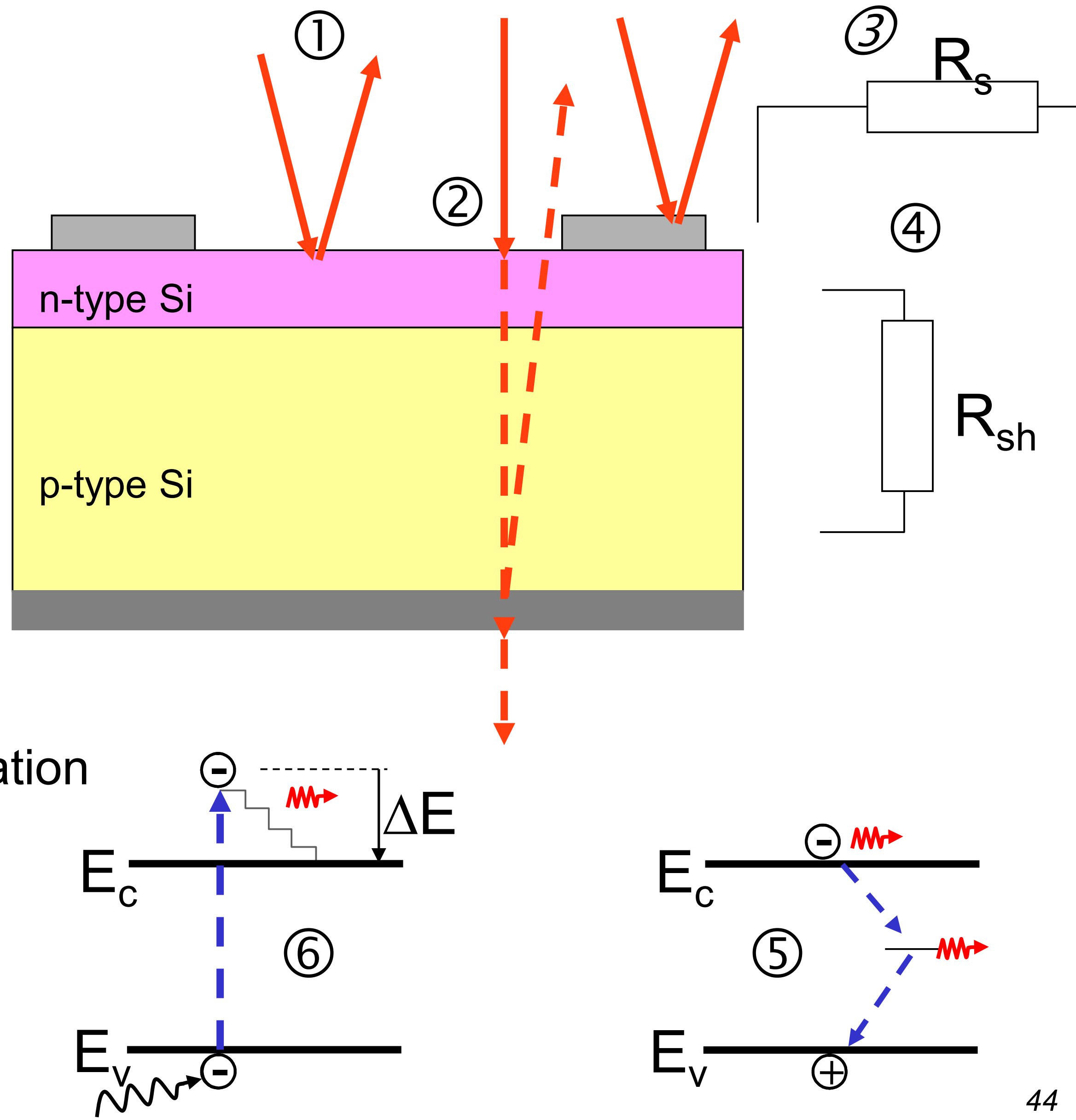
- Maximum efficiency of single-junction solar cell is **33.7%**
- Higher efficiencies are possible for **multi-junction** solar cells

W. Shockley and H.J. Queisser, "Detailed Balance Limit of Efficiency of p-n Junction Solar Cells", J. Appl. Phys. 1961

Main losses

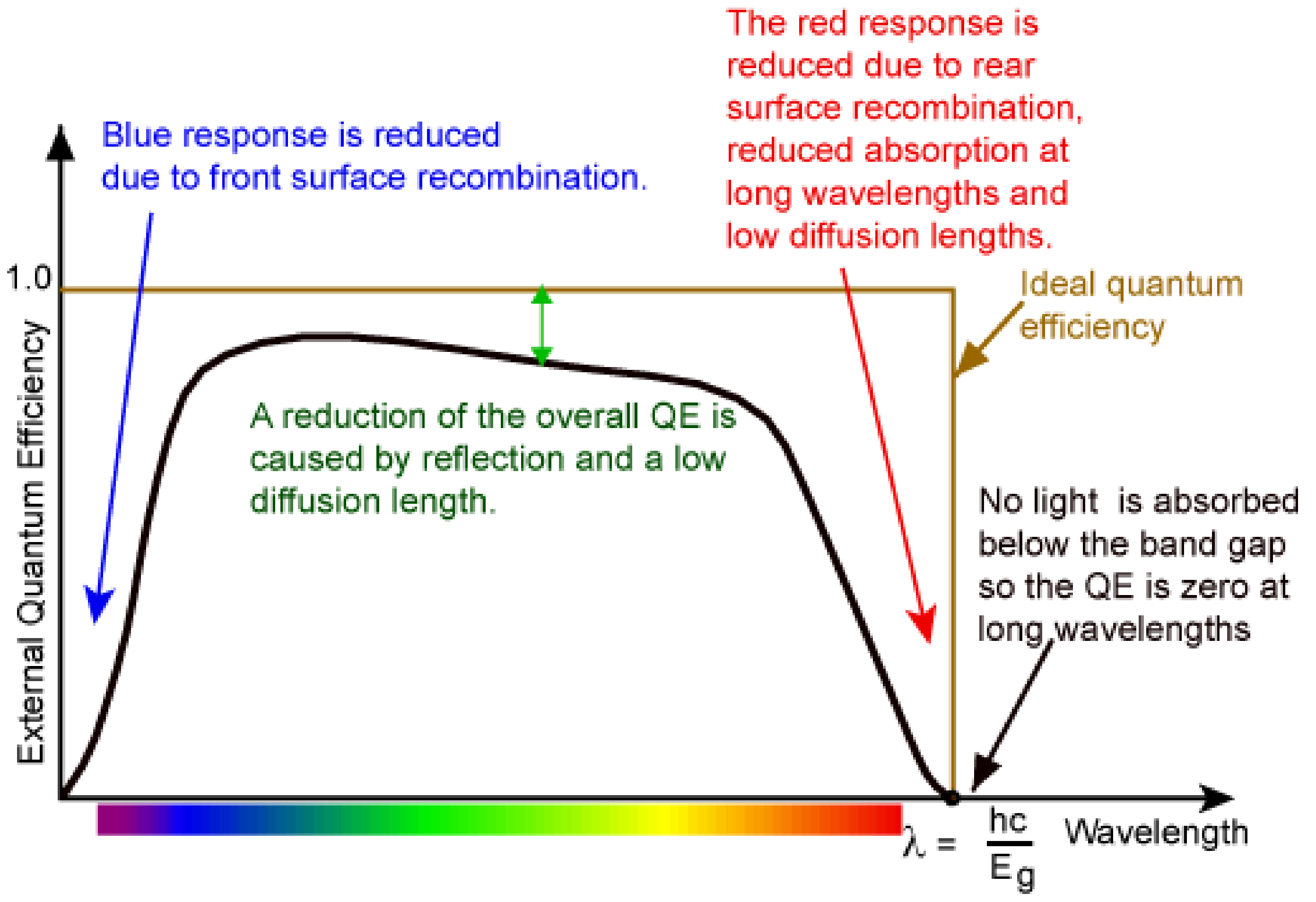
MAIN LOSSES

1. Reflection
2. Incomplete absorption
3. Shading
4. Parasitic resistance
   a. series resistance
   b. shunt resistance
5. Non radiative recombination
6. Thermalisation



Quantum efficiency

$$QE = \frac{electrons}{photons} \times 100\%$$



Quantum efficiency for different cells

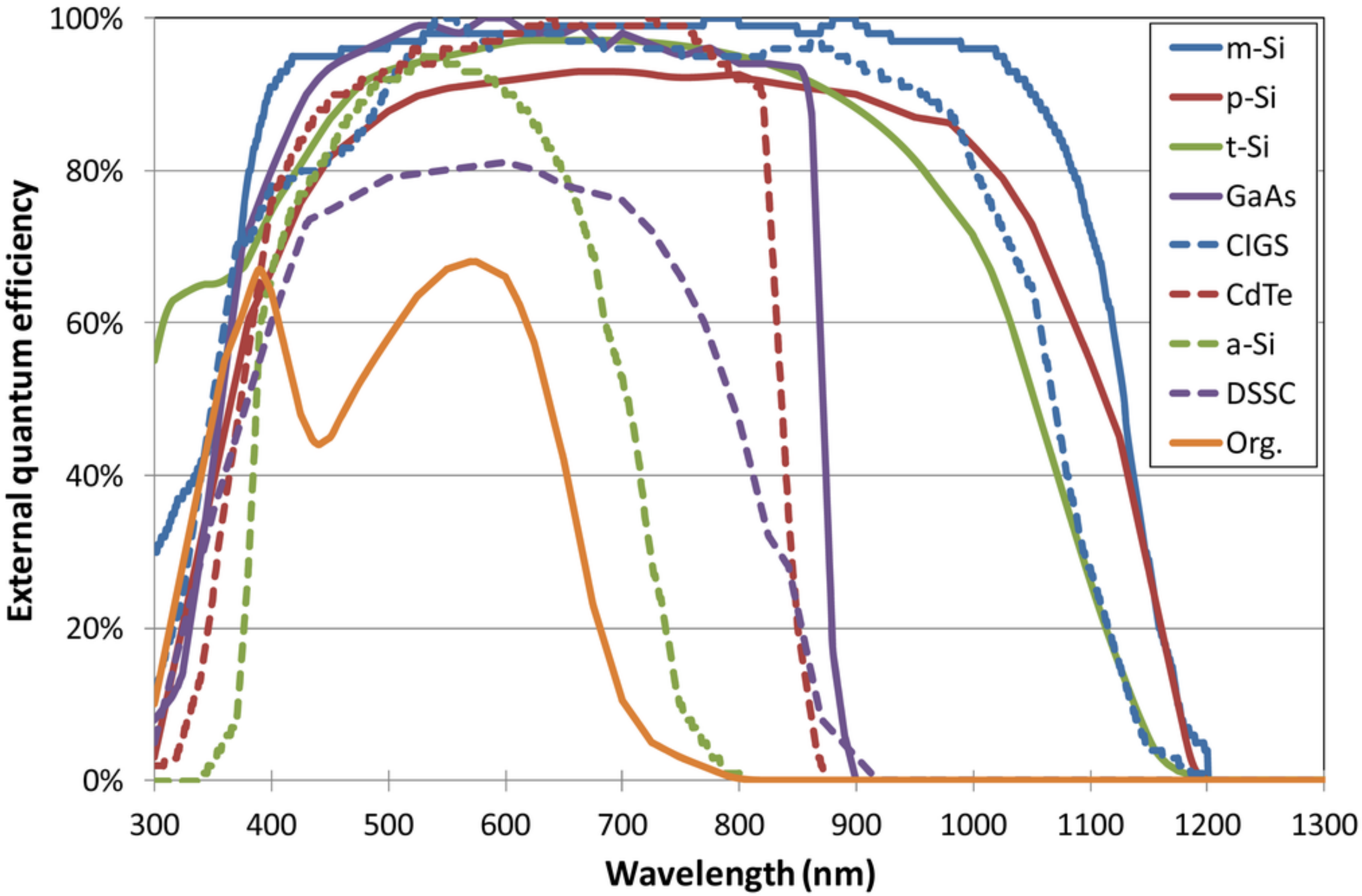
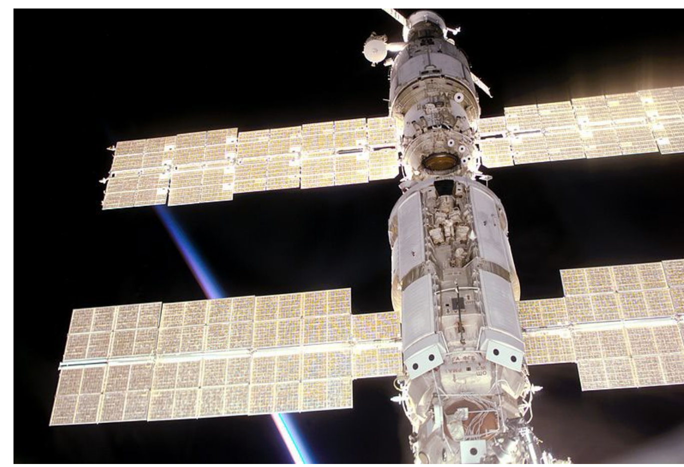
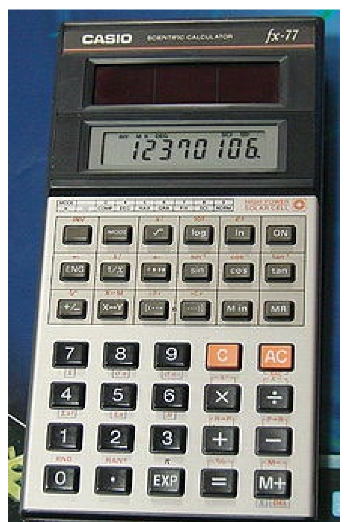


