Thermodynamics of energy conversion

11) PHOTOVOLTAICS

11) Photovoltaics

11.1. PHOTOVOLTAIC HISTORY

Albert Einstein, *1879, Ulm – †1955 Princeton

Albert Einstein, "Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt", Annalen der Physik, Band 17, Seite 132-148.

Einstein Nobelprize for Physics 1921.

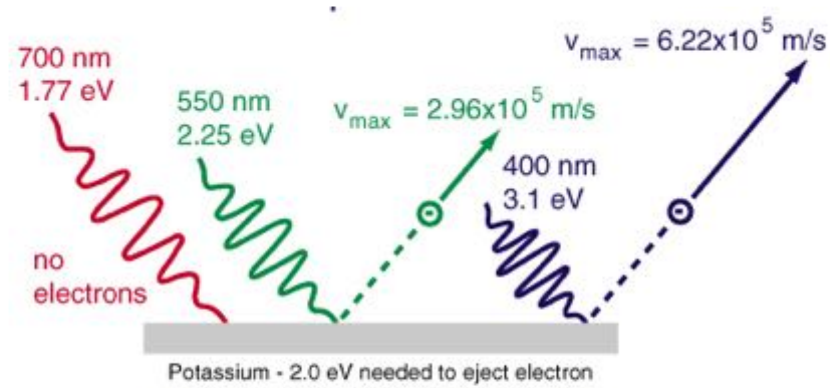
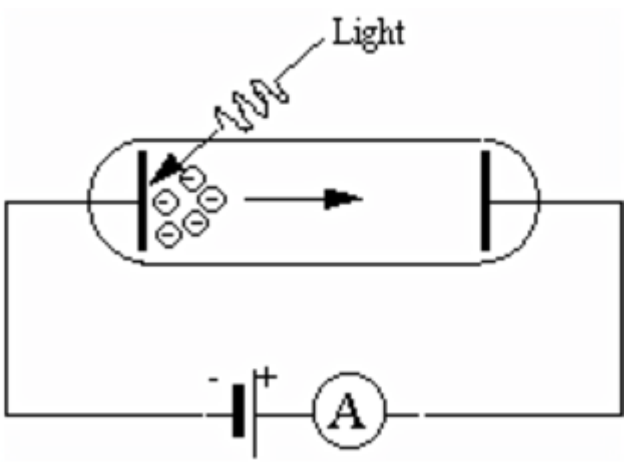
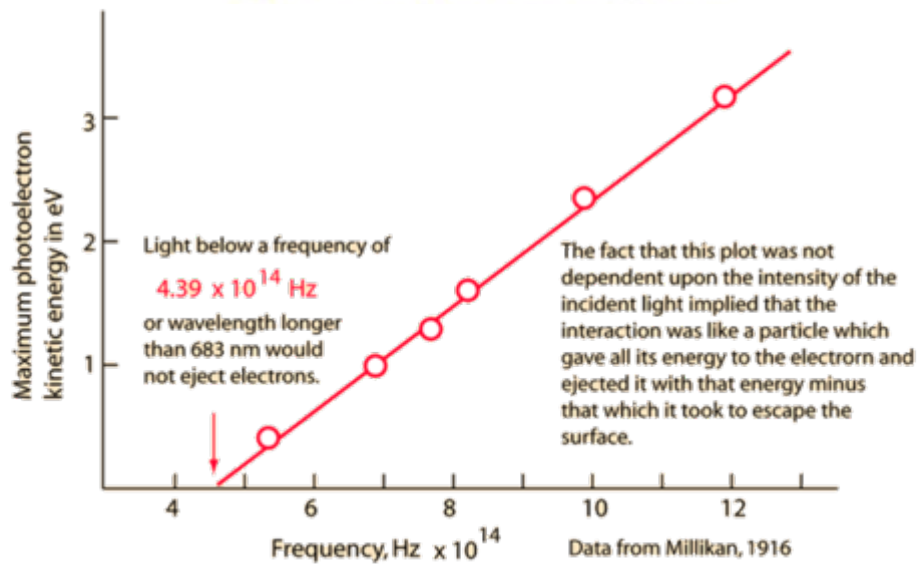


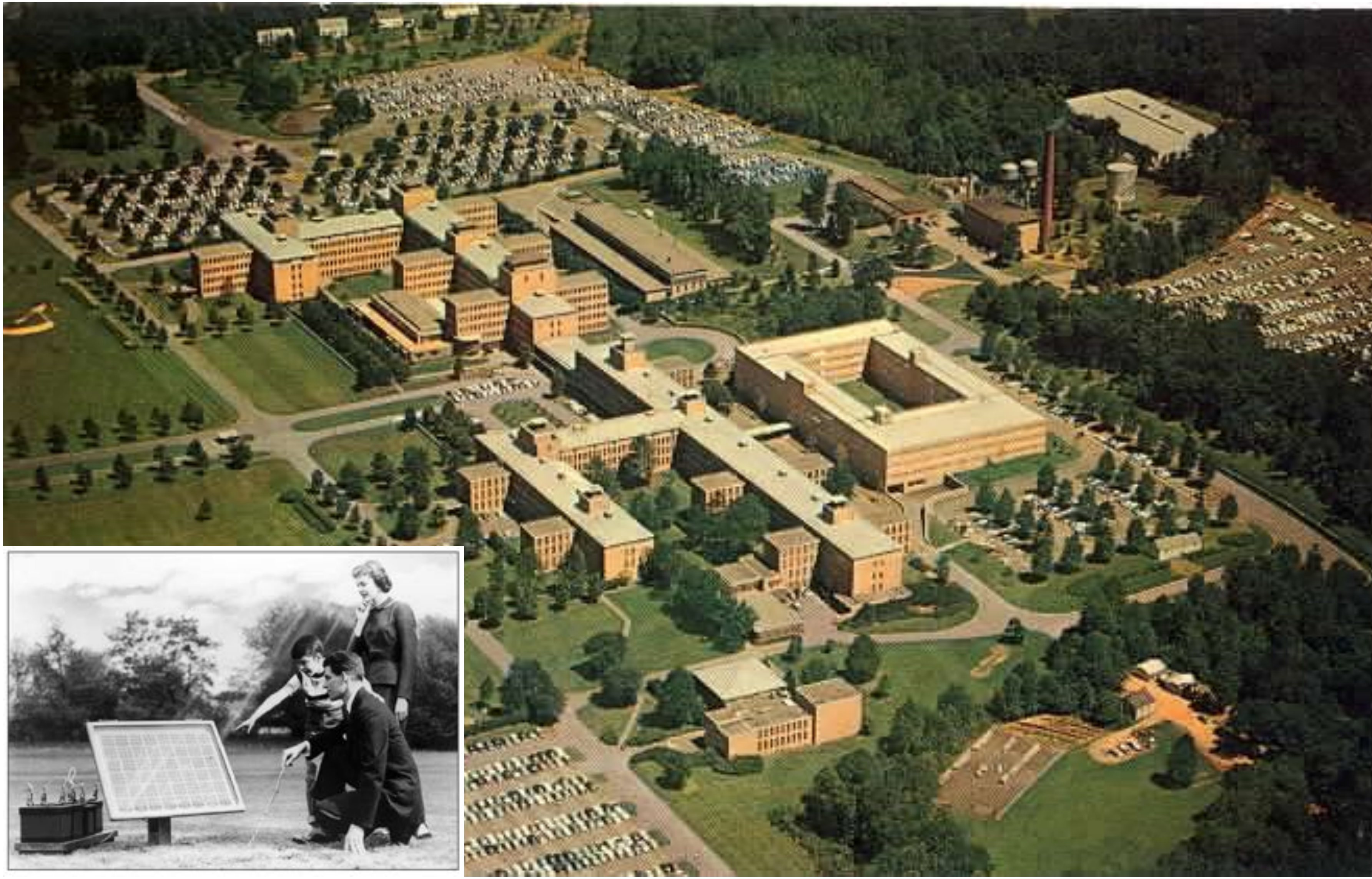
PHOTO EFFECT

$$h \cdot \nu = E_{kin.} + B$$



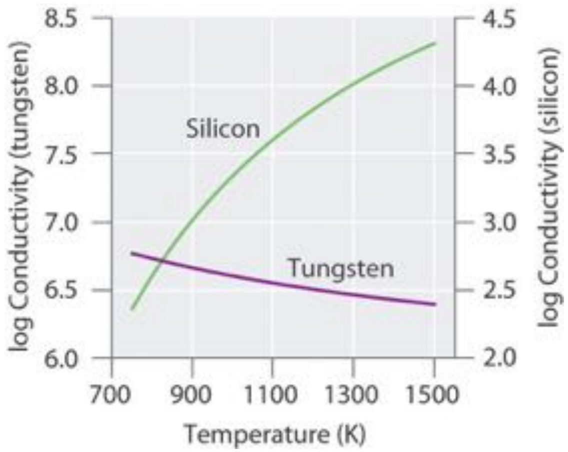


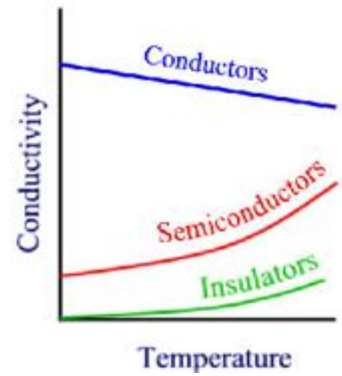
11.1.1. FIRST PHOTOVOLTAIC PANEL

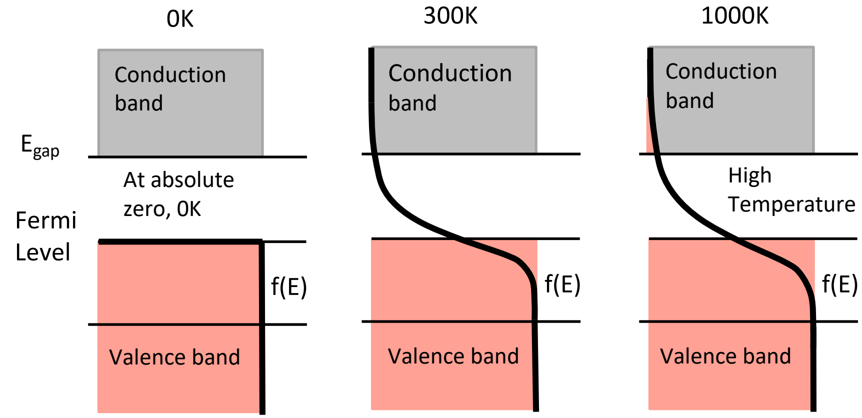


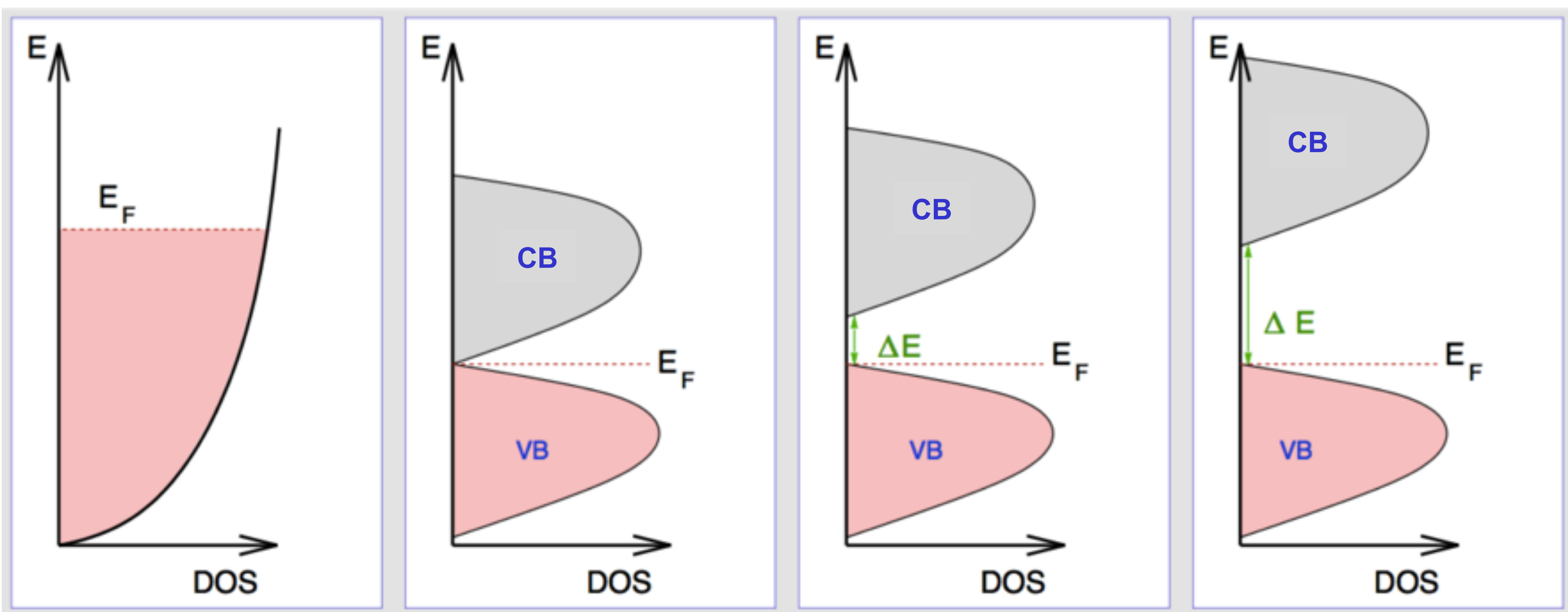
AT&T Bell Laboratories, Murray Hill, NJ, USA, advertisement for first commercial photovoltaic cells (Look magazine, 1956)

11.2. ELECTRONS IN SOLIDS



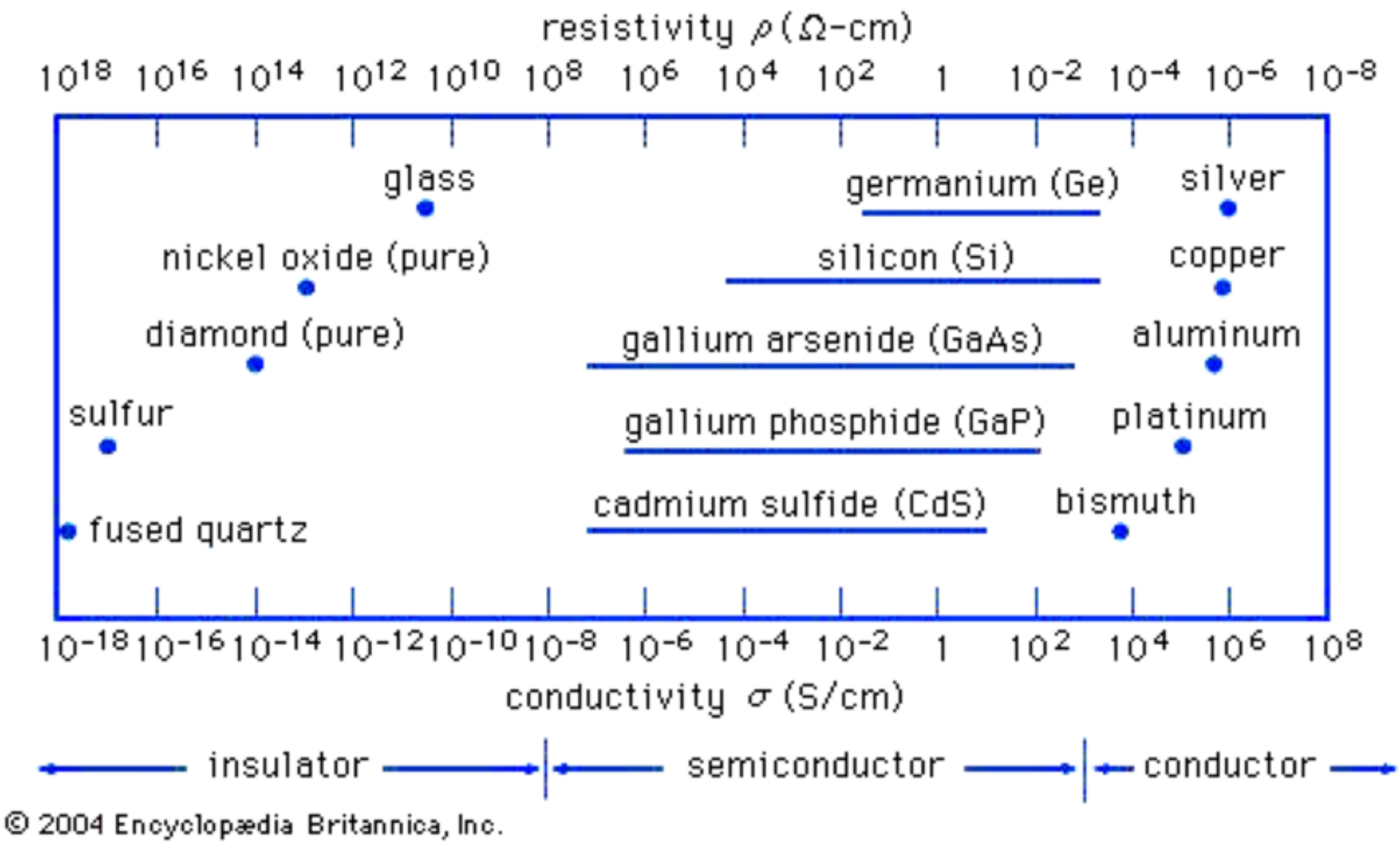




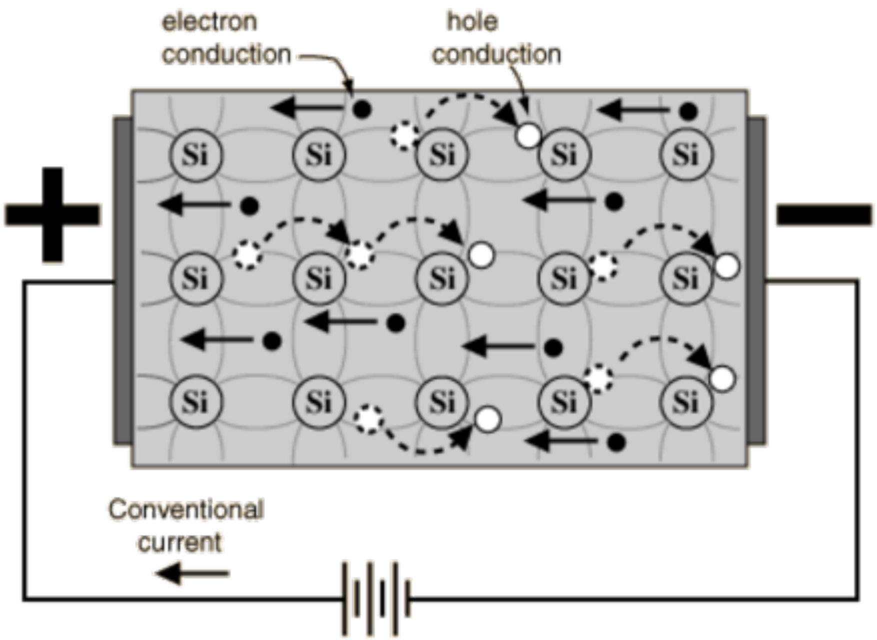


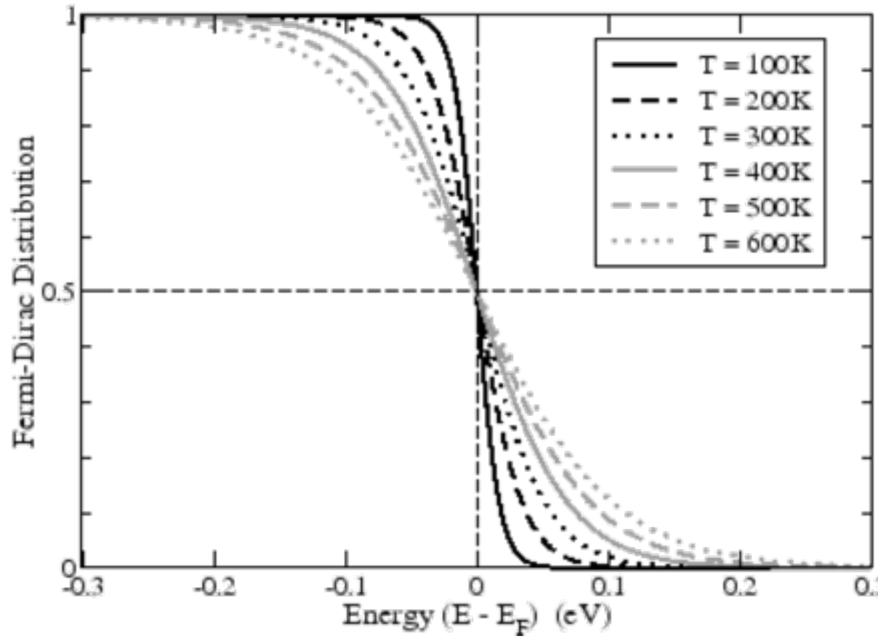
Metal | Half metal | Semiconductor | Insulator

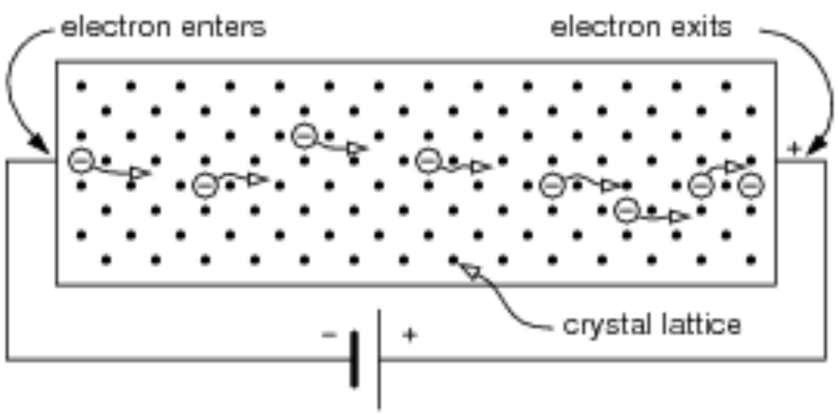
11.2.1. CONDUCTIVITY



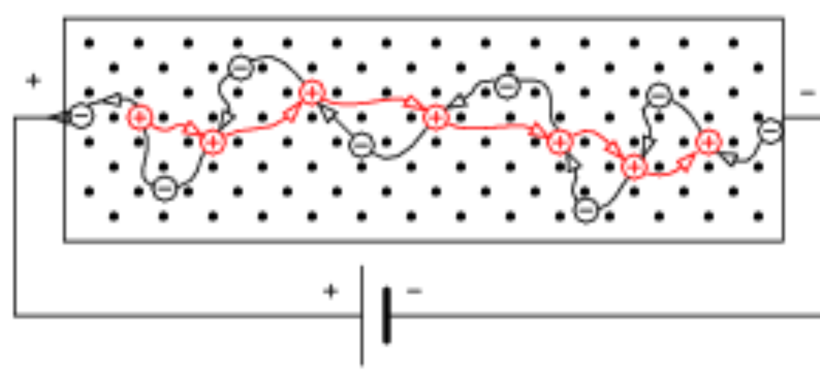
11.2.2. SEMICONDUCTOR







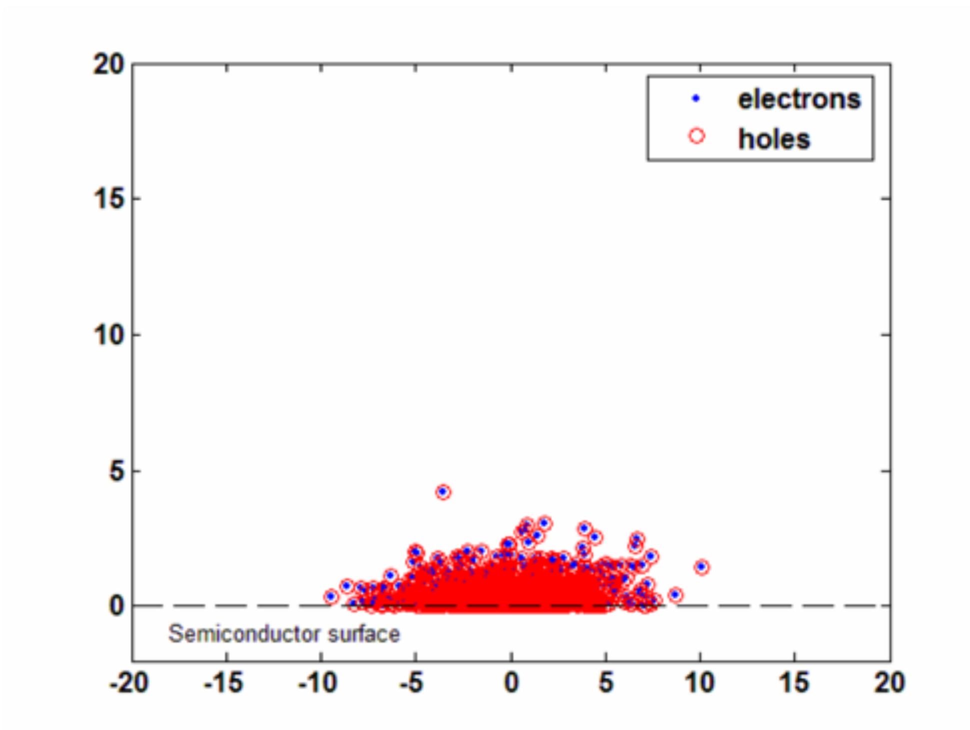
(a) N-type

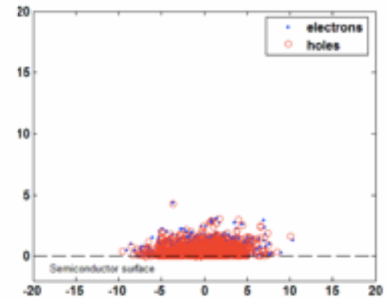


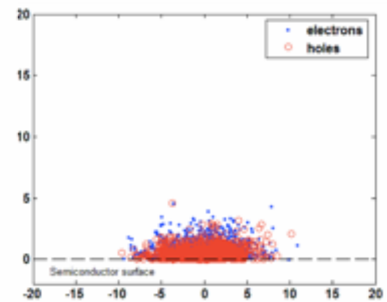
(b) P-type

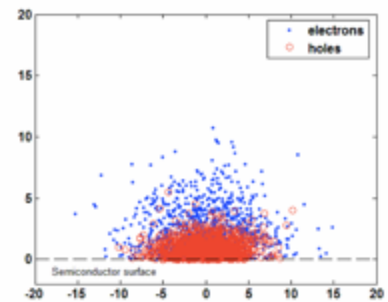
11.2.3. DEMBER EFFECT

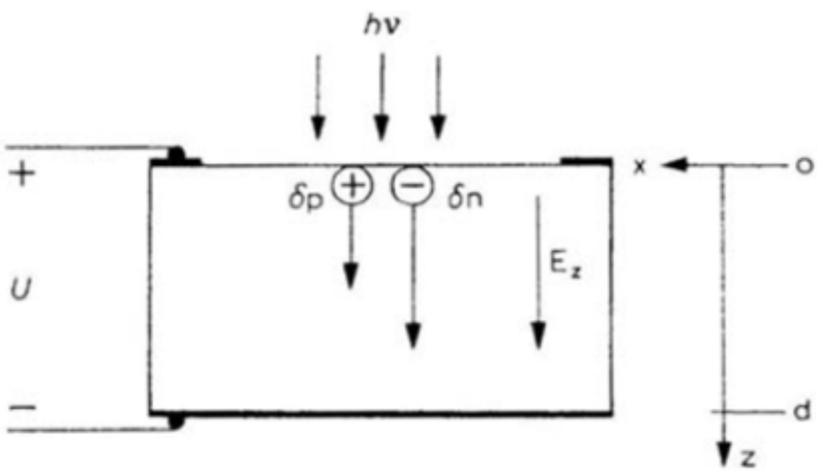
Harry Dember (* 11. Juli 1882 in Leimbach; † 22. März 1943 in New Brunswick, New Jersey