Image from: Energies 2014, 7(3), 1500-1516; doi:10.3390/en7031500

Generations of solar cells

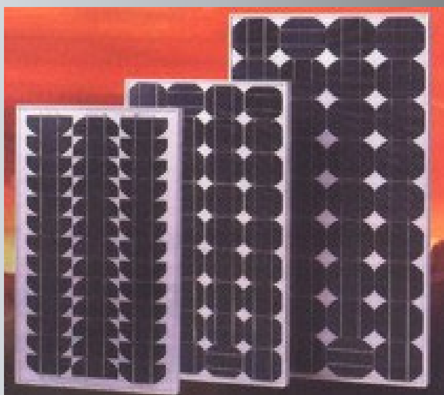
By application:





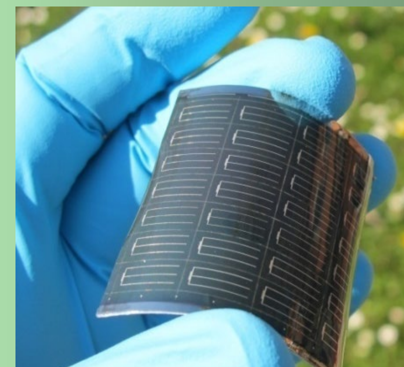
Generations of solar cells

1st Generation:
Silicon - Wafer based



- Absorber thickness: 100-200µm
- Limited by wafer size
- Rigid
- Heavy
- 55 years old (mature technology, 95% market)
- Limited cost reduction potential

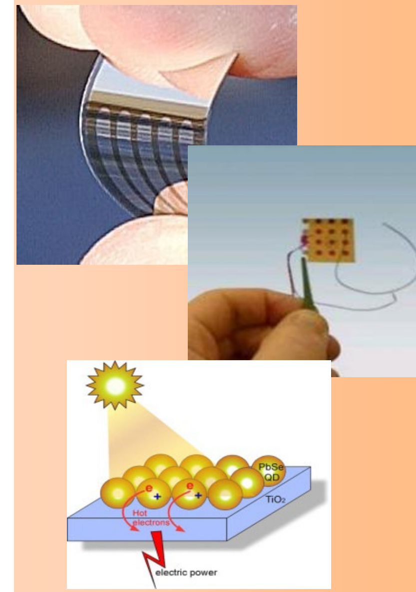
2nd Generation:
Thin-films: a-Si, CIGS, CdTe, DSSC perovskites



Rigid substrate	**Flexible substr**
Absorber thickness: <3µm	
Large area deposition	R-2-R
Monolithic integration	
Rigid	Flexible
Heavy	Light-weight
20 years old	pilot production

- Low-cost potential for mobile apps, BIPV, light-weight

3rd Generation:
Quantum dot, tundem, new concepts

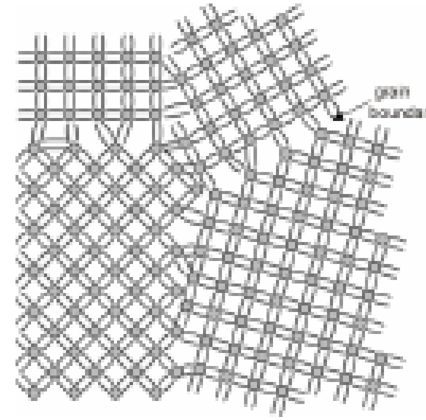


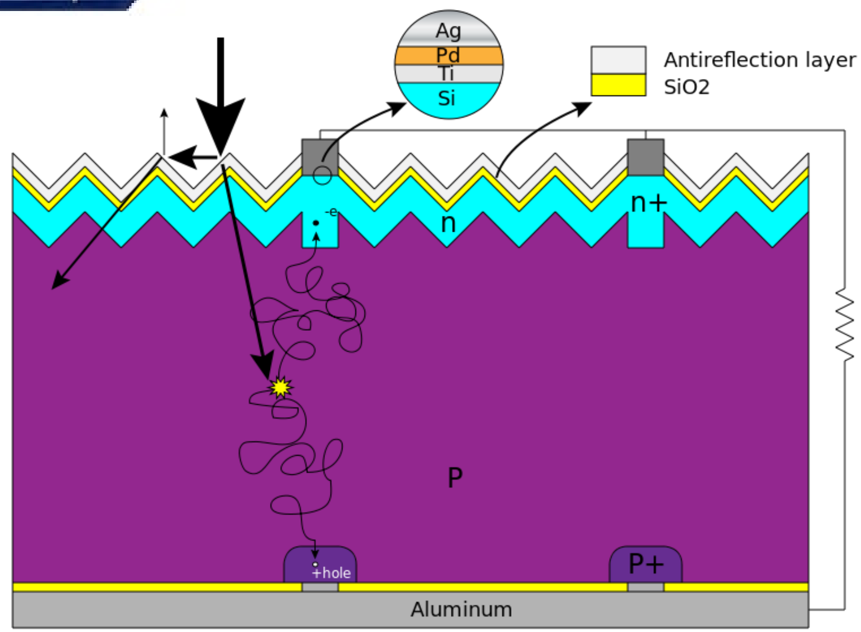
- Mainly in R&D stage
- Possibly low-cost & high-eff

1st generation: crystalline silicon

Monocrystalline Si

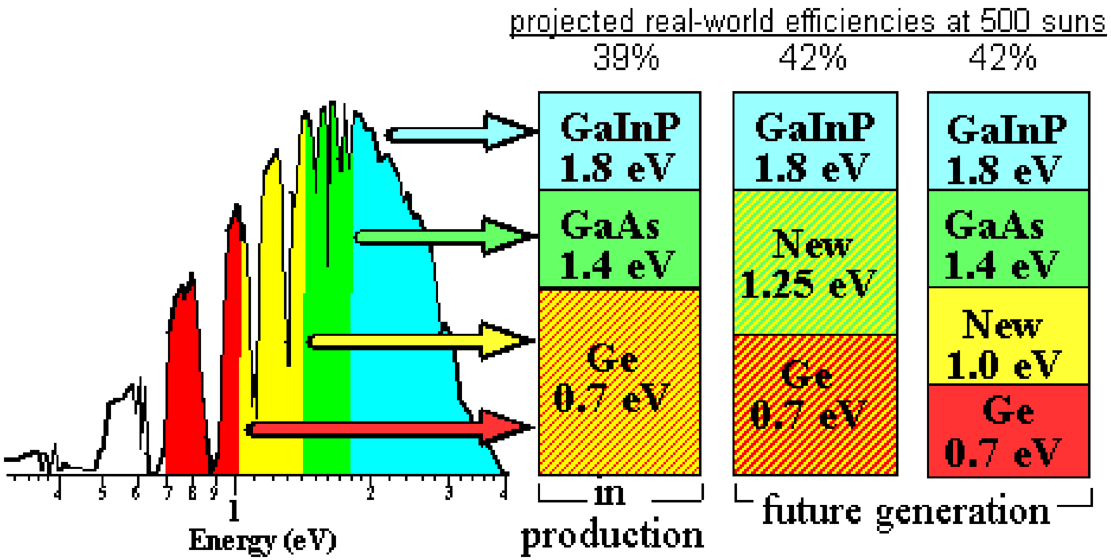
Polycrystalline Si

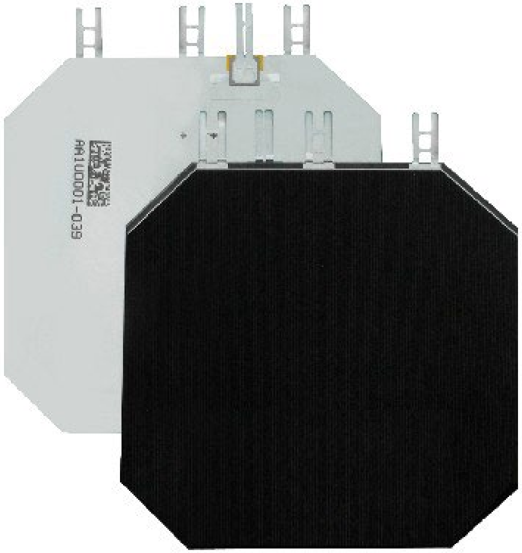




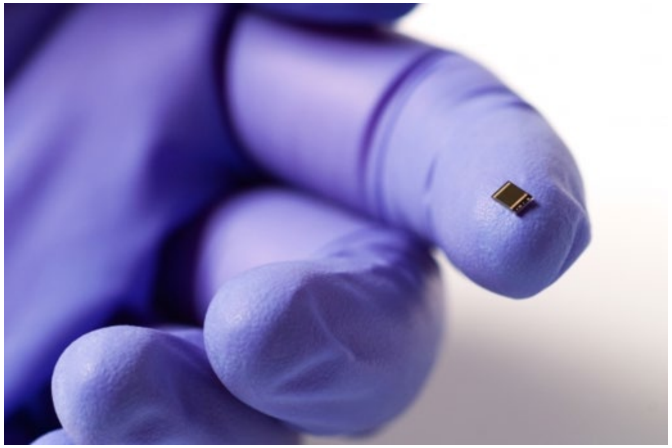
www.wikimedia.org

III-V and multi-junction solar cells



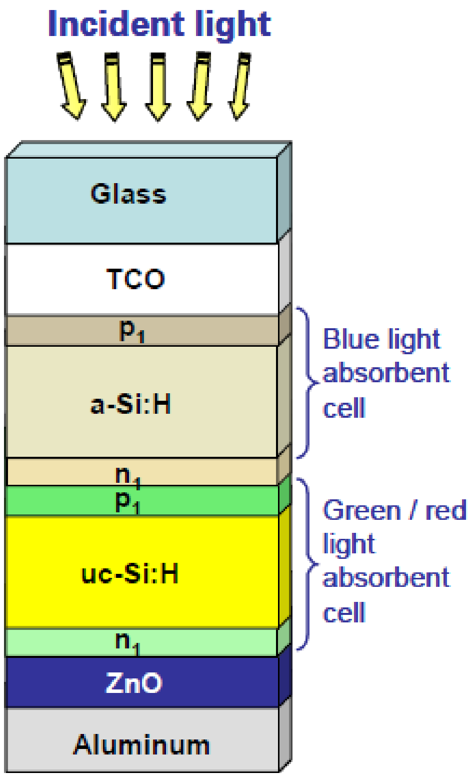


- Combination of wafer and thin-film technology based on GaAs compounds
- More complete utilization of solar spectrum in multi-junction cells
- Highest efficiency of 47.1% (6-junction, under concentrated light)

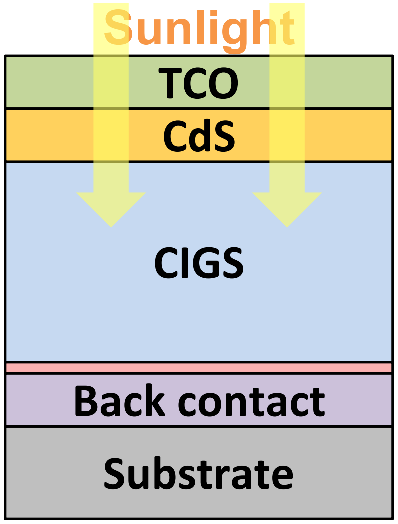


2^{nd} generation: thin film solar cells

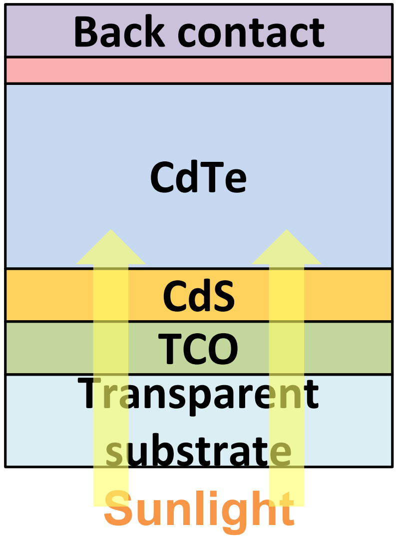
Amorphous Si
(a-Si)



$Cu(In,Ga)Se_2$
(CIGS)