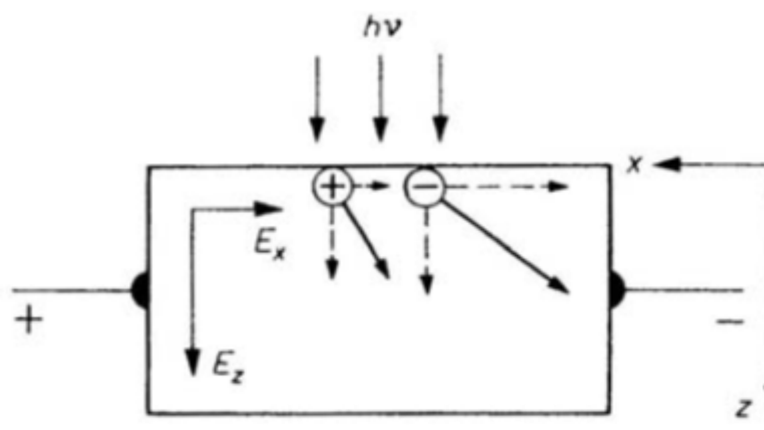




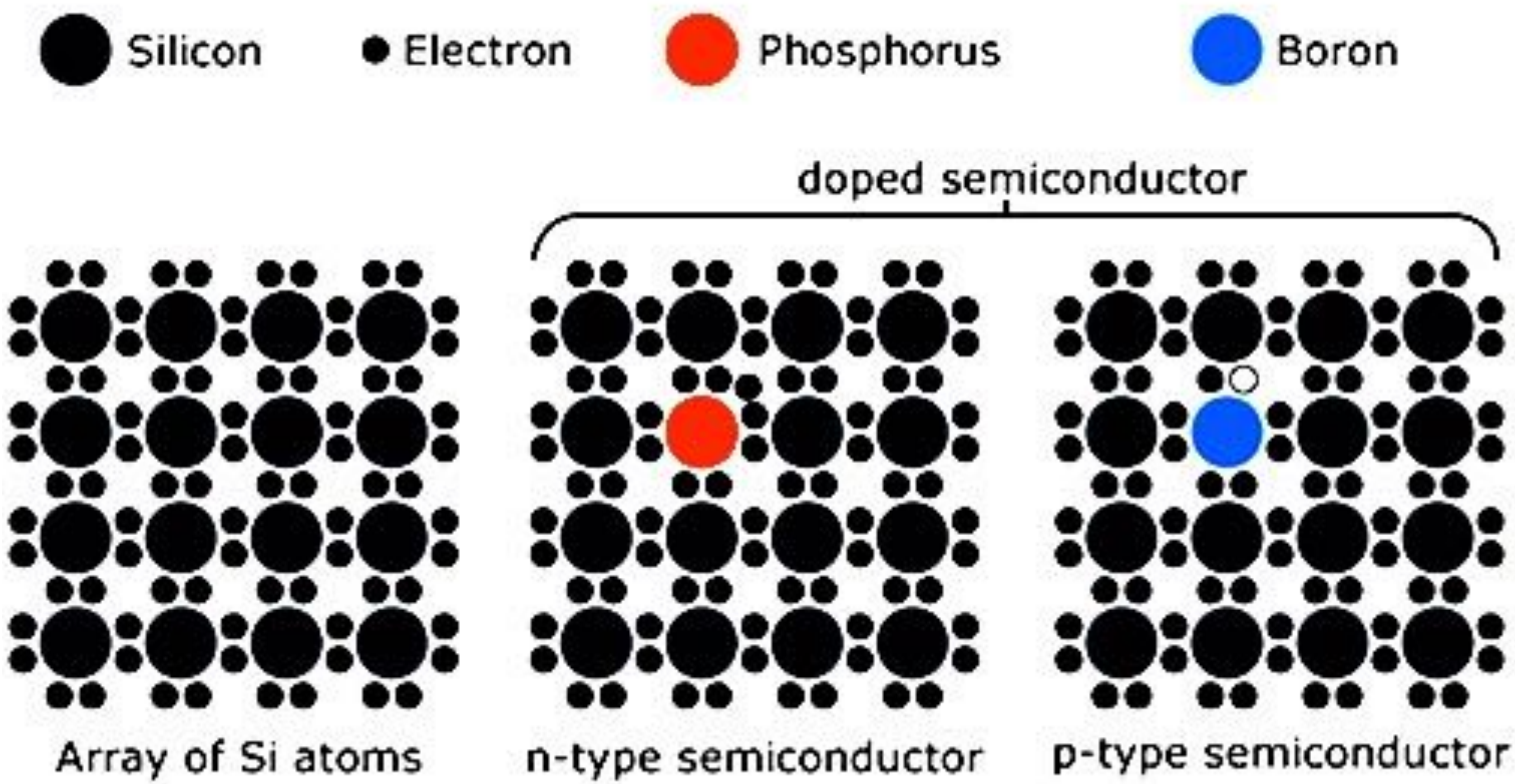




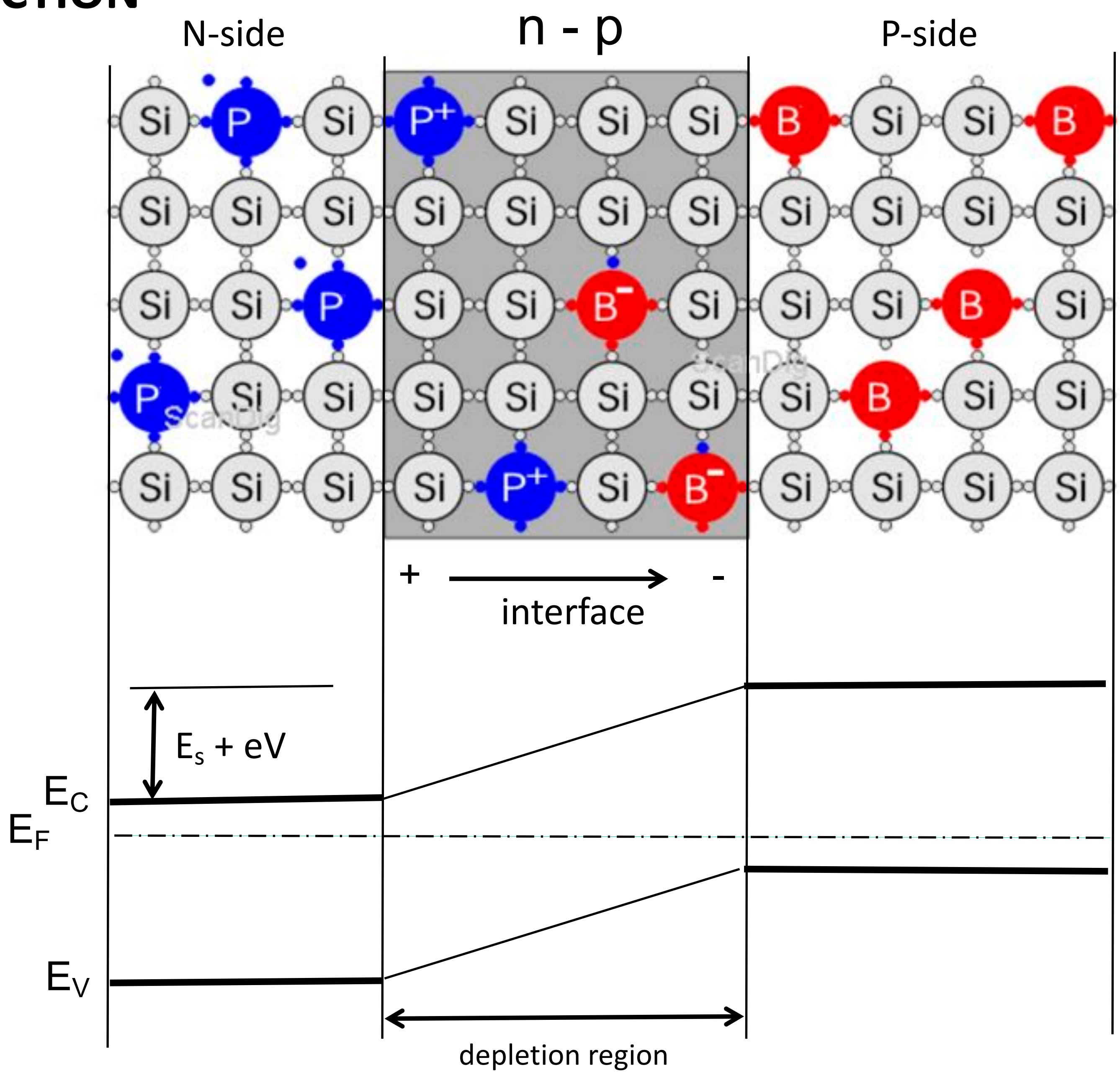




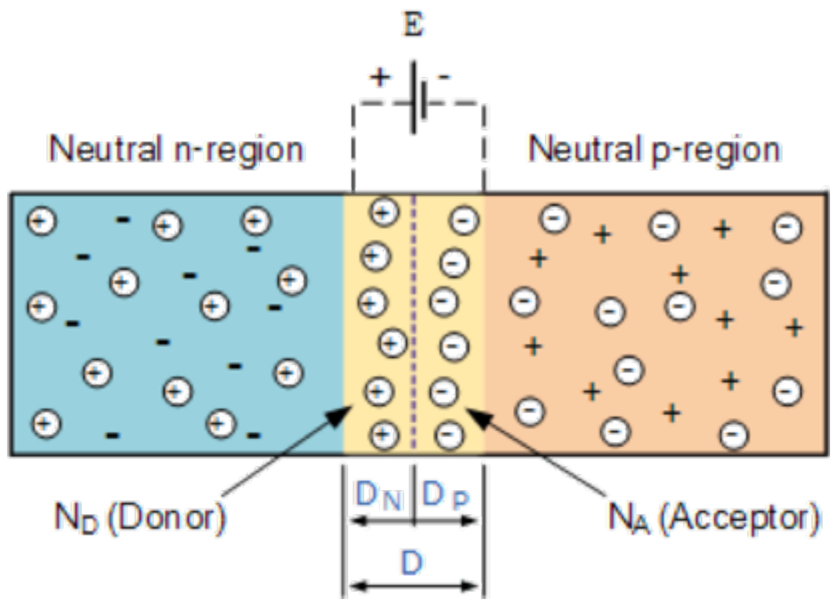
11.2.4. DOPING OF SEMICONDUCTORS

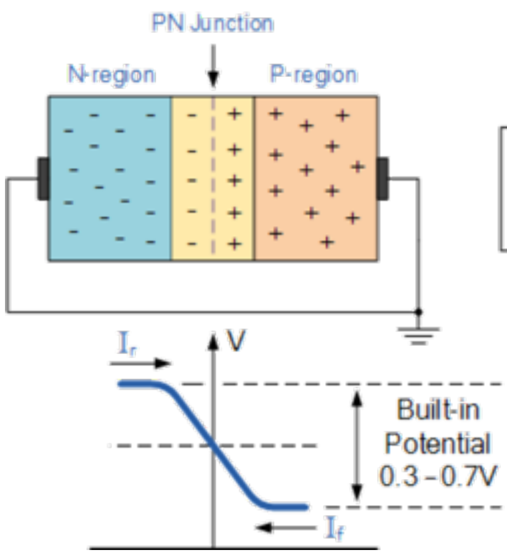


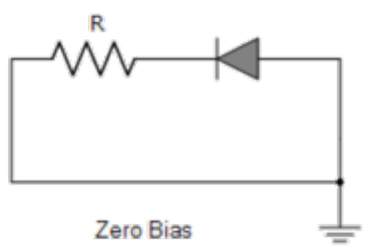
11.2.5. np-JUNCTION

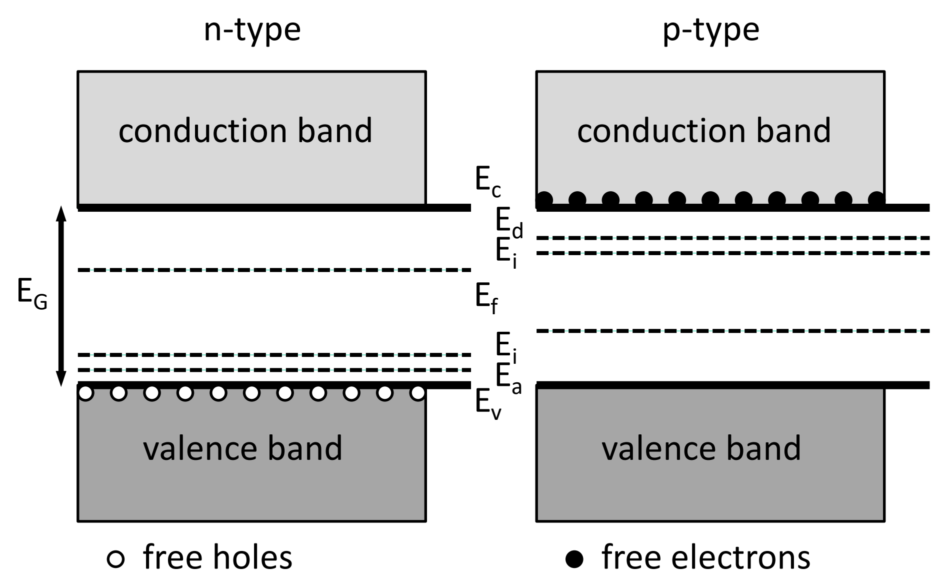


11.2.6. ELECTRON DISPLACEMENT AT np-JUNCTION

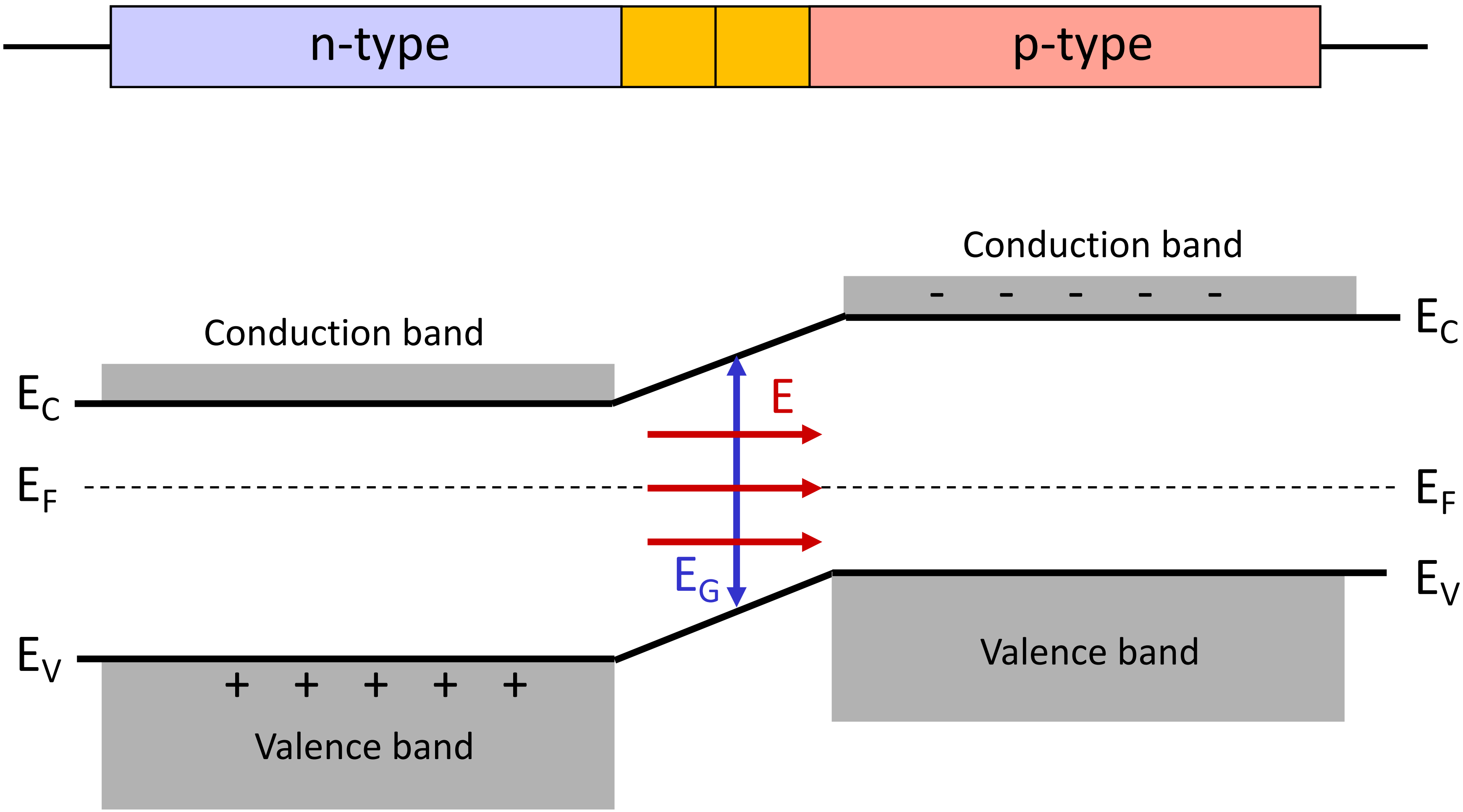




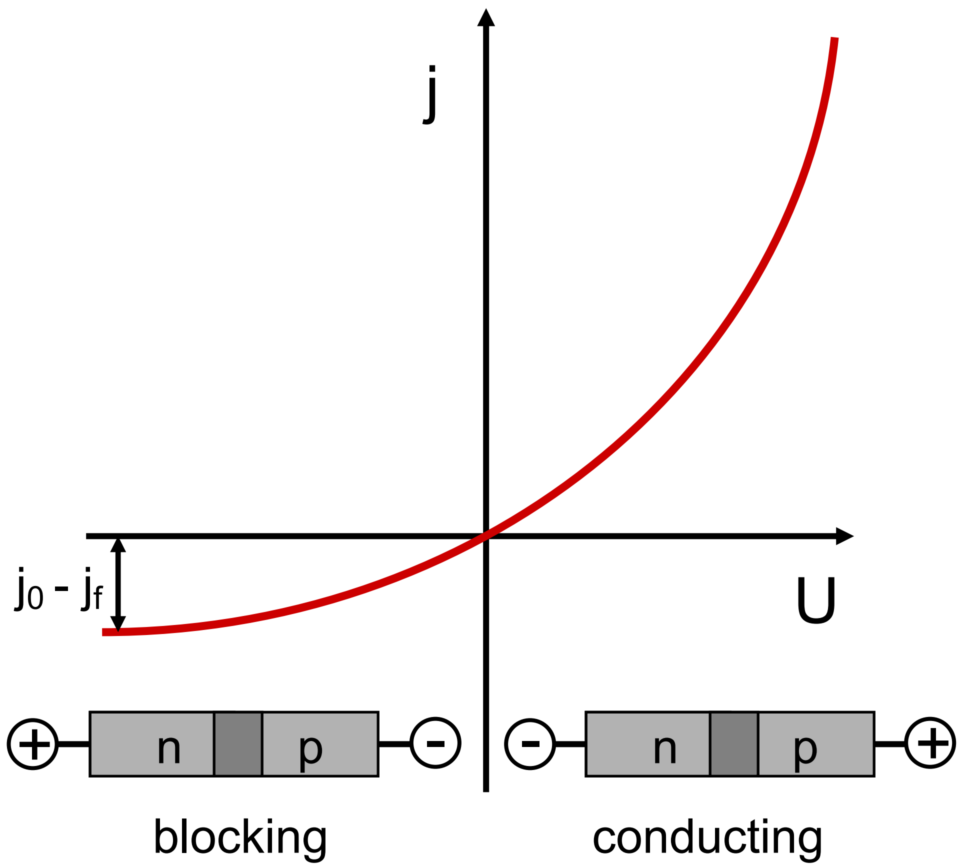




11.2.7. EQUILIBRATION OF THE FERMI ENERGY AT np-JUNCTION

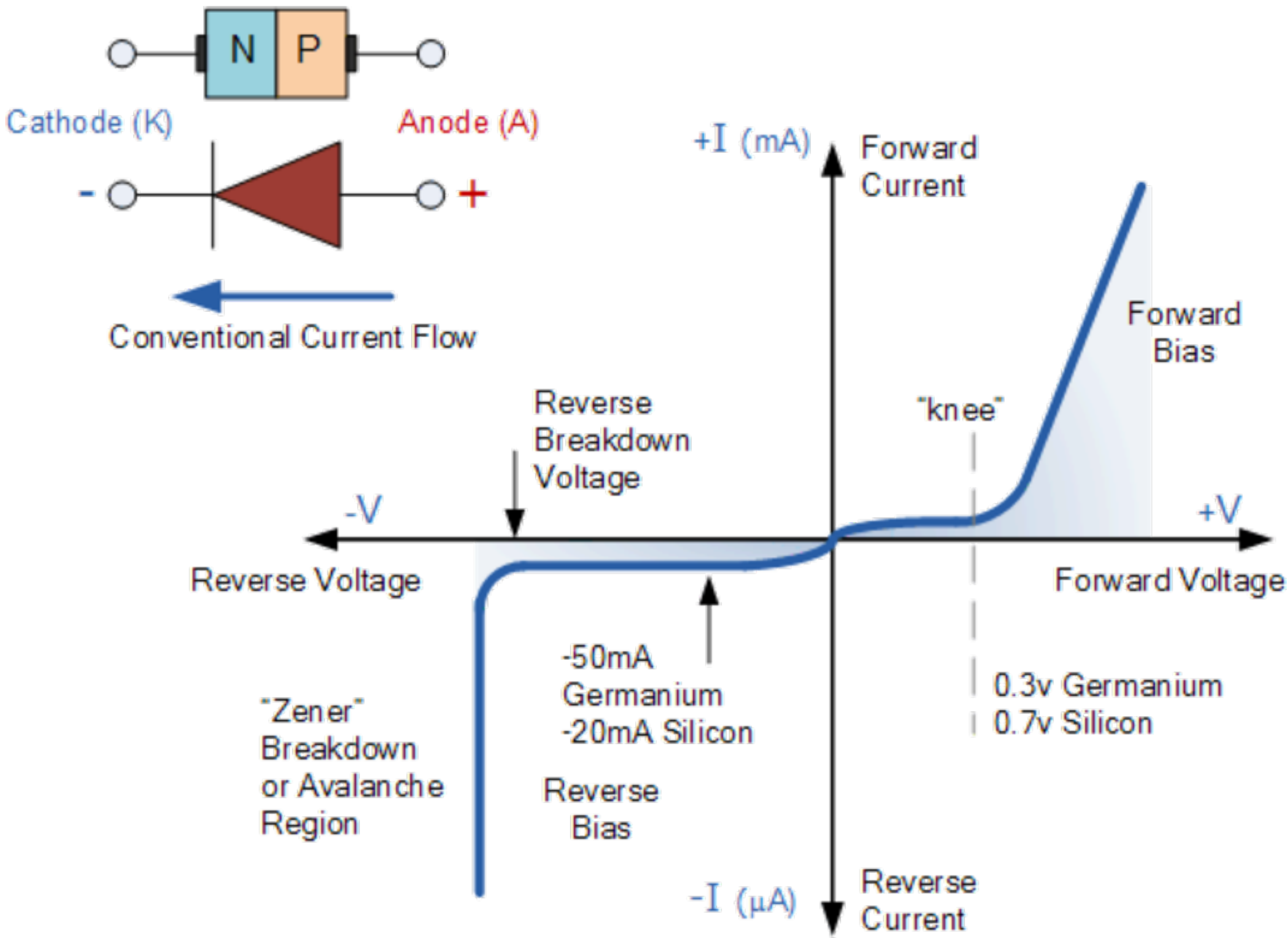


11.2.8. CURRENT-VOLTAGE CURVE ACROSS np-JUNCTION

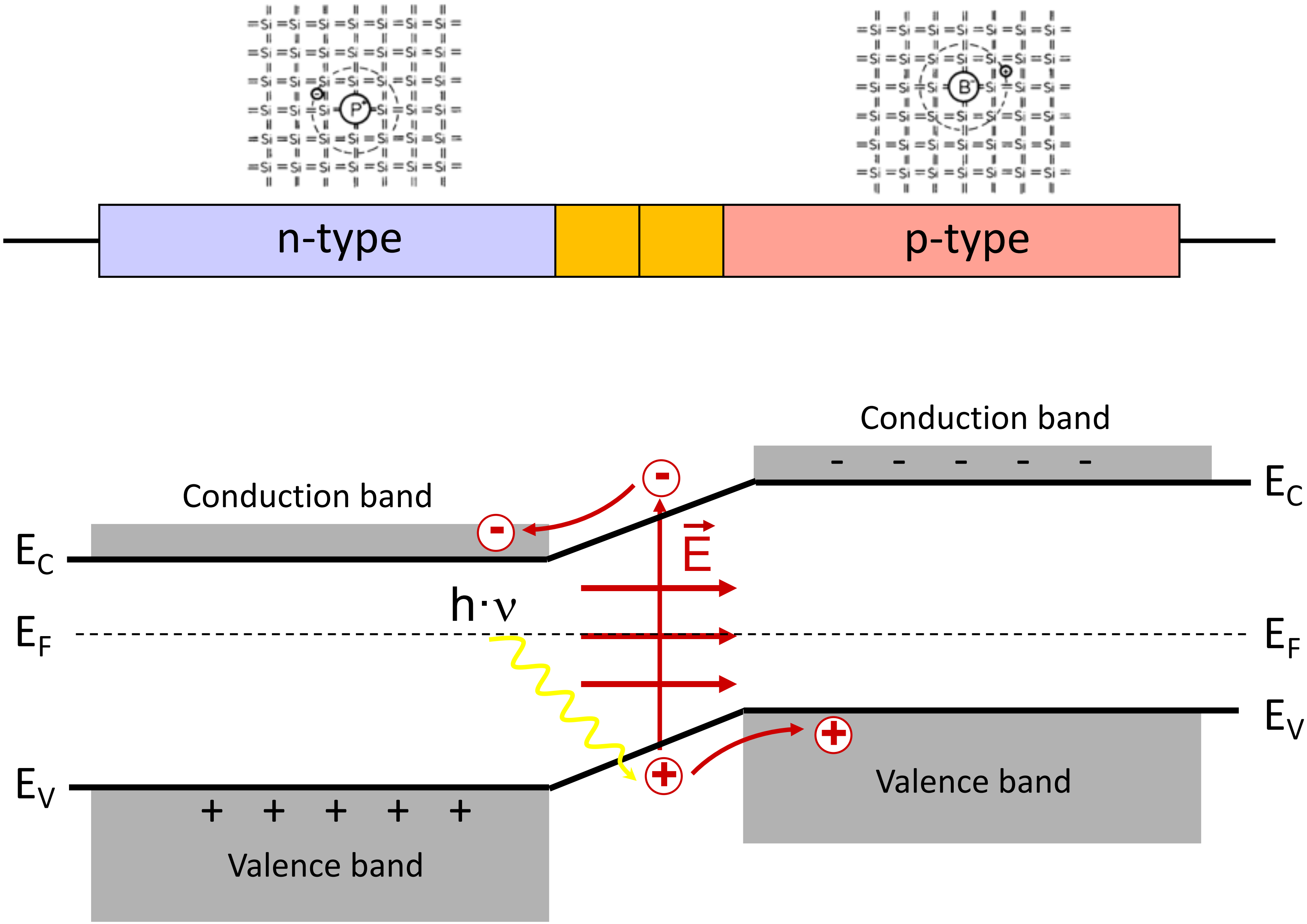


$$j = j_0 \cdot \left\{ e^{\frac{e \cdot U}{k \cdot T}} - 1 \right\} - j_f$$

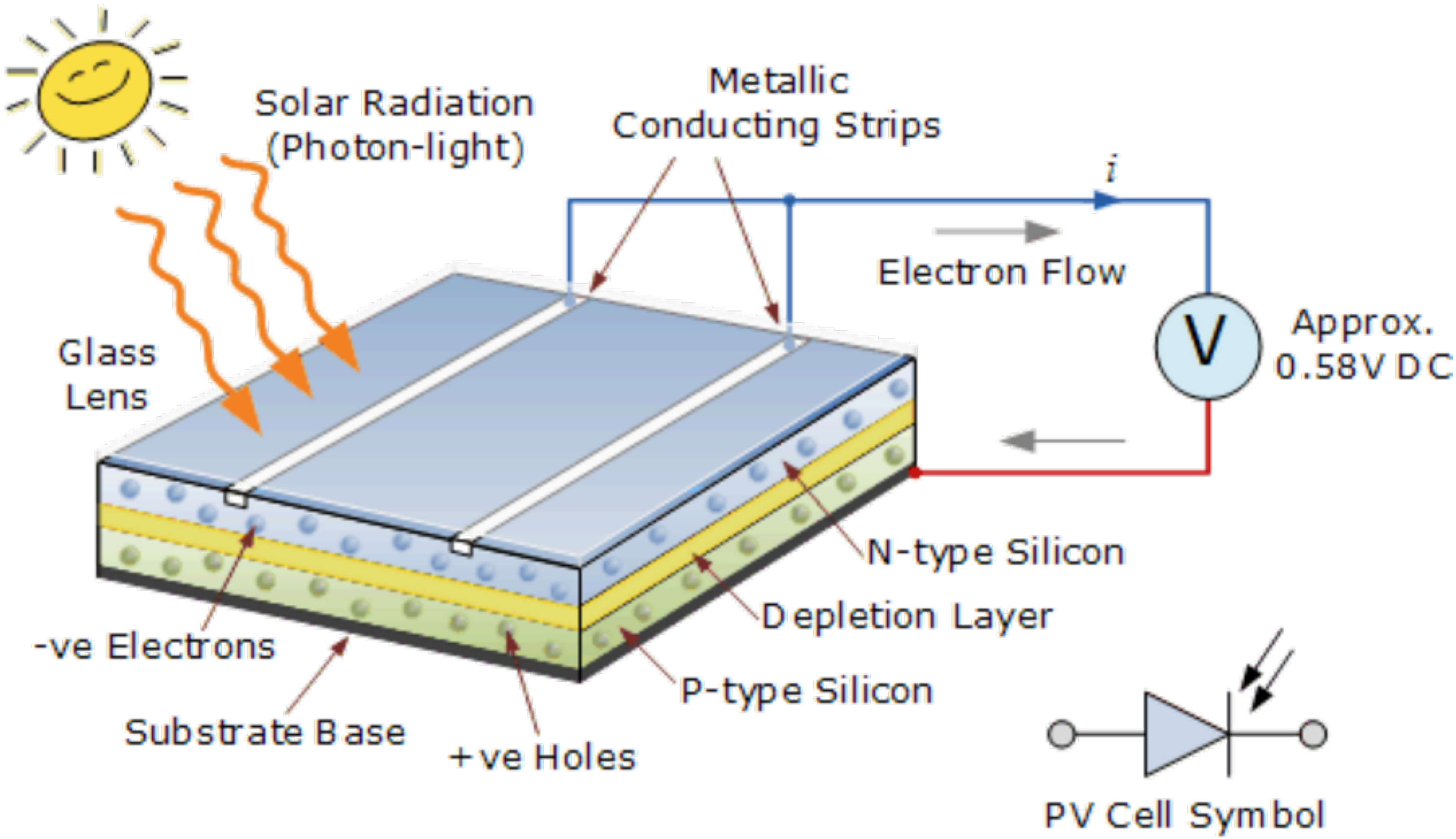
11.2.9. np-JUNCTION DIODE



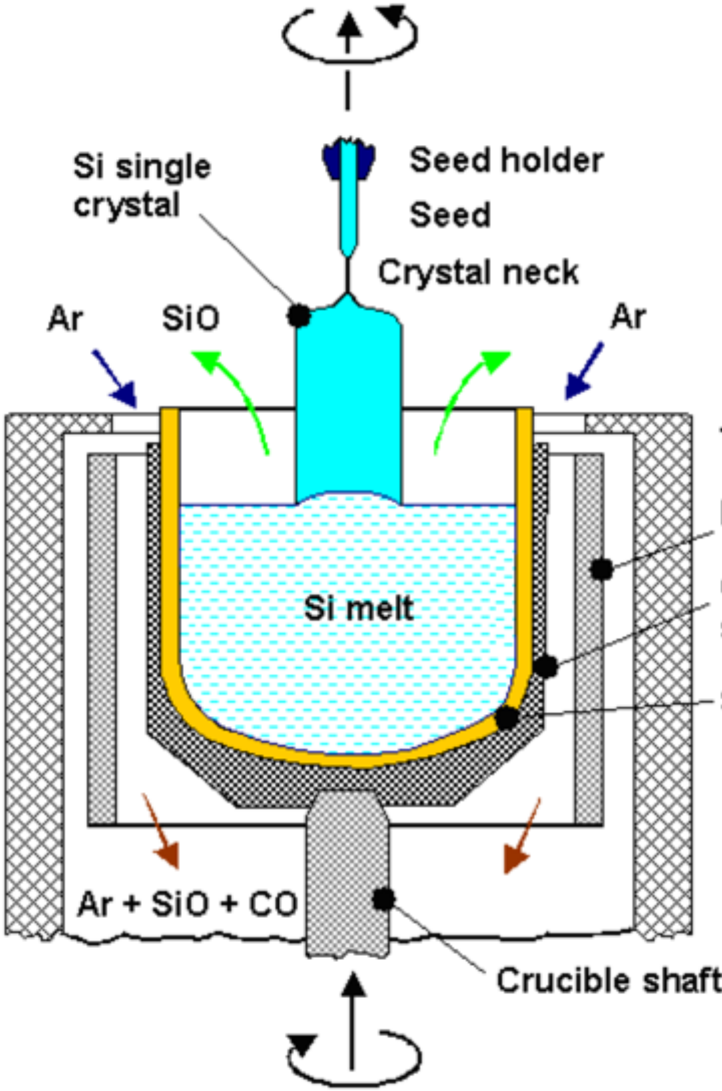
11.2.10. EXITATION np-INTERFACE



11.3. CONSTRUCTION OF A PHOTOVOLTAIC CELL



11.3.1. SILICON SINGLE CRYSTAL



$SiO_2 + C \rightarrow Si + CO_2$

$SiO_2 + 3HCl \rightleftarrows Si + HSiCl_3$

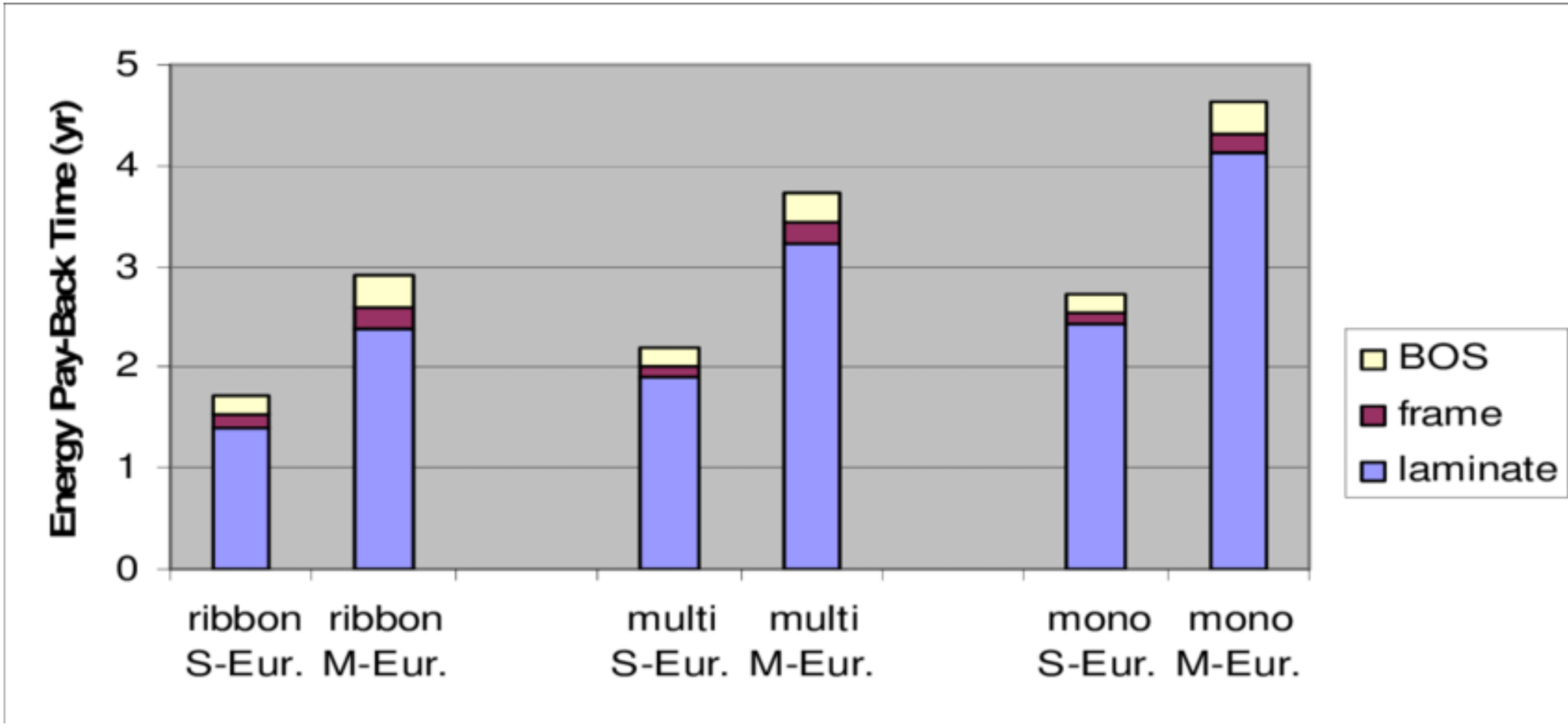
$T_m(Si) = 1410°C$

$\Delta H_m(Si) = 50.66$ kJ/mol