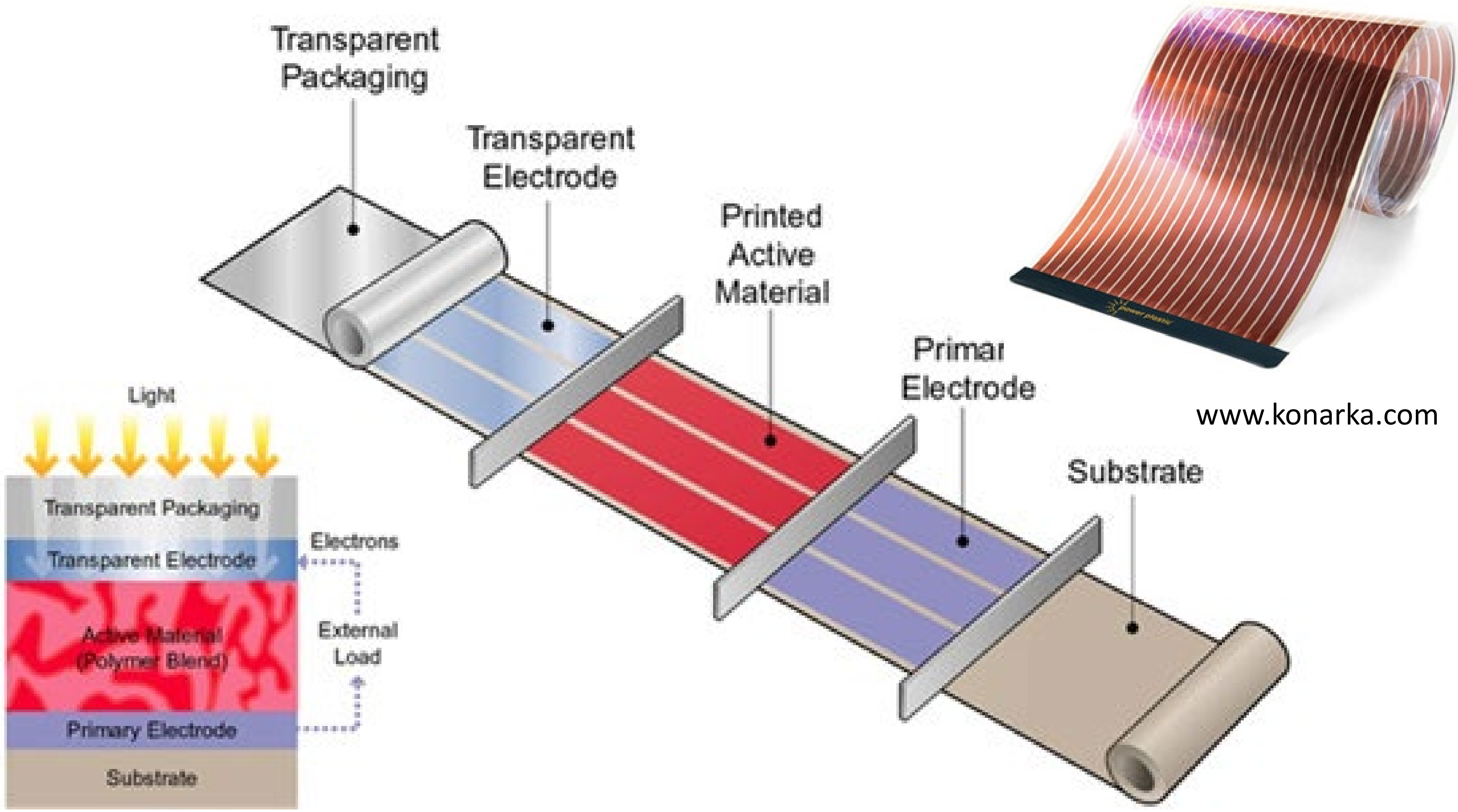


CdTe



- Thin films are deposited on substrates
- Thickness of light-absorbing layer 0.5…10 μm

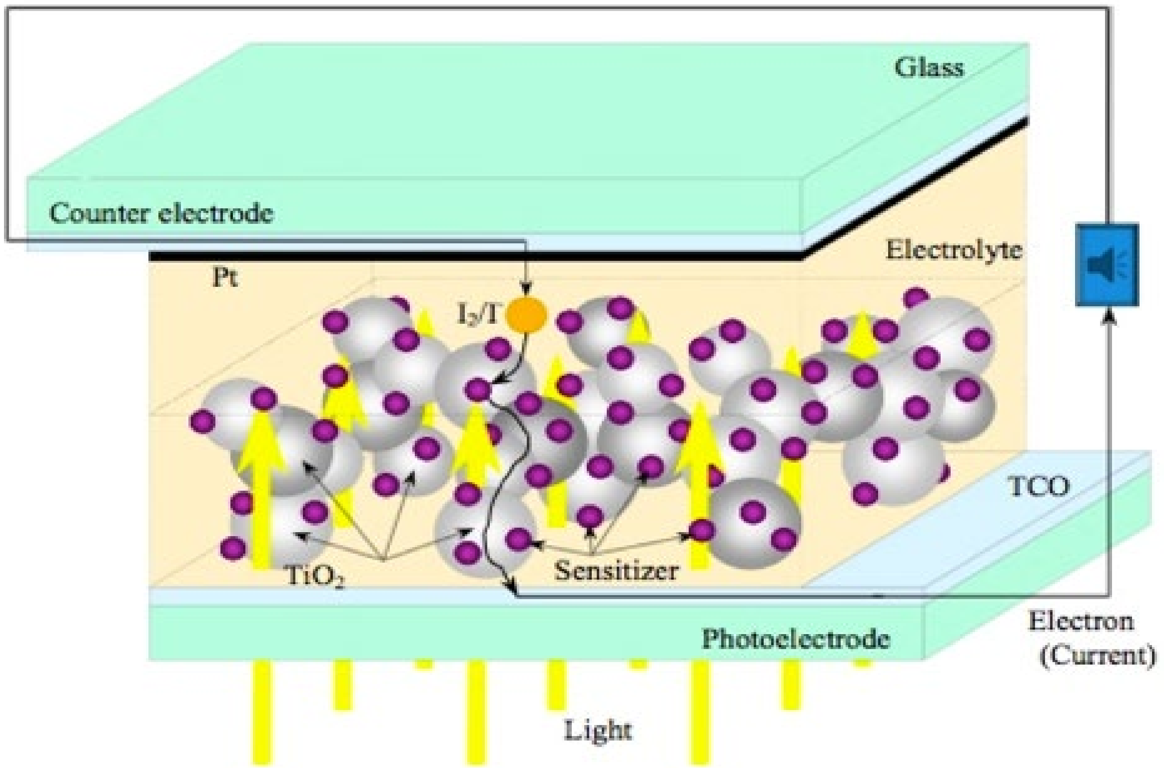
Organic solar cells (OPV)

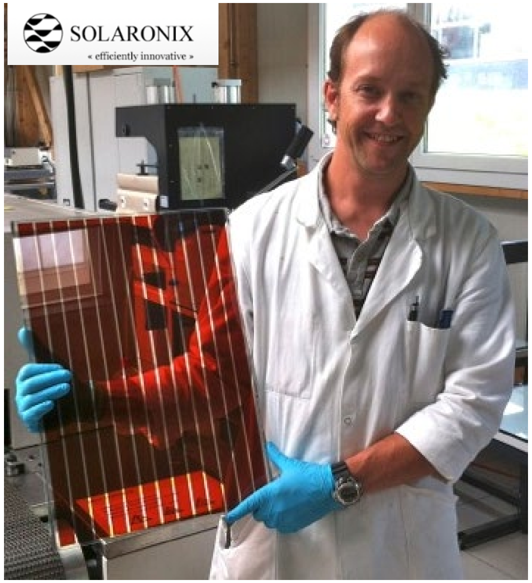


www.konarka.com

- Light absorber is polymer or small organic molecules

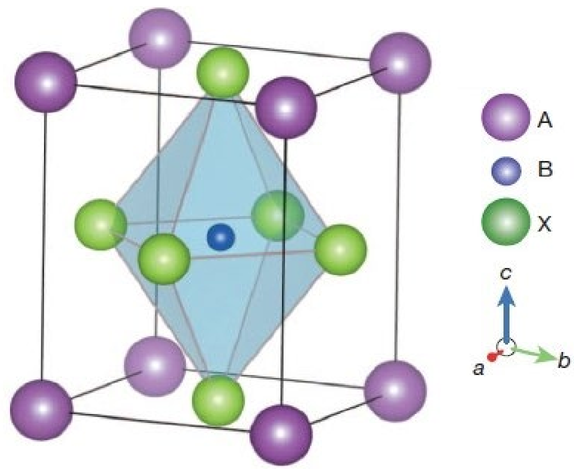
Dye-sensitized solar cells (DSSC)

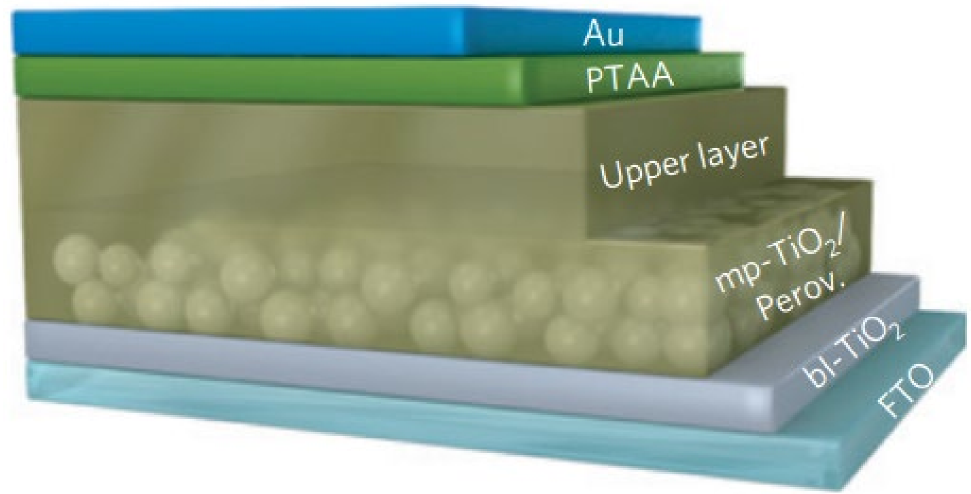




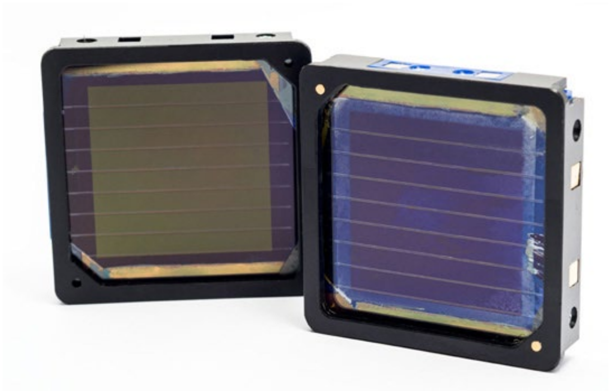
- Hybrid technology consisting of organic dyes, inorganic contacts and electrolyte

Perovskite solar cells



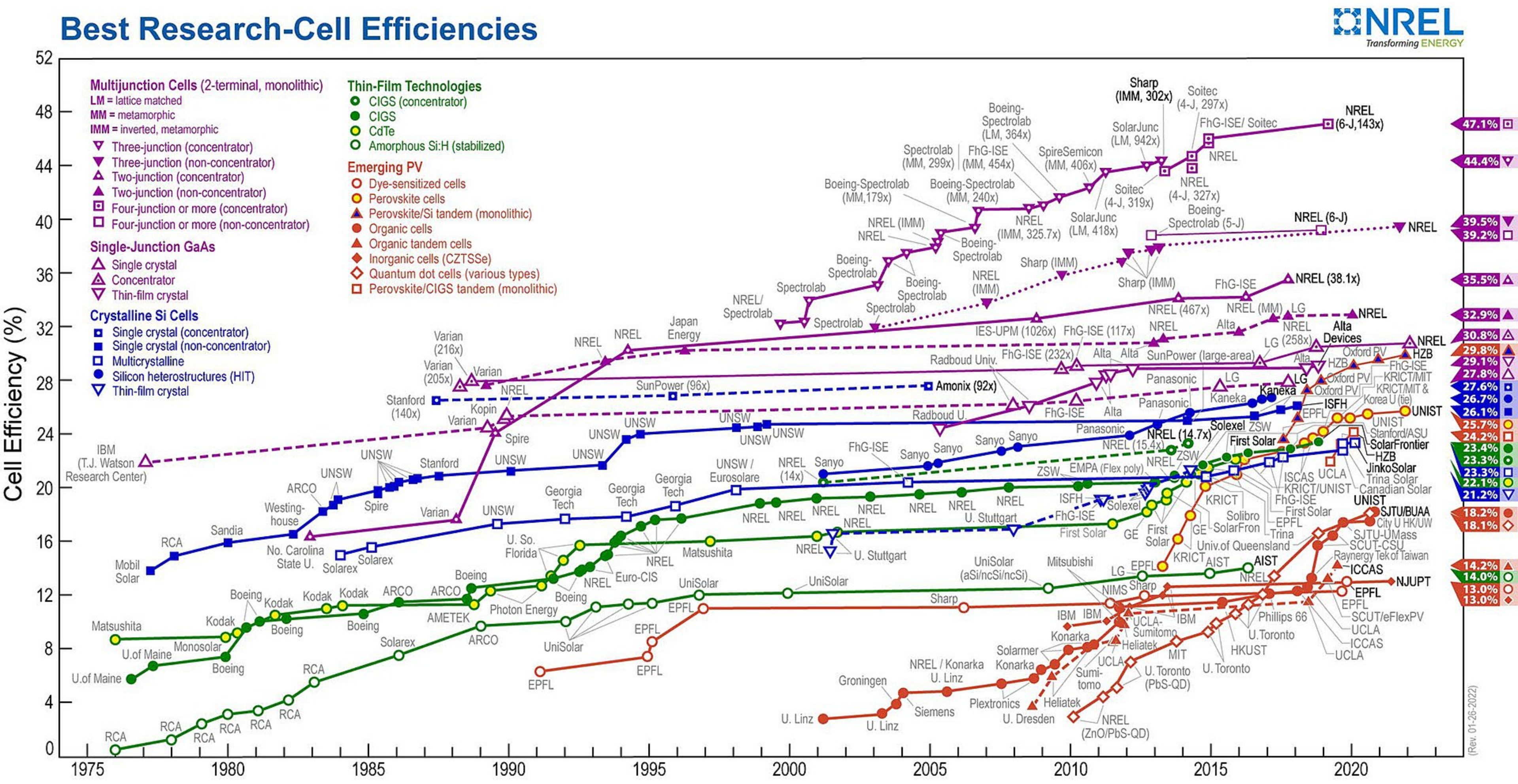


- Relatively new technology with rapid efficiency progress till 25.7% (2022) – initial small-scale production mainly in China.
- Based on organometal compounds ABX_3 with the cubic structure of mineral perovskite $CaTiO_3$
- Simpliest ABX_3 representative $CH_3NH_3PbX_3$ (methylammonium lead halide)



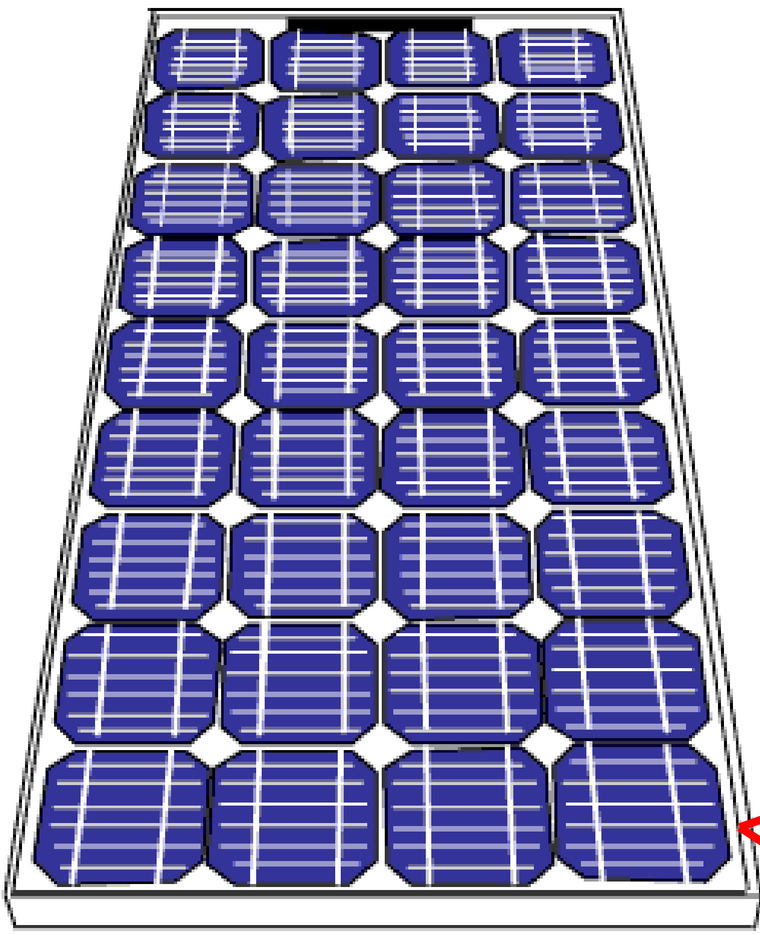
IMEC: perovskite mini-modules

Progress in solar cell efficiency

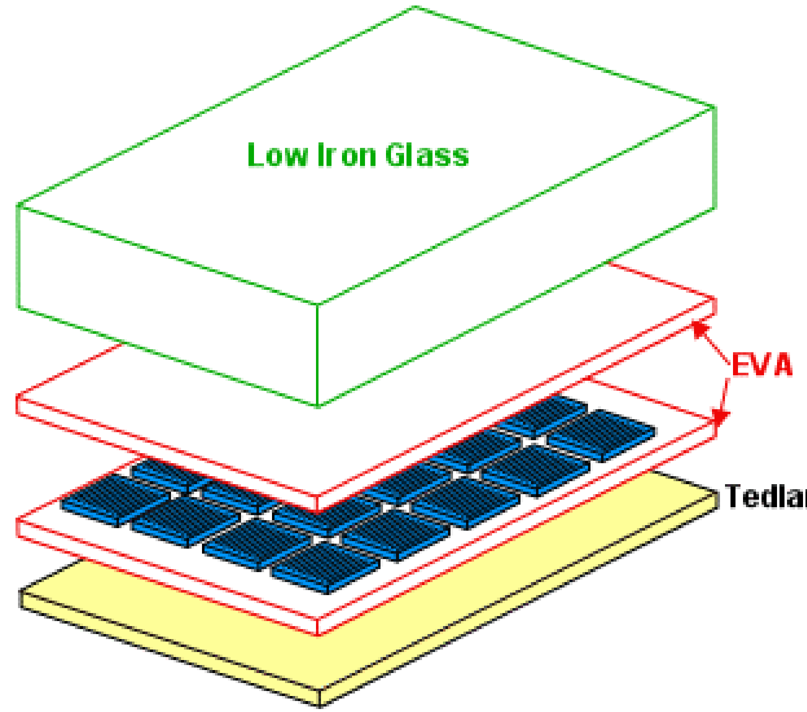


https://en.wikipedia.org/wiki/Solar_cell_efficiency, June 2022

PV modules (example c-Si)



www.pveducation.org



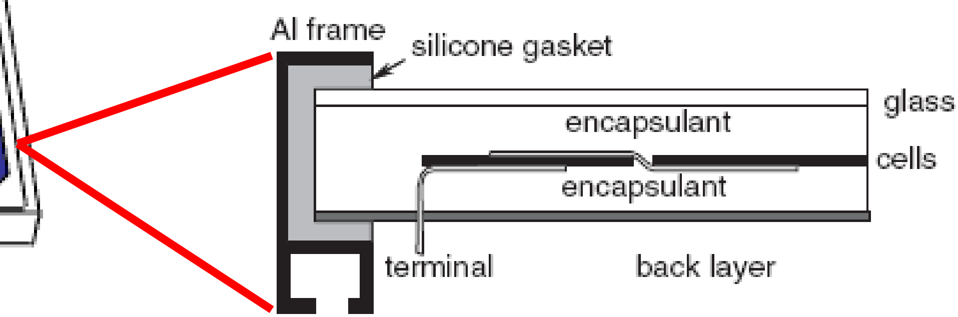
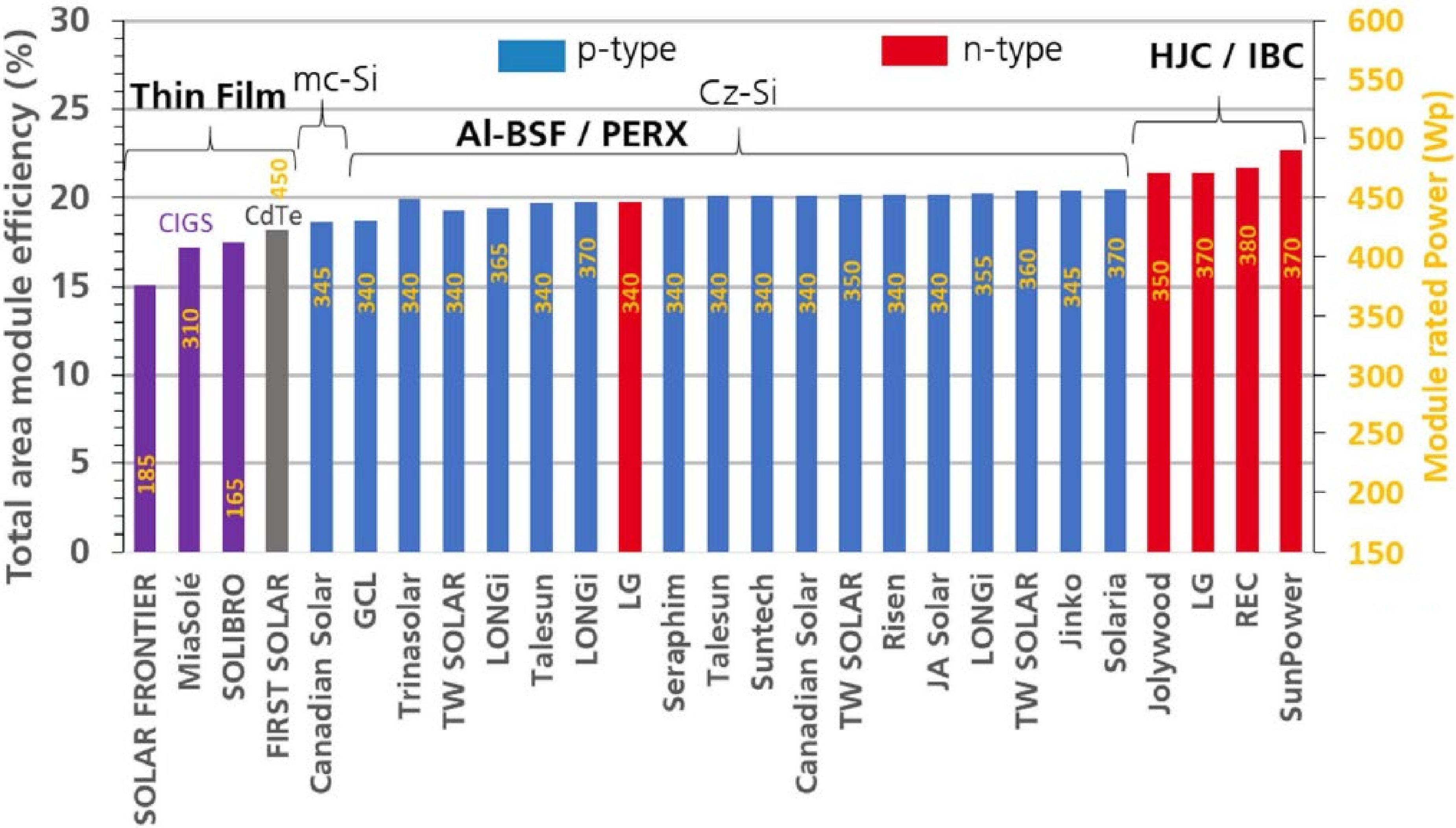


Figure 7.19 Cross- section of a standard module

Handbook of Photovoltaic Science and Engineering, 2011

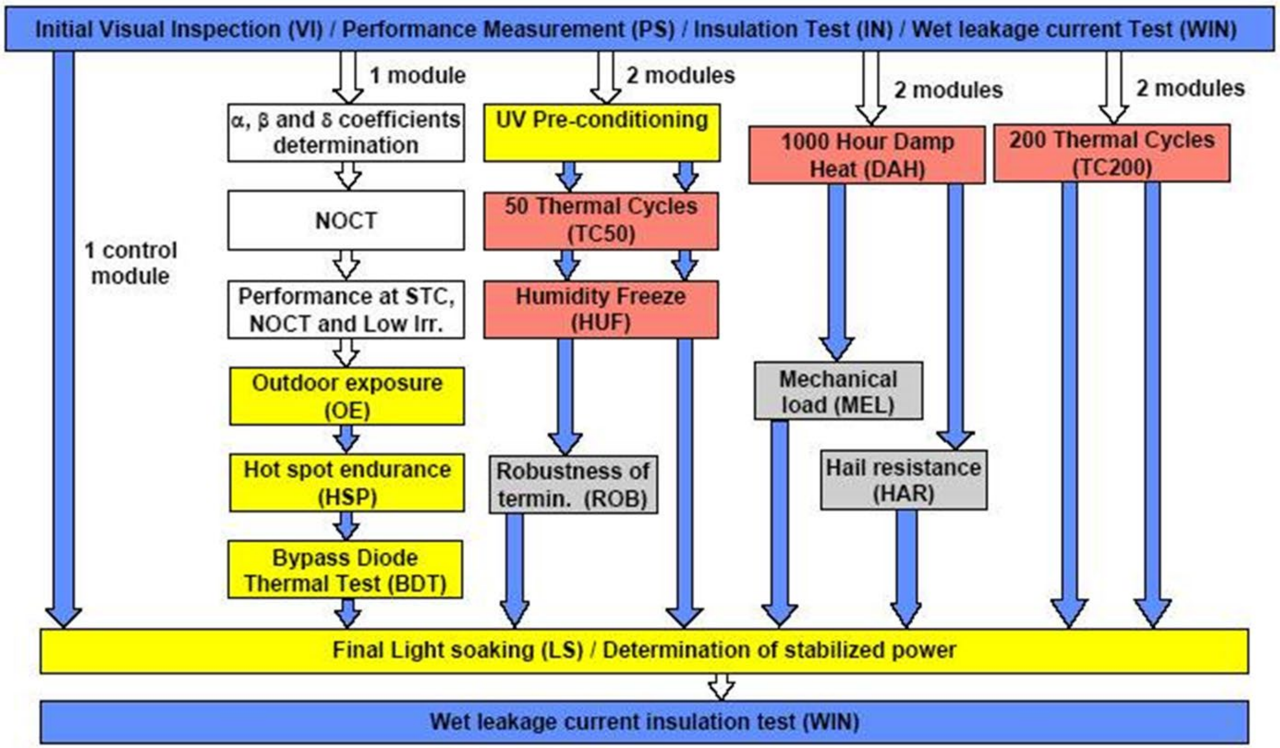
PV module efficiency



Source: Photovoltaics report, Fraunhofer Institute, Sept 2020

PV module certification

- ➢ IEC 61215: life-time testing for crystalline silicon PV
- ➢ IEC 61646: life-time testing for thin-film PV