$T_m = 1414$ °C

$\Delta H_m = 0.5$ kWh/kg

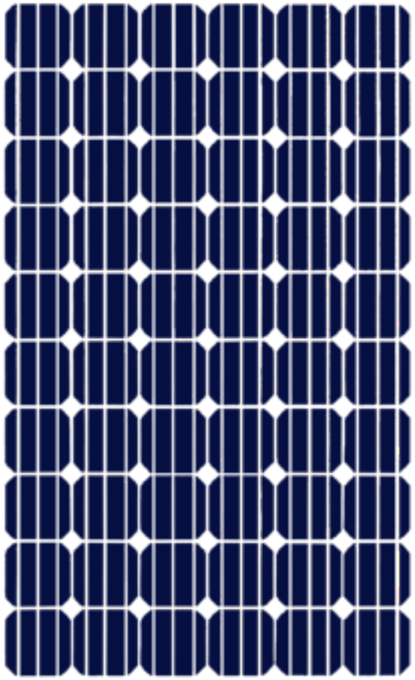
11.3.2. SILICON PAY-BACK-TIME



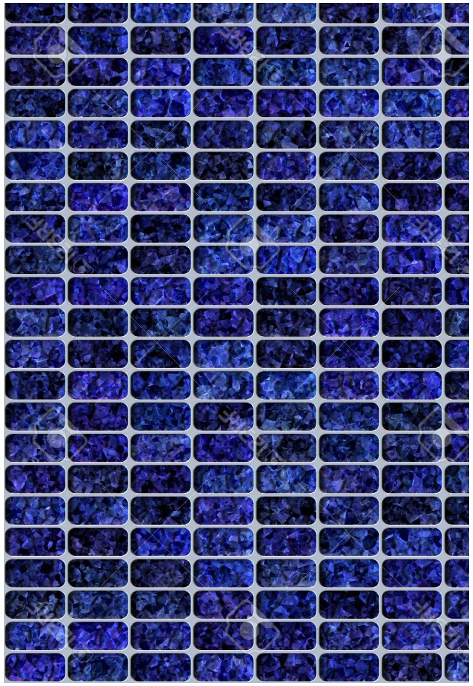
Energy Pay-Back Times of 1.7 - 2.7 y are found for South-European locations irradiation (1700 kWh·m^{-2}·a^{-1}), while life-cycle CO_2 emission is in the 30-46 g/kWh range. Clear perspectives exist for further improvements with roughly 40-50%.

Erik Alsema and Mariska J de Wild, "Environmental Impact of Crystalline Silicon Photovoltaic Module Production"MRS Online Proceedings Library (OPL), Volume 895 (Symposium G – Life-Cycle Analysis Tools for “Green” Materials and Process Selection) 2005 , 0895-G03-05 https://doi.org/10.1557/PROC-0895-G03-05Published online: 26 February 2011

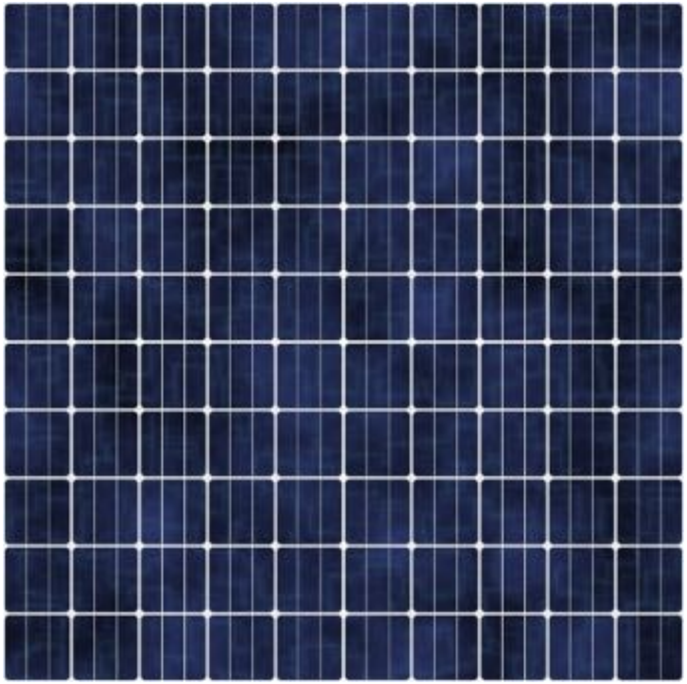
11.3.3. Si PHOTOVOLTAIC CELLS



crystalline



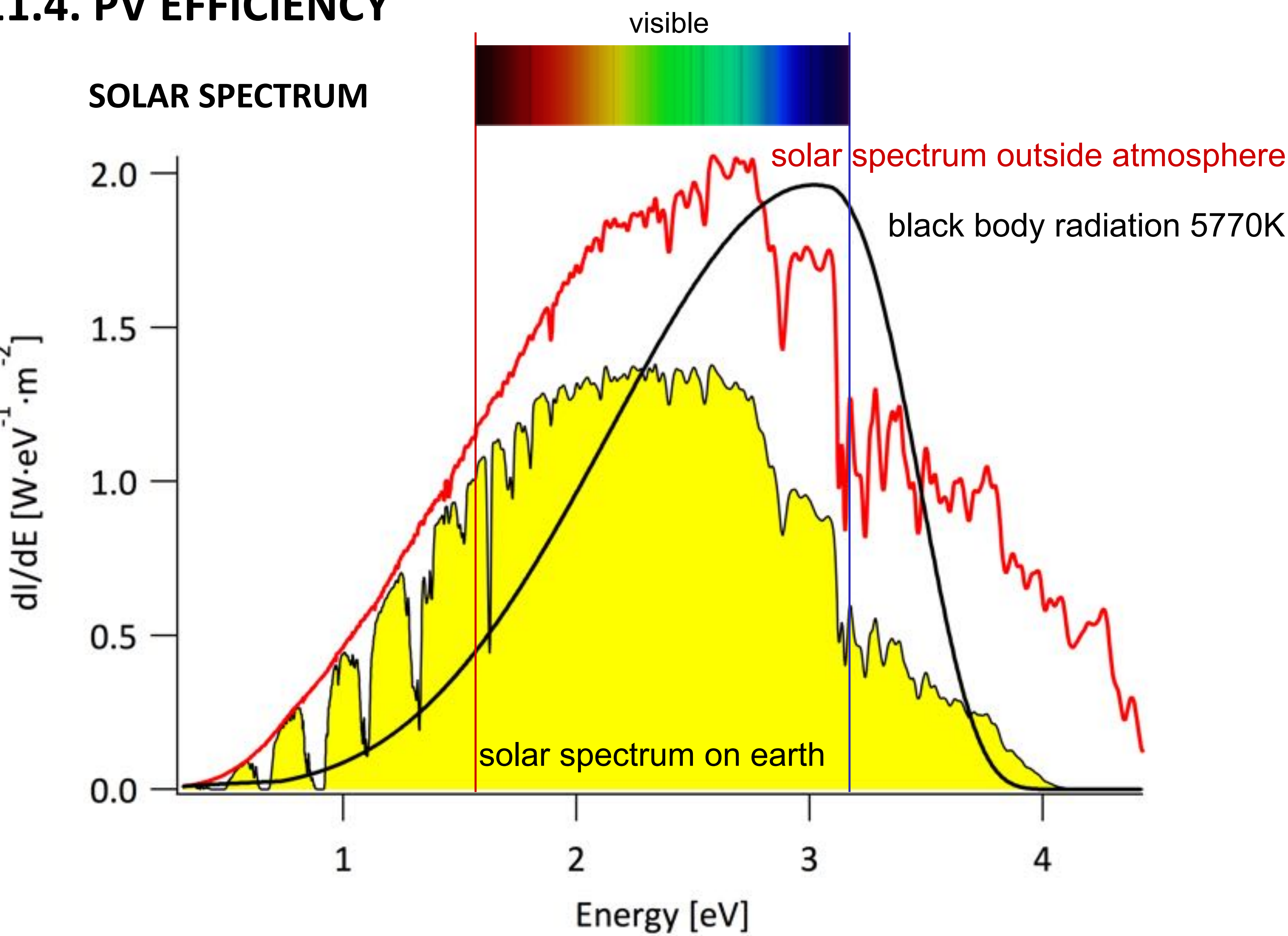
polycrystalline



amorphous

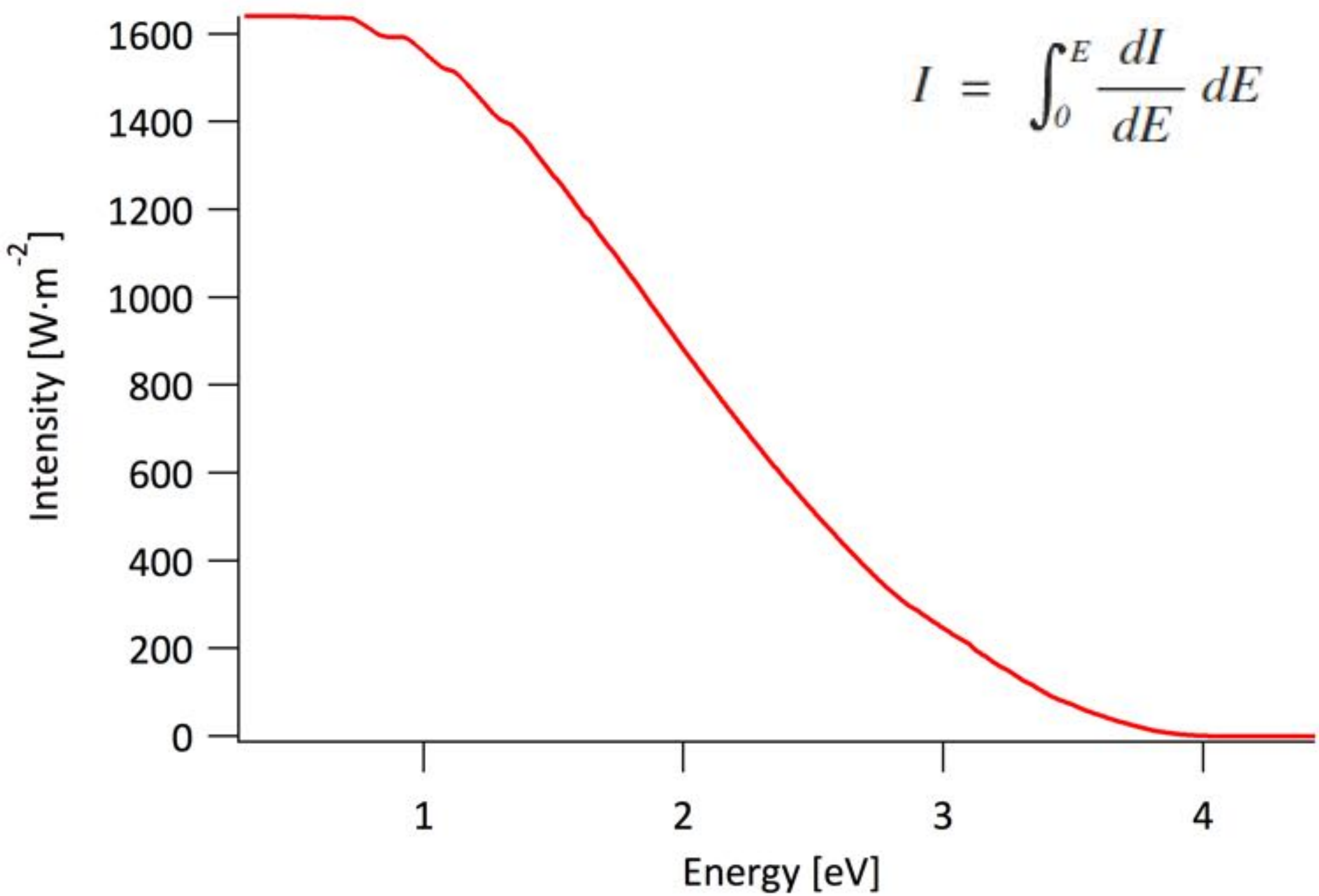
11.4. PV EFFICIENCY

SOLAR SPECTRUM



Ref.: C. H. Henry, "Limiting efficiencies of ideal single and multiple energy gap terrestrial solar cells", Journal of Applied Physics 51, 4494 (1980); doi: 10.1063/1.328272

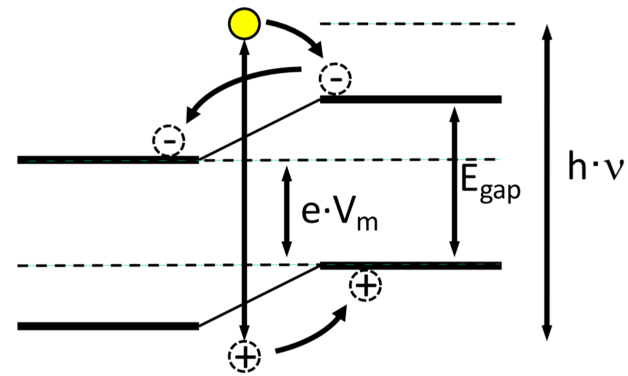
11.4.1. INTEGRATED ENERGY

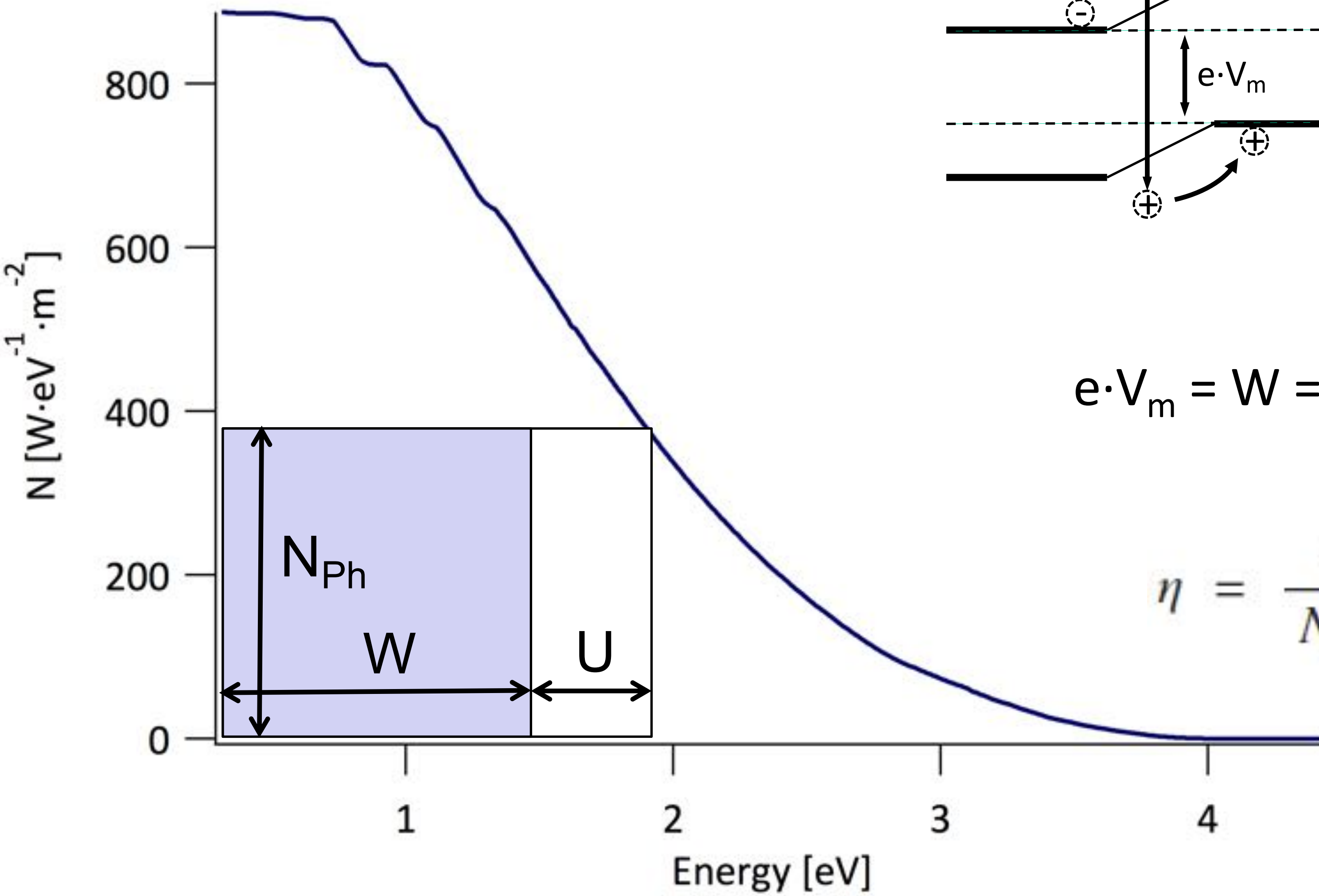


Ref.: C. H. Henry, "Limiting efficiencies of ideal single and multiple energy gap terrestrial solar cells", Journal of Applied Physics 51, 4494 (1980); doi: 10.1063/1.328272

11.4.2. NUMBER OF PHOTONS

$$N_{Ph} = \int_0^N \frac{dI}{dE}$$





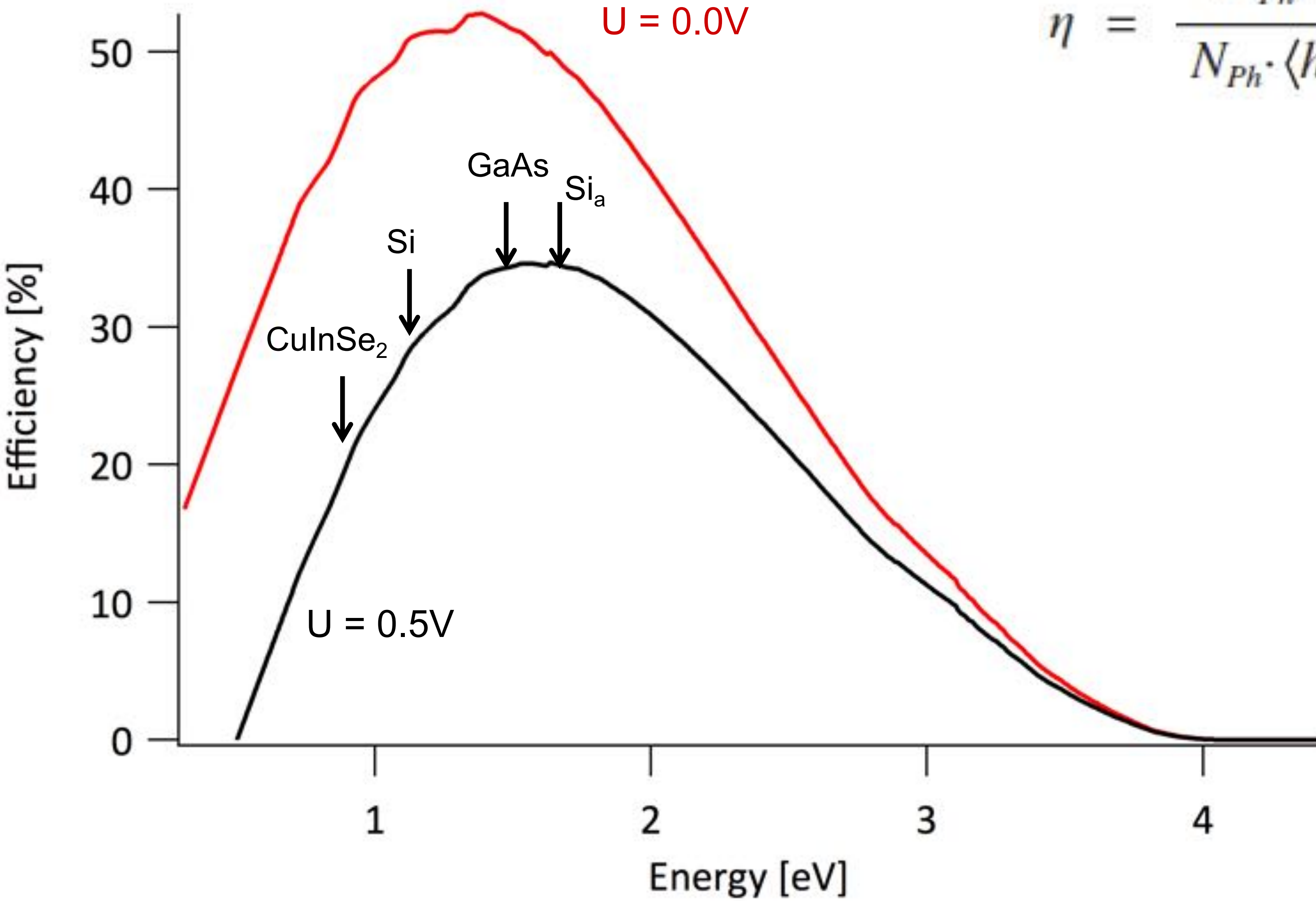
$$e \cdot V_m = W = E_{gap} - U$$

$$\eta = \frac{N_{Ph} \cdot W}{N_{Ph} \cdot \langle h \cdot \nu \rangle}$$

Ref.: C. H. Henry, “Limiting efficiencies of ideal single and multiple energy gap terrestrial solar cells”, Journal of Applied Physics 51, 4494 (1980); doi: 10.1063/1.328272

11.4.3. EFFICIENCY IDEAL SINGLE GAP

$$\eta = \frac{N_{Ph} \cdot W}{N_{Ph} \cdot \langle h \cdot \nu \rangle}$$

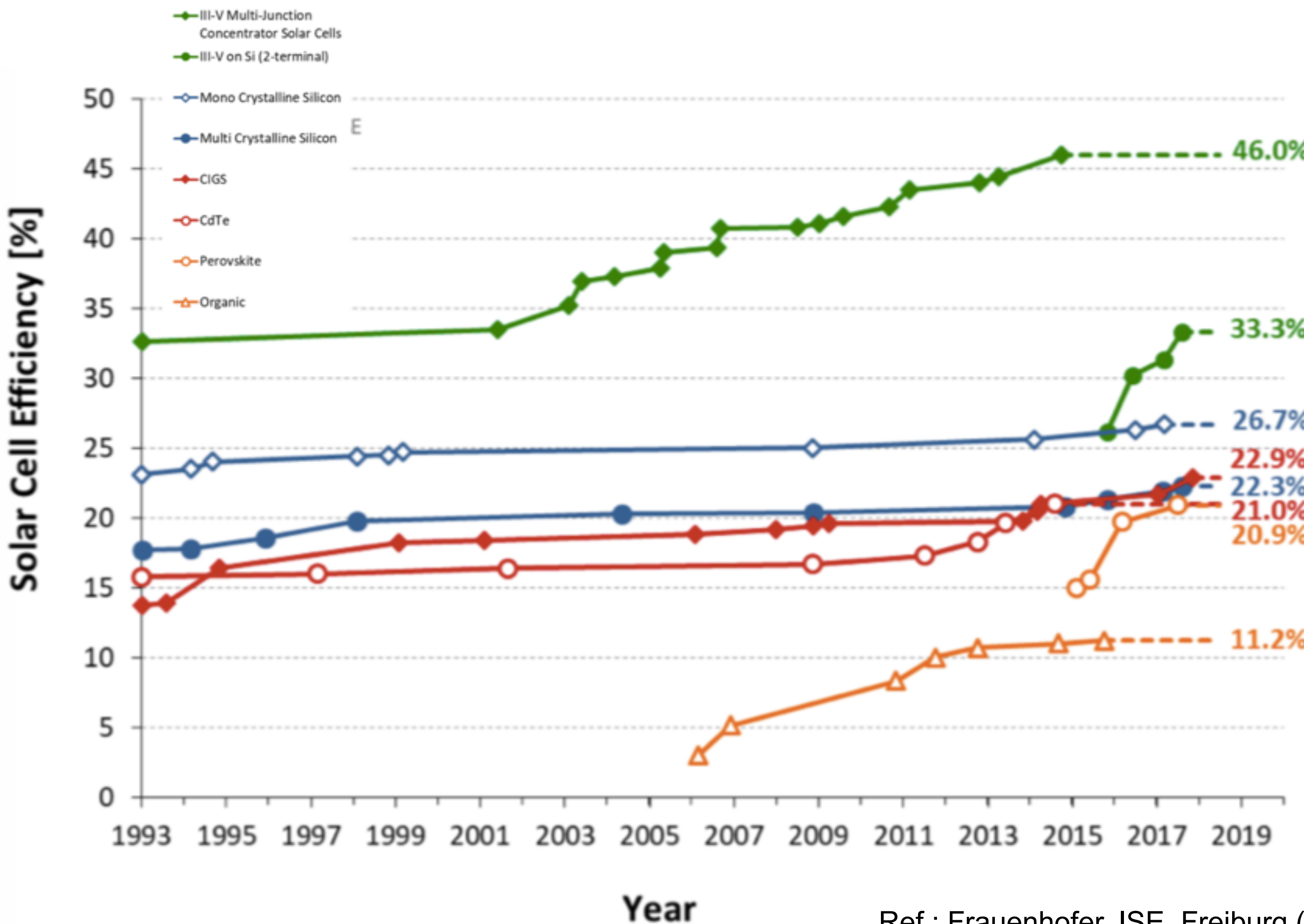


Ref.: C. H. Henry, “Limiting efficiencies of ideal single and multiple energy gap terrestrial solar cells”, Journal of Applied Physics 51, 4494 (1980); doi: 10.1063/1.328272