Courtesy: A. Virtuani, SUPSI

- Accelerated life-time testing corresponds to ~20 years outdoor
- Typical warranty: > 90% power 10 years, > 80% power after 25 years
- Warranty ≠ Lifetime (PV module can serve for 30…40 years and more…)

Module degradation

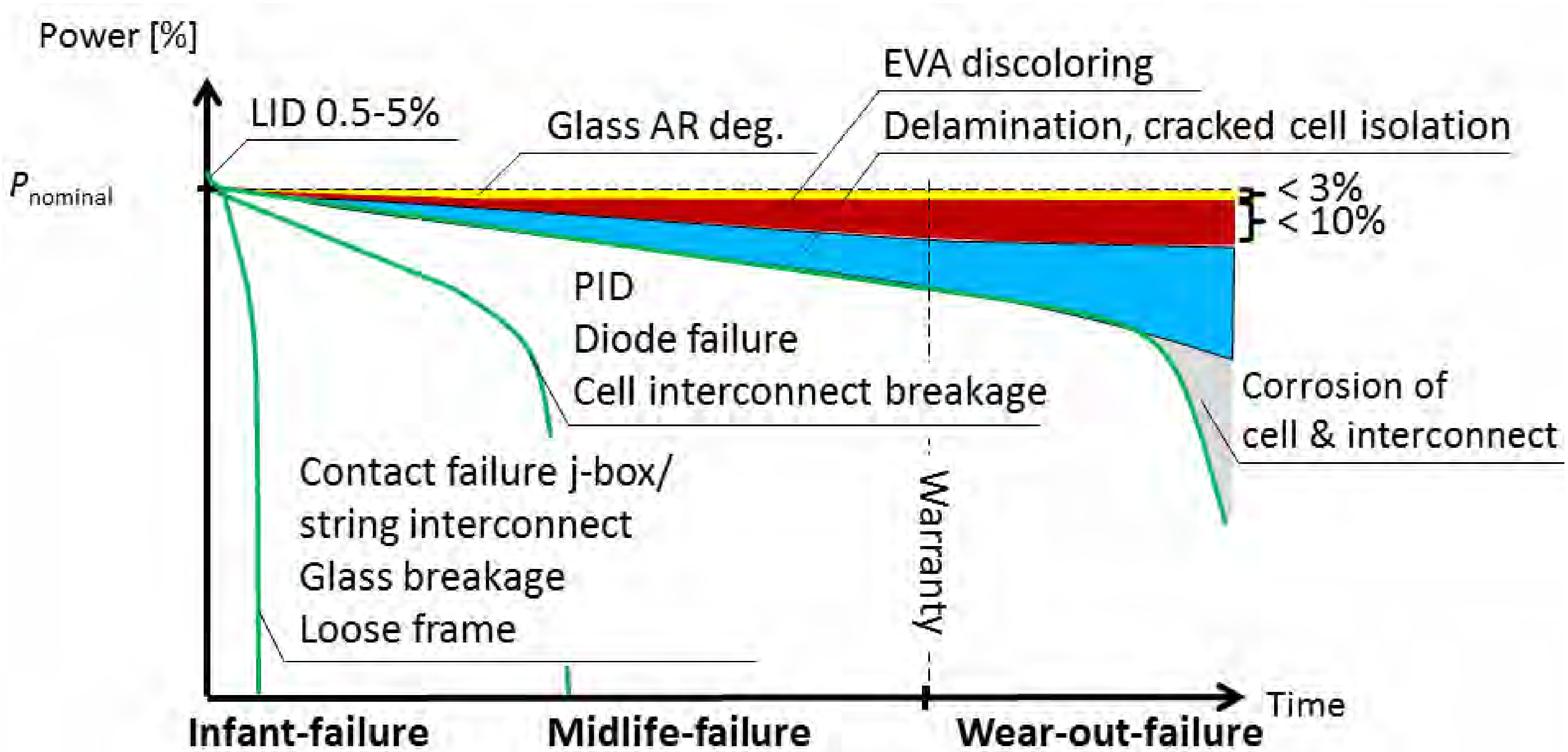
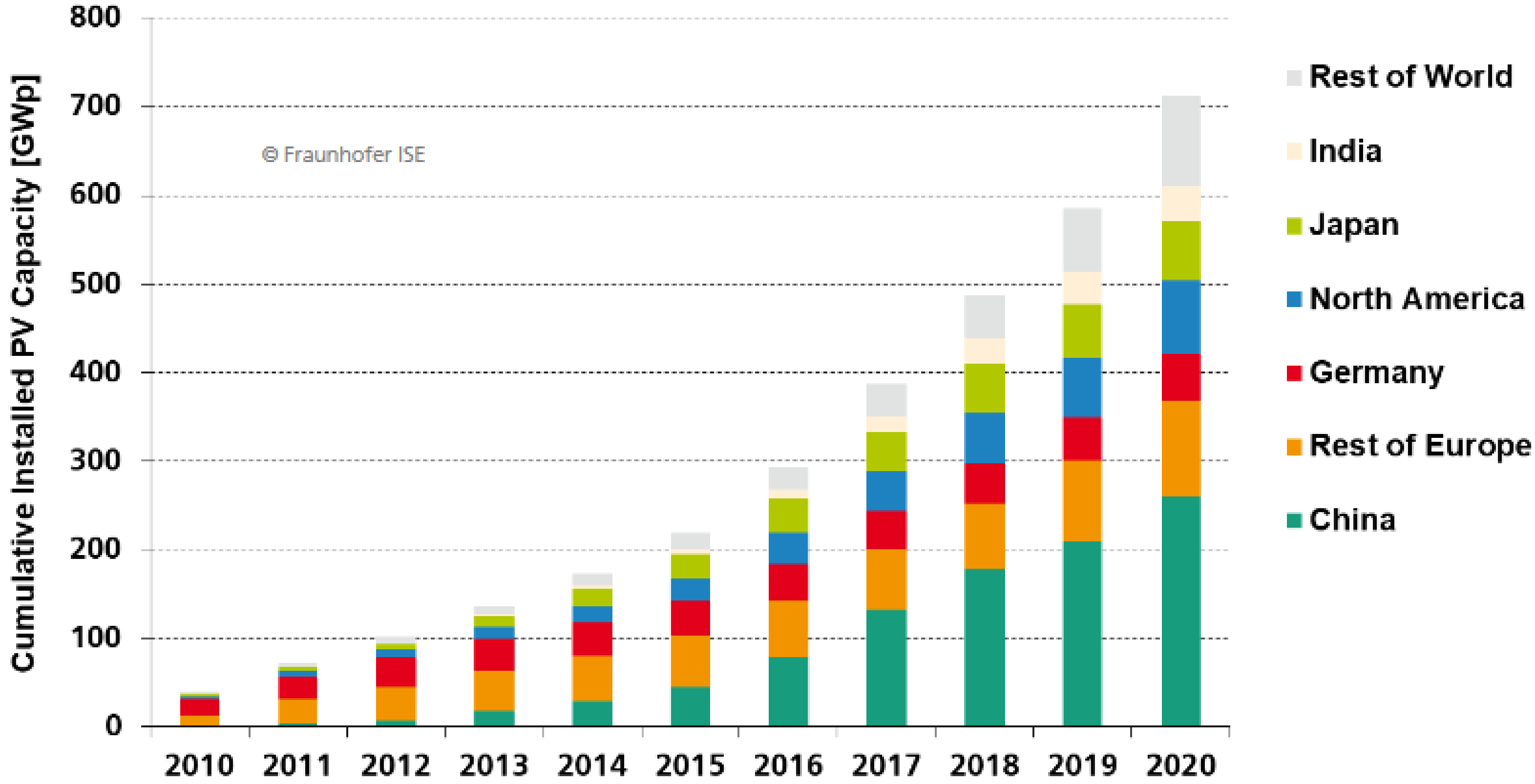


Fig. 3.1: Three typical failure scenarios for wafer-based crystalline photovoltaic modules are shown. Definition of the used abbreviations: LID – light-induced degradation, PID – potential induced degradation, EVA – ethylene vinyl acetate, j-box – junction box.

Report IEA-PVPS T13-01:2014

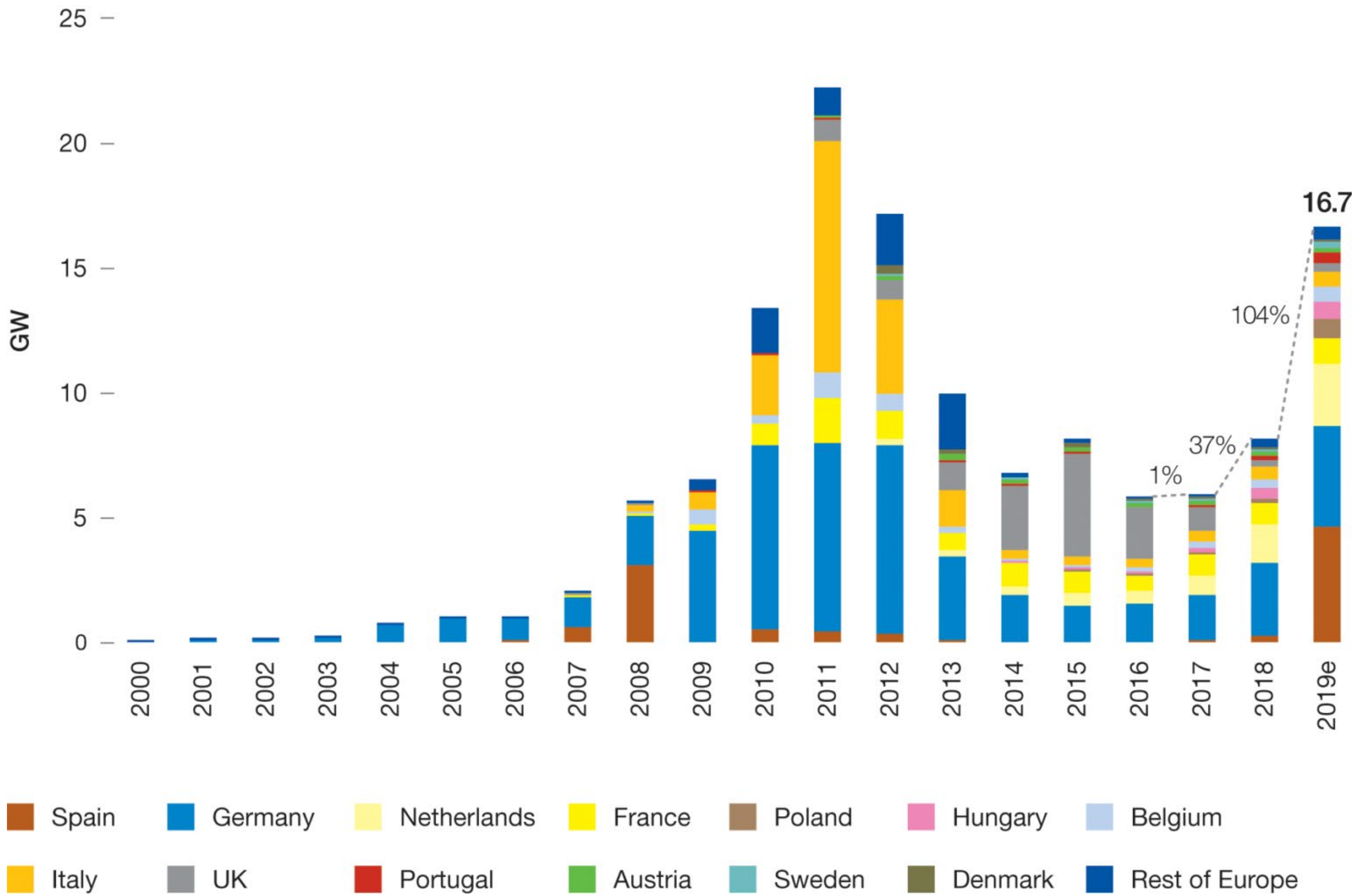
PV economics

Global PV installations



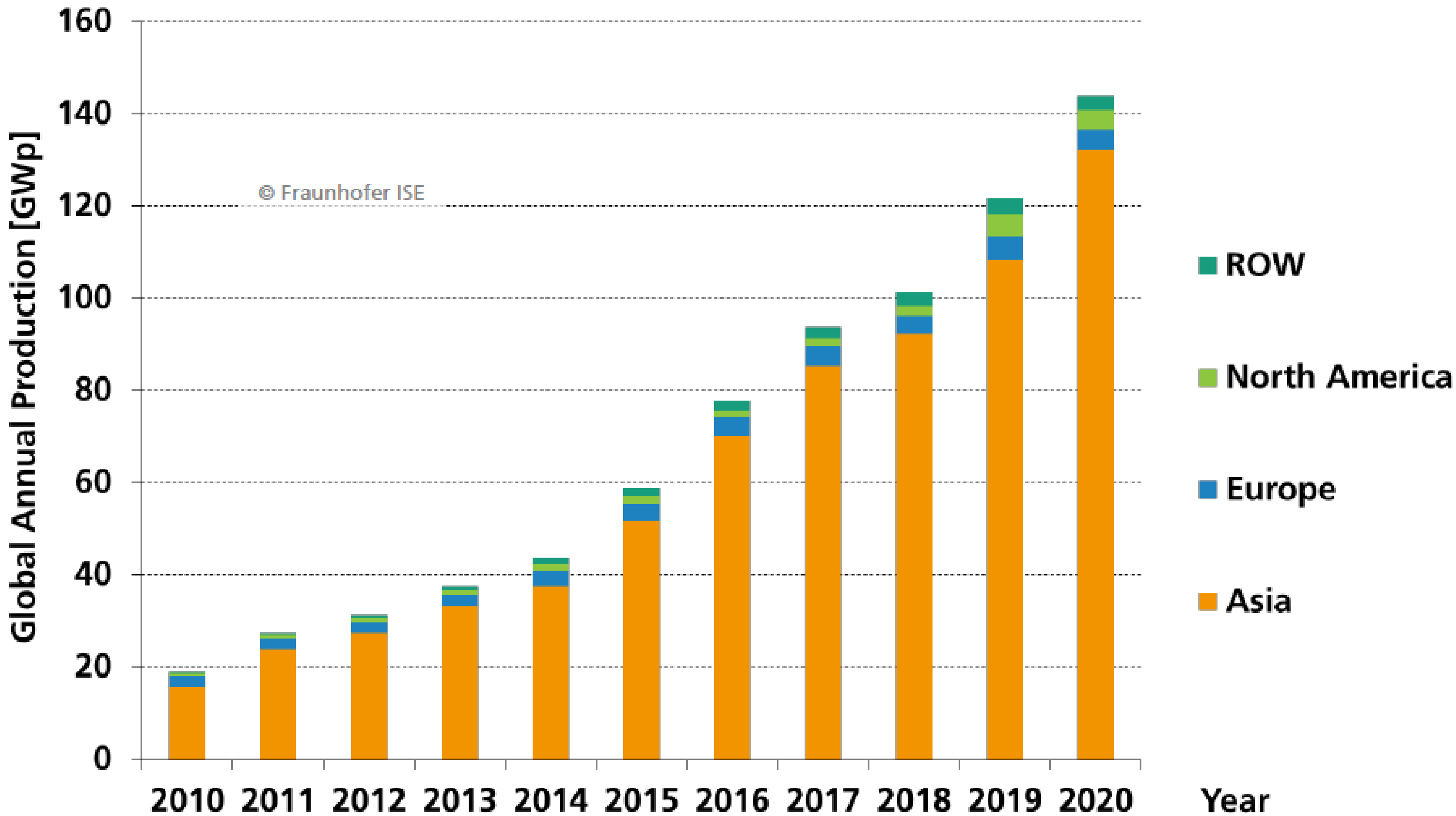
Source: Photovoltaics report,
Fraunhofer Institute ISE, Feb 2022

Annual PV installations in Europe 2000-2019



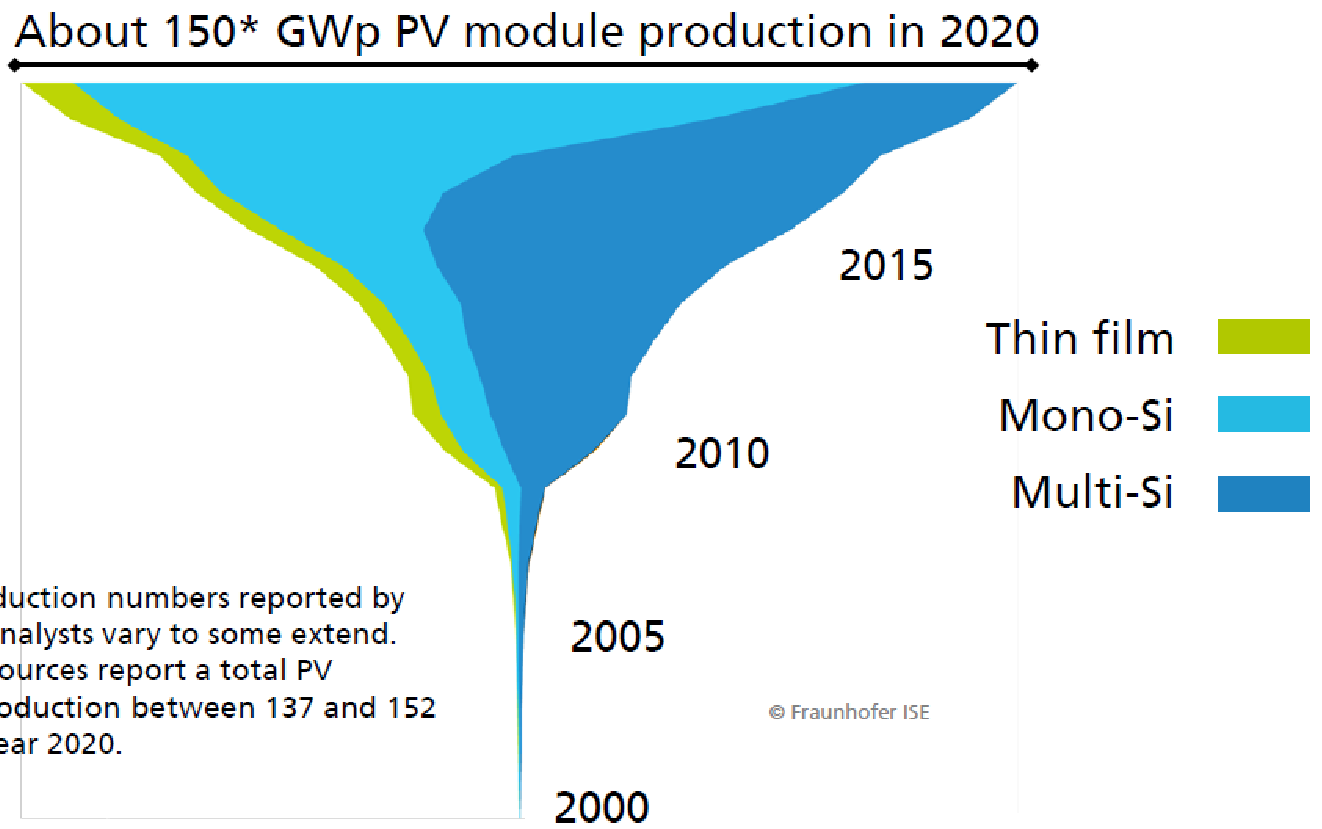
Source: www.solarpowereurope.org

PV module production by region



Source: Photovoltaics report, Fraunhofer Institute ISE, Feb 2022

Annual PV Production by Technology
Worldwide (in GWp)

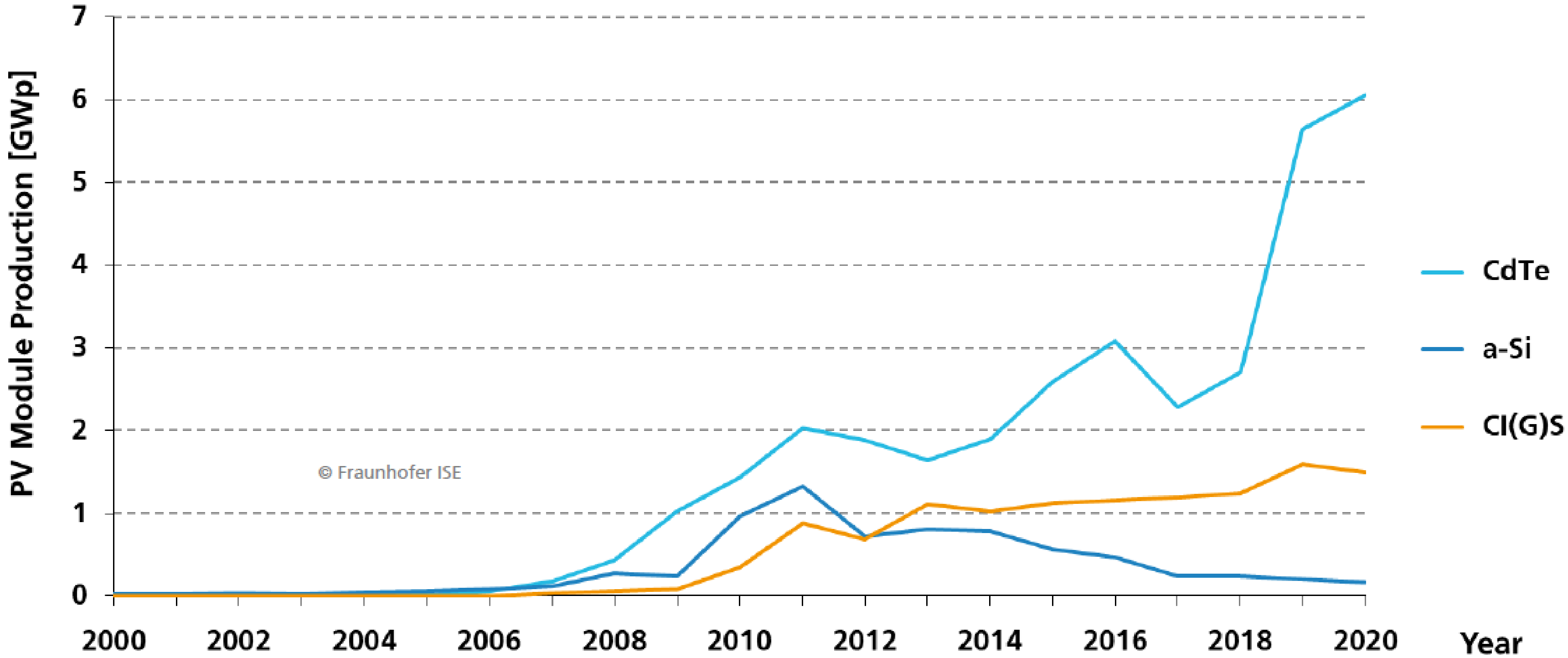


*2020 production numbers reported by different analysts vary to some extend. Different sources report a total PV module production between 137 and 152 GWp for year 2020.

Source: Photovoltaics report, ISE Fraunhofer, Feb 2022

Thin-Film Technologies

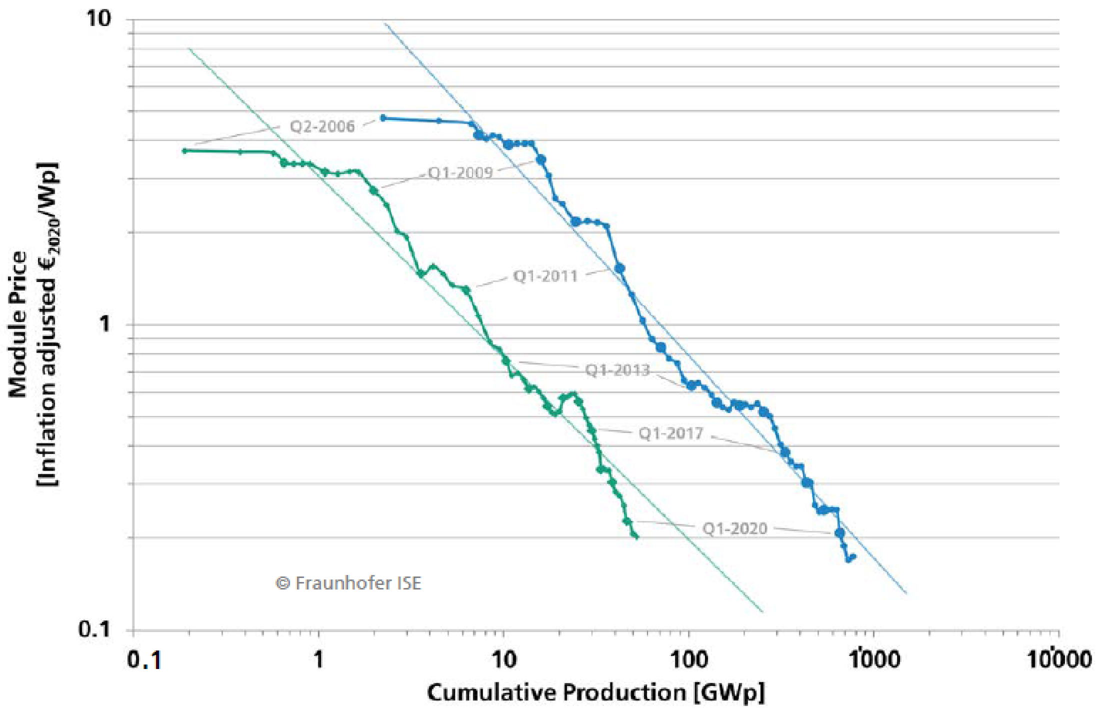
Annual Global PV Module Production



Source: Photovoltaics report, Fraunhofer Institute ISE, Feb 2022

Price Learning Curve by Technology

Cumulative Production up to Q4-2020



Estimated cumulative PV module production up to Q4-2020:

c-Si	773 GWp
Thin Film	52 GWp

Crystalline Technology

(from Q2-2006 to Q4-2020) LR 32

Thin Film Technology

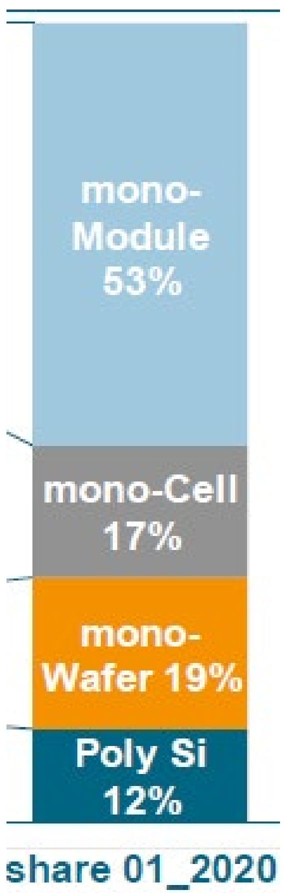
(from Q2-2006 to Q4-2020) LR 30

Source: Photovoltaics report,
Fraunhofer Institute ISE, Feb 2022

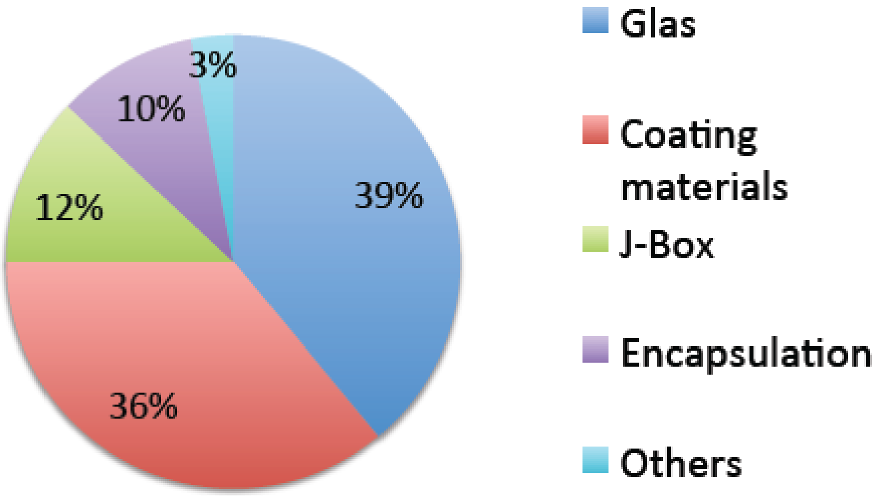
- Price of PV modules falls by ~24% upon doubling capacity
- Thin film PV has the same price as Si but for 10 smaller production

PV module cost structure

Crystalline Si module



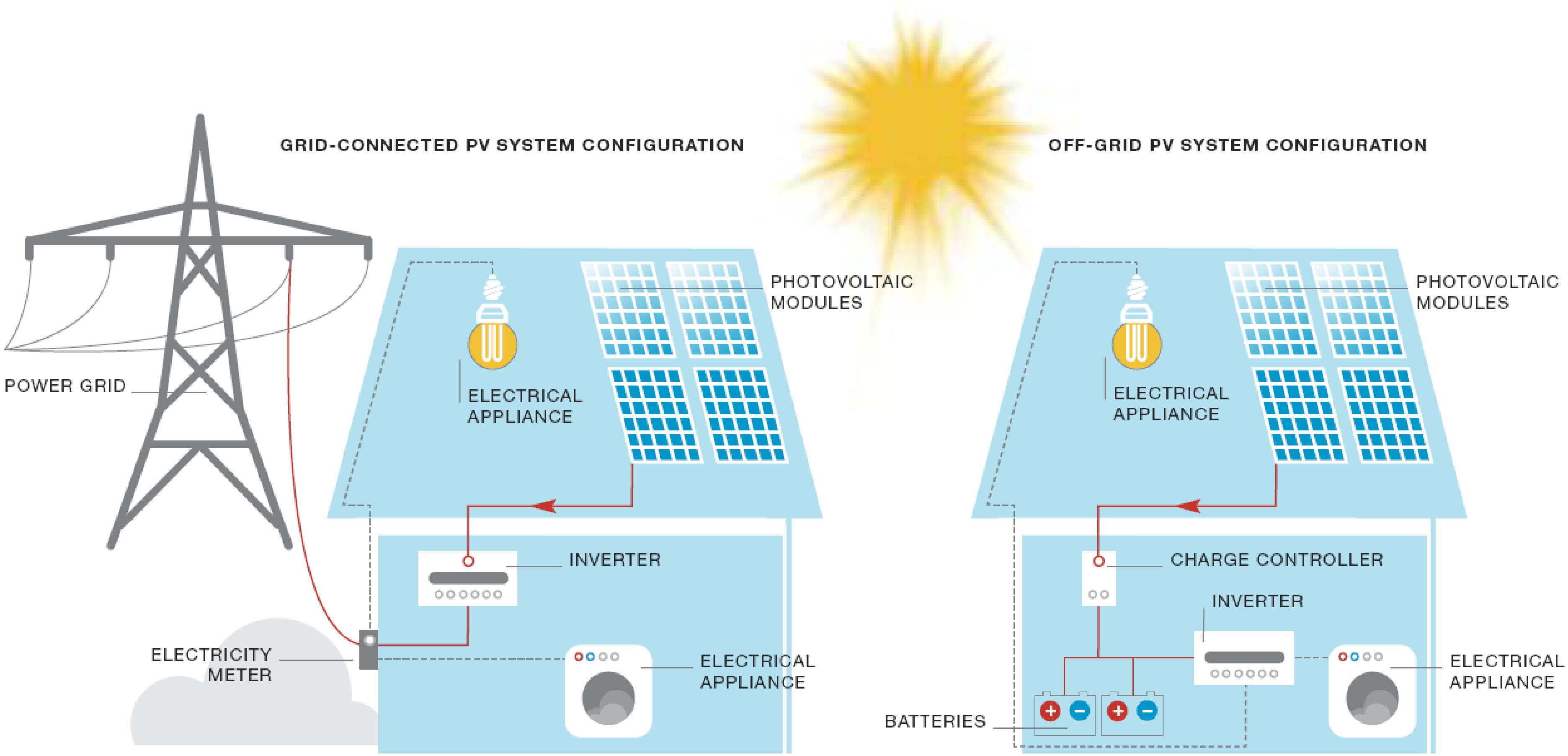
Thin film module (CIGS)



PICON Solar, 2011

International Technology Roadmap for Photovoltaic, April 2020

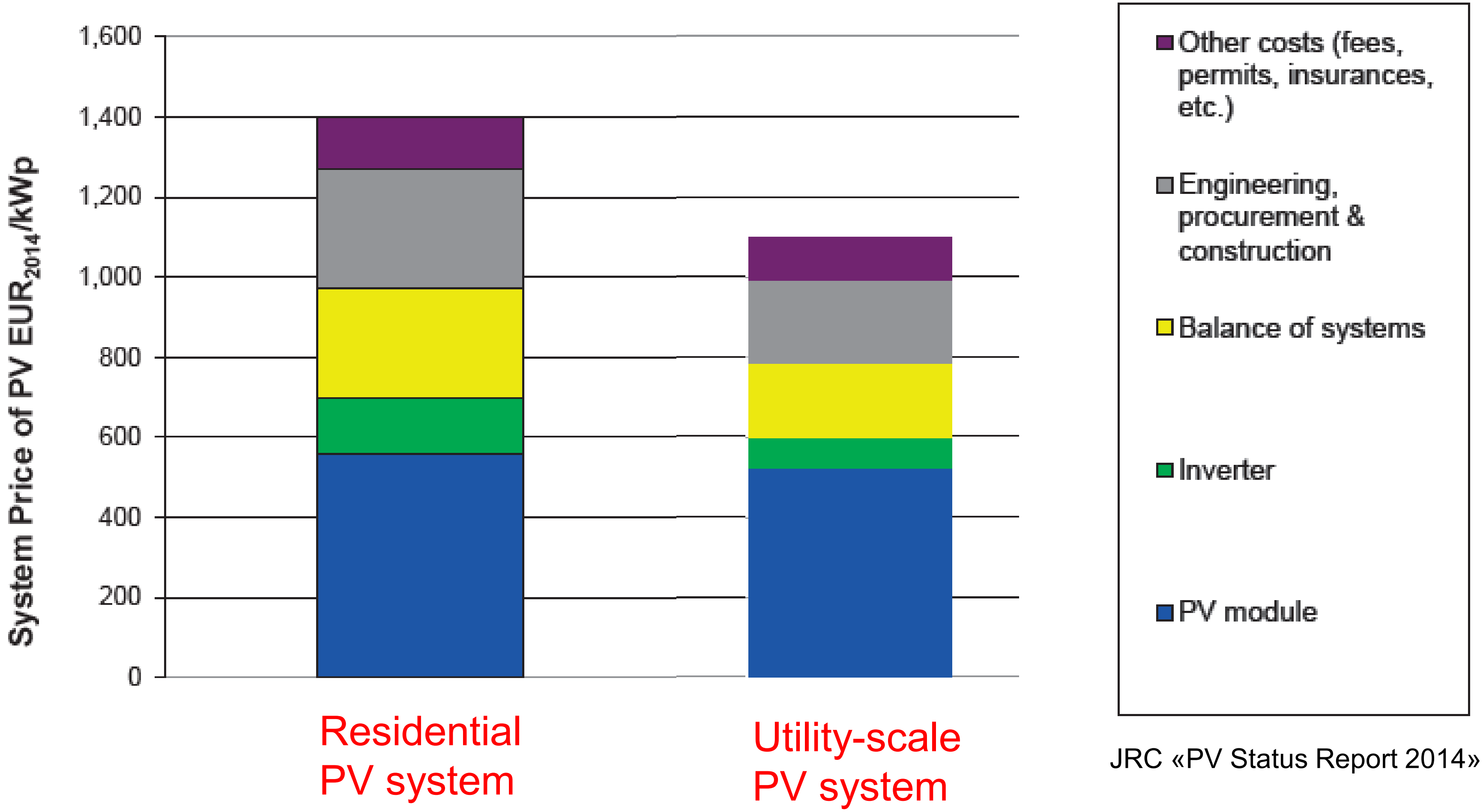
PV systems



source: EPIA.

- PV systems components: PV modules, electricity meter; AC isolator, fusebox, inverter, charge controller, generation meter, DC isolator, cabling, mounting, etc.…

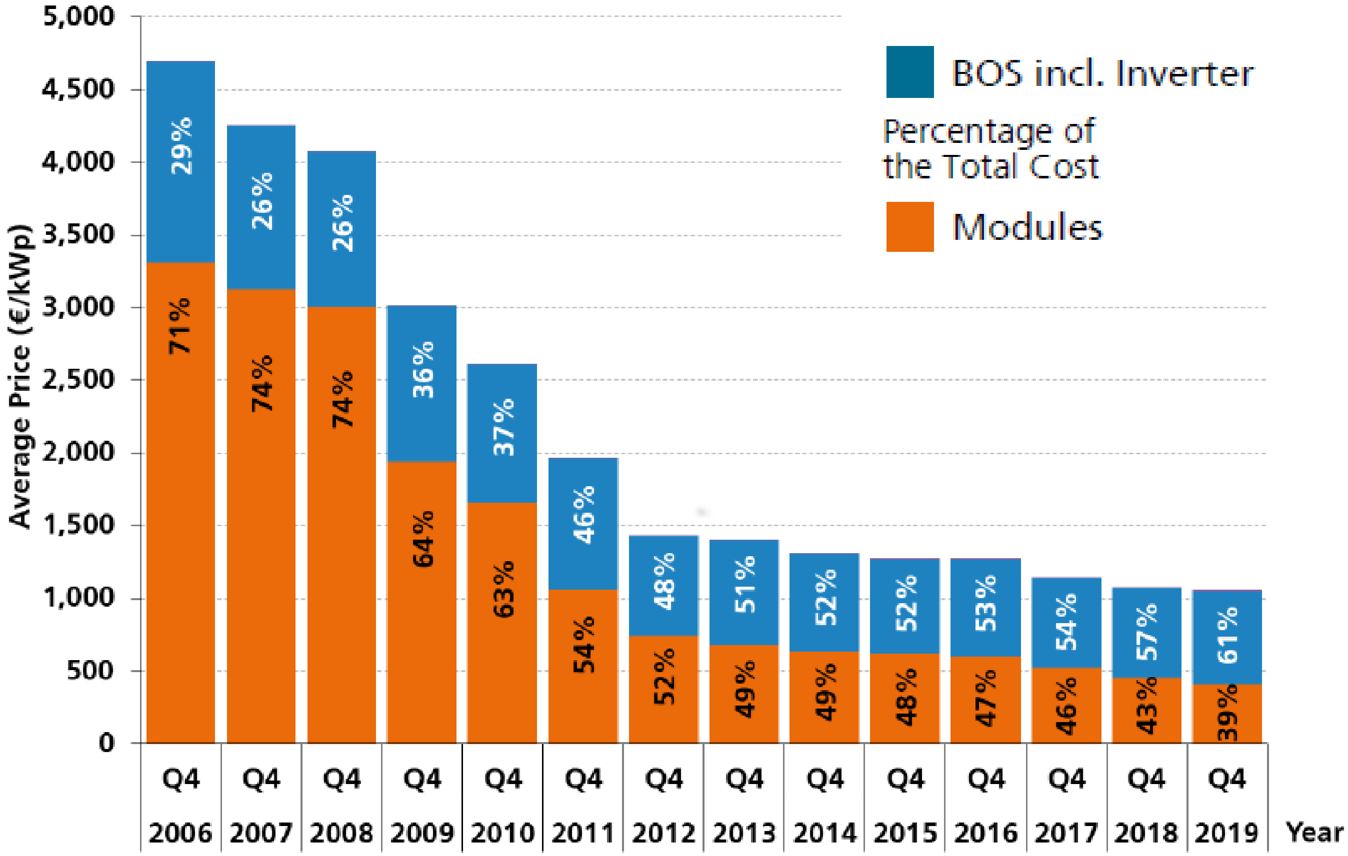
PV system costs



JRC «PV Status Report 2014»

- Module cost < 50% of the total PV system cost!

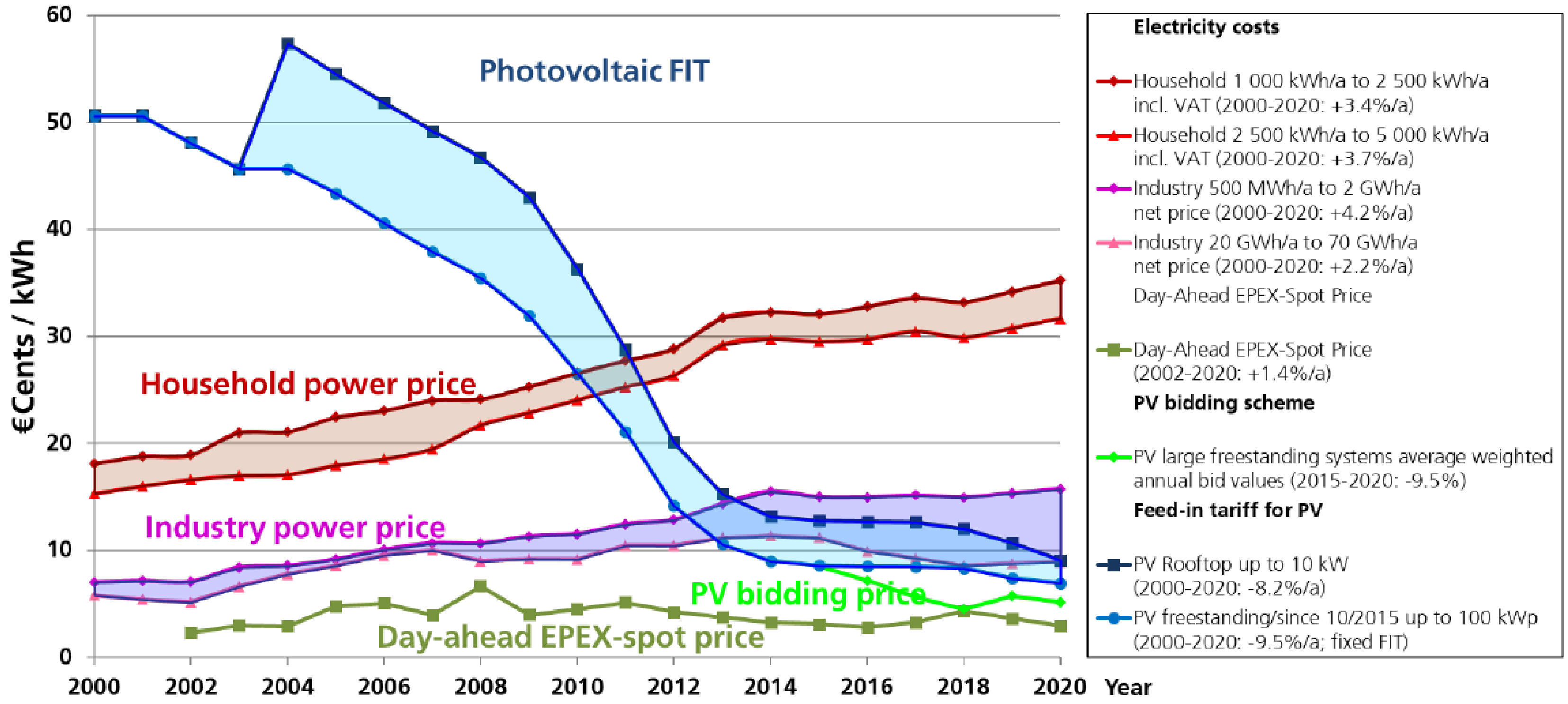
Average Price for PV Rooftop Systems in Germany
(10kWp - 100kWp)



Source: Photovoltaics report, Fraunhofer Institute ISE, Sept 2020

- Modules represent a smaller part of the overall system cost – that is why module efficiency matters

Electricity Prices, PV Feed-In Tariffs (FIT) and bidding scheme in Germany



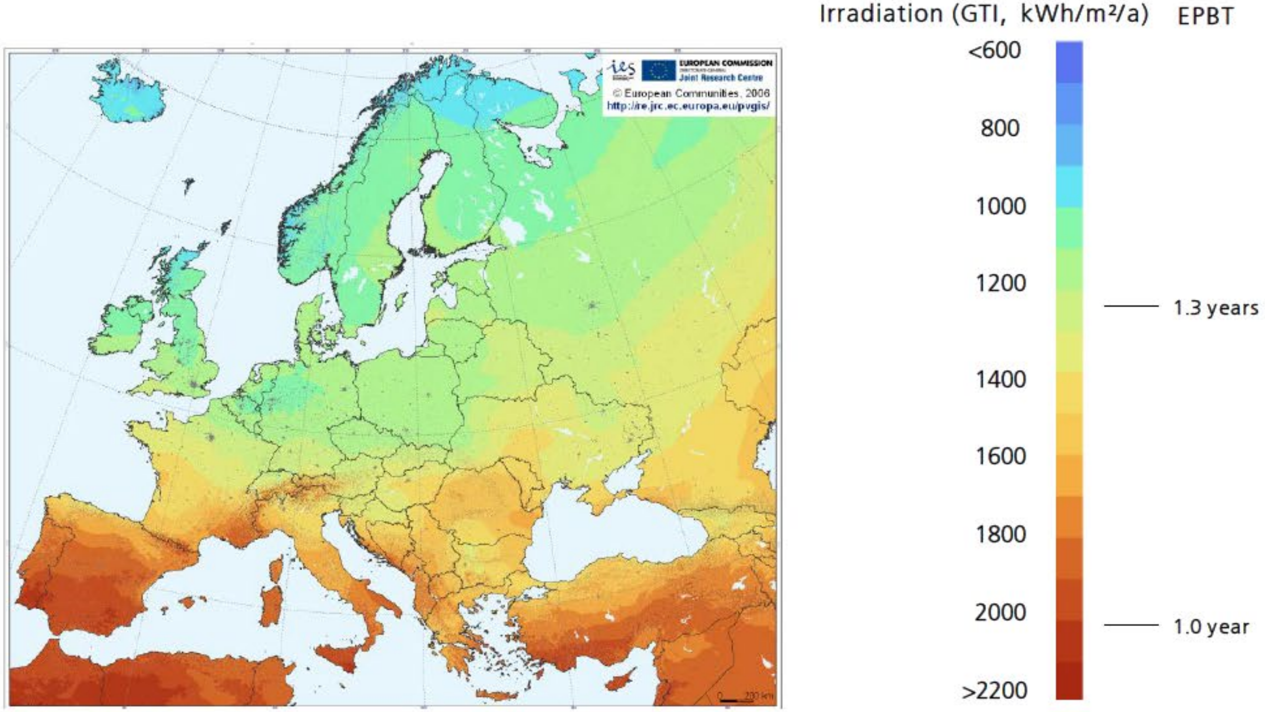
- PV tender price is **5 ct€ / kWh** (Germany in 2018-2020)

Source: Photovoltaics report, Fraunhofer Institute ISE, Feb 2022

Energy payback time (EPBT)

$$EPBT = \frac{E_{input}}{E_{output}/year}$$

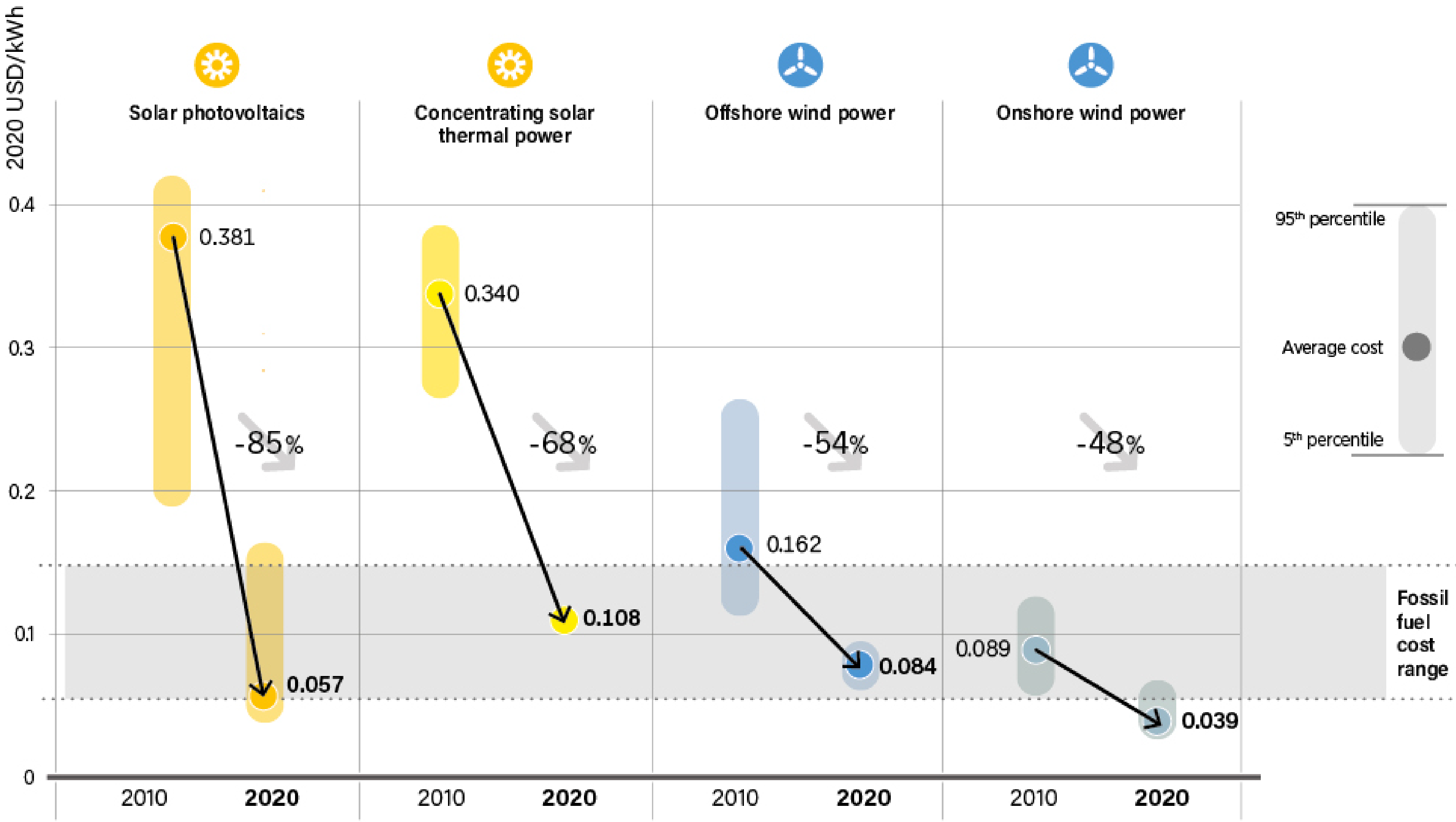
- Rooftop PV-system using mono-crystalline Silicon cells* produced in China
- EPBT is dependent on irradiation, but also on other factors like grid efficiency**.
- Better grid efficiency in Europe may decrease the EPBT by typically 9.5 % compared to PV modules produced in China.



Photovoltaics report, ISE Fraunhofer, Feb 2022

- 1-2 years to generate equivalent amount of energy that was used for manufacturing PV modules (depends on technology and location)

Global Levelised Costs of Electricity from Newly Commissioned Utility-scale Renewable Power Generation Technologies, 2010 and 2020



Source: IRENA.

http://www.ren21.net/status-of-renewables/global-status-report/