11.4.4. EFFICIENCY OF VARIOUS PHOTOVOLTAIK CELLS

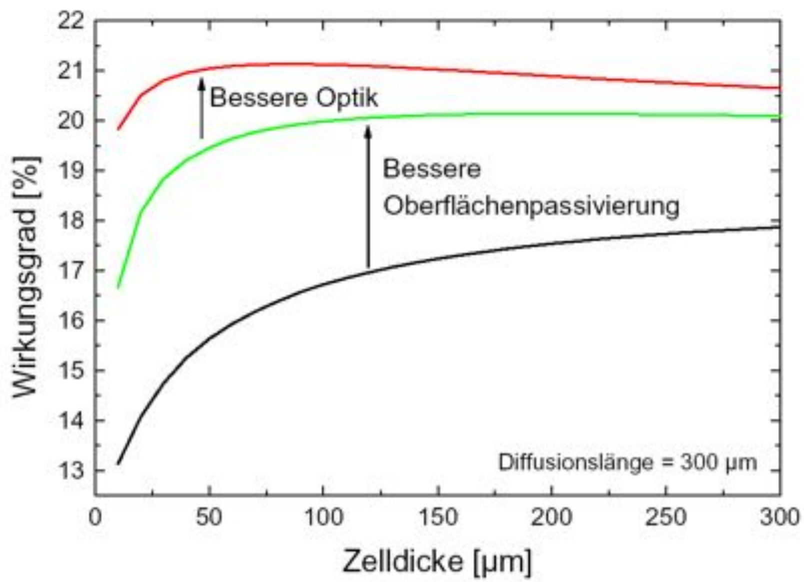
Material	**Type**	**Efficiency [%]**
Silicon	surface structure	24
GaAs	mono-crystalline cells	25
CdTe	thin film cell	16
CuIn-Se_2	thin film cell	17
Si/GaAs	Tandem cell	31
GaAs/GaSb	Tandem cell concentrated	33
Silicon	concentrated	27
Silicon	metal-insulator-cell	18
TiO_2/dye	Grätzel-cell	10

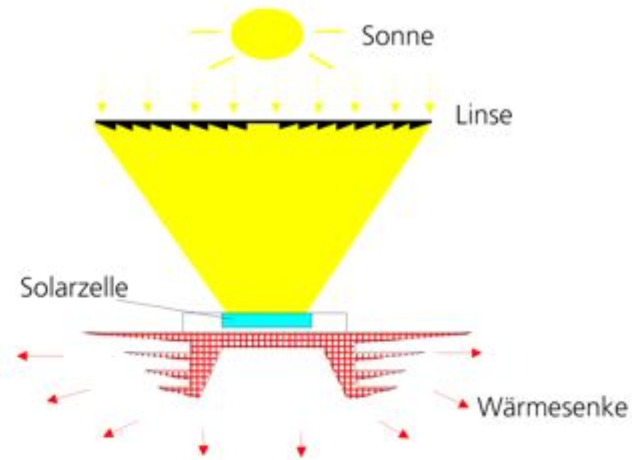
11.4.5. DEVELOPMENT OF PHOTOVOLTAIC CELLS



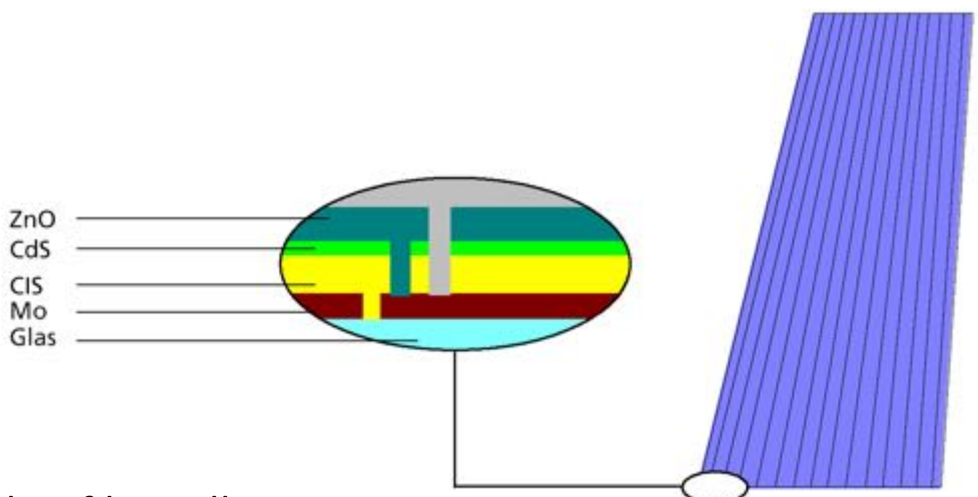
Ref.: Frauenhofer, ISE, Freiburg (D)

11.5. IMPROVEMENTS OF PV

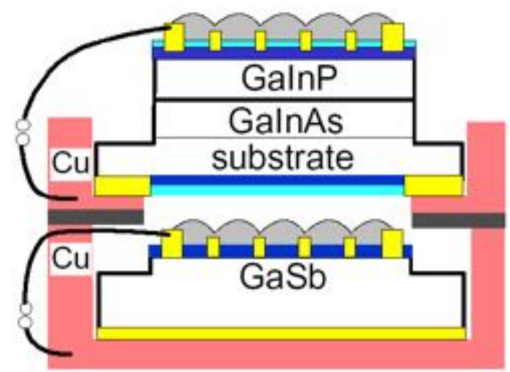




Concentrator cell



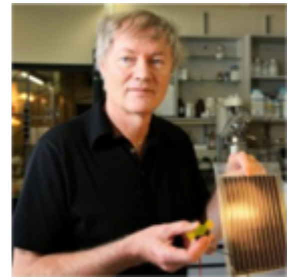
Thin film cells



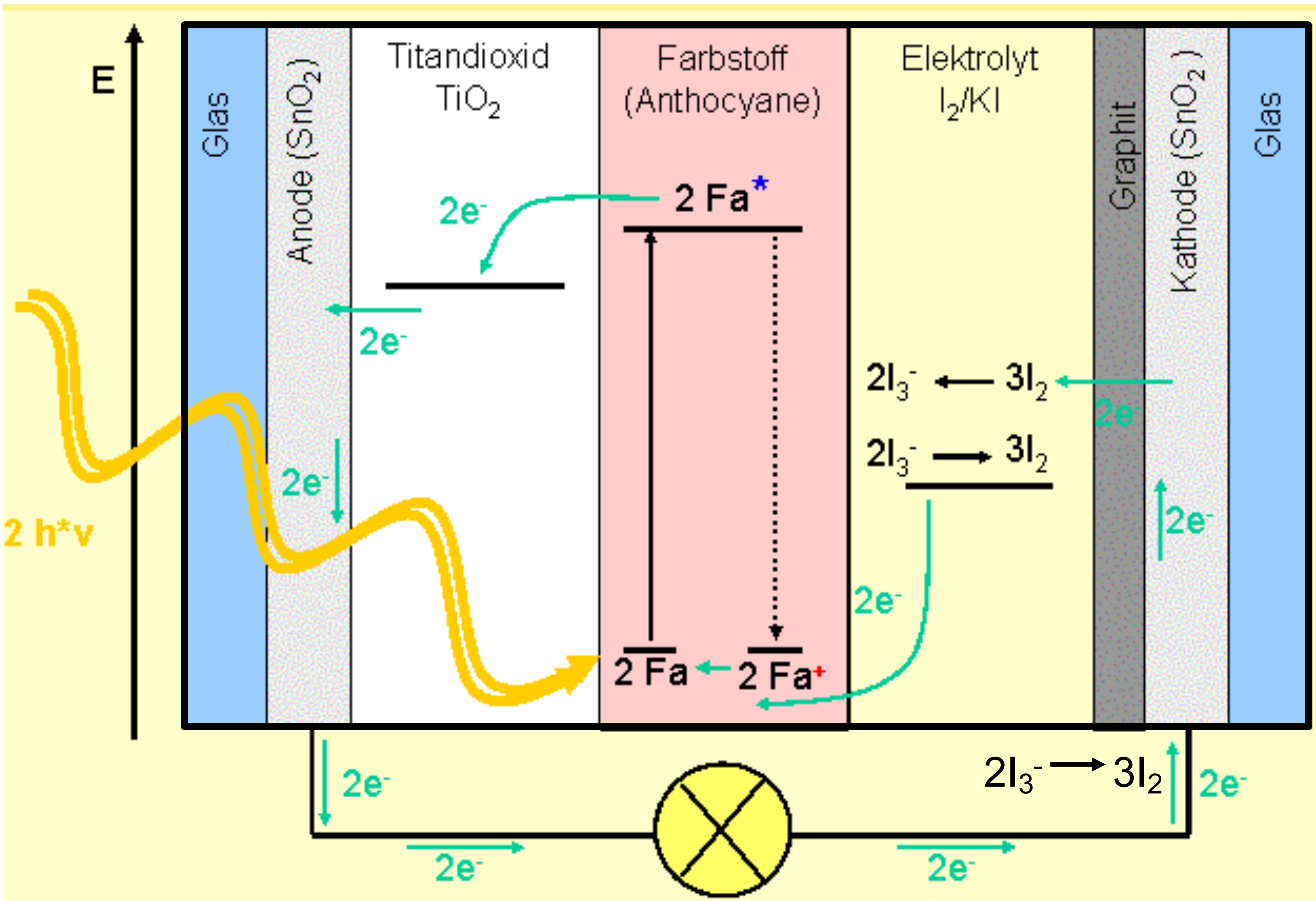
33.5 % (C = 308, AM1.5 direkt)

Tandem-cell

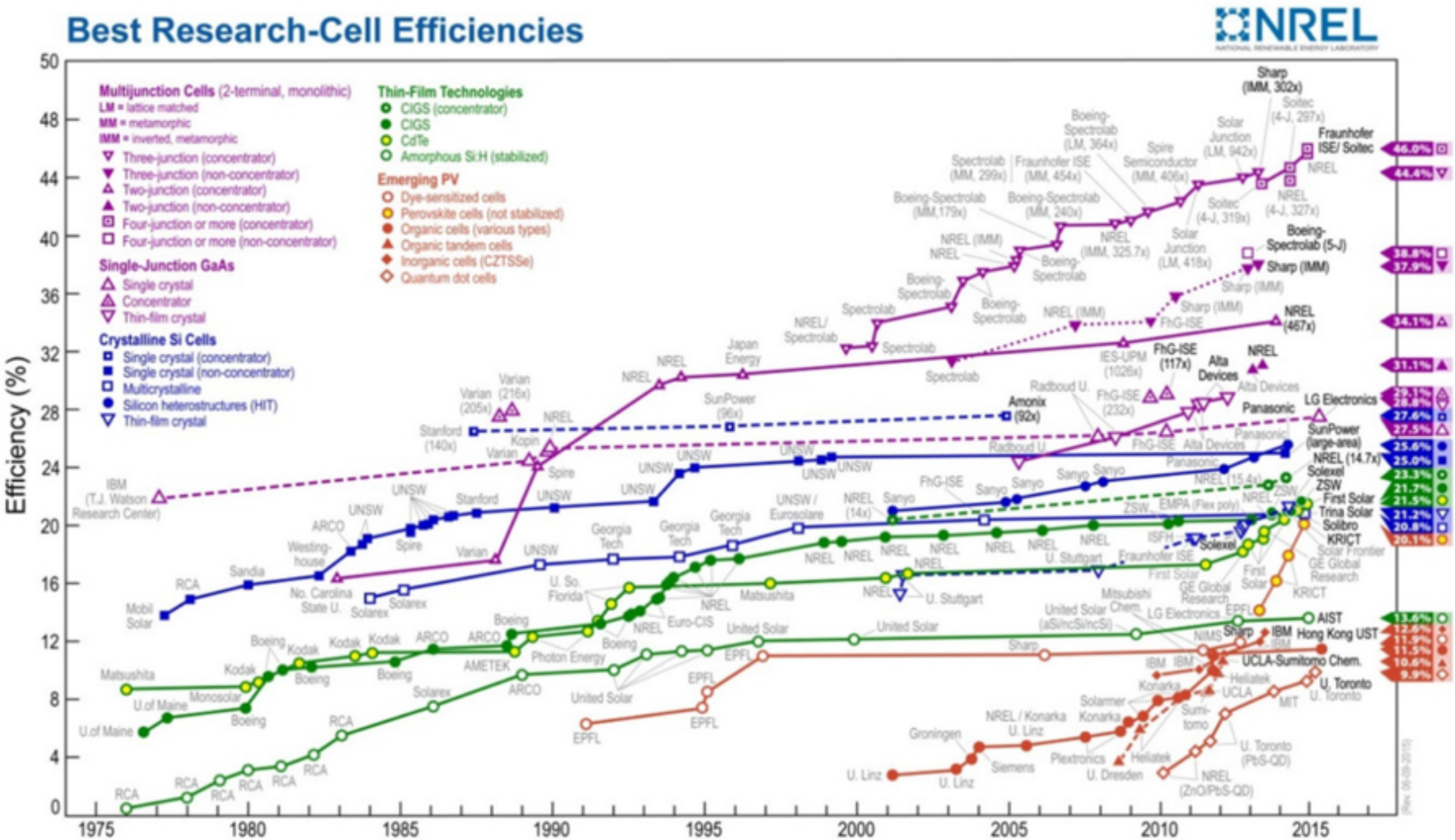
11.5.1. GRÄTZEL CELL



Michael GRÄTZEL (EPFL)
11. Mai 1944,
Dorfchemnitz, Germany

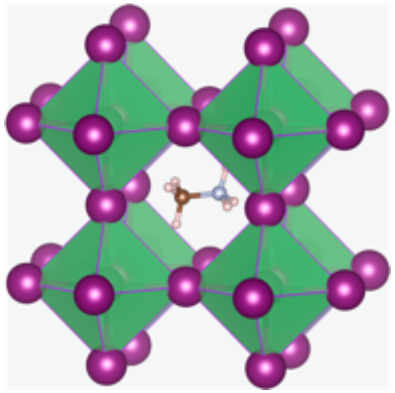


11.5.2. BEST RESEARCH-CELL EFFICIENCY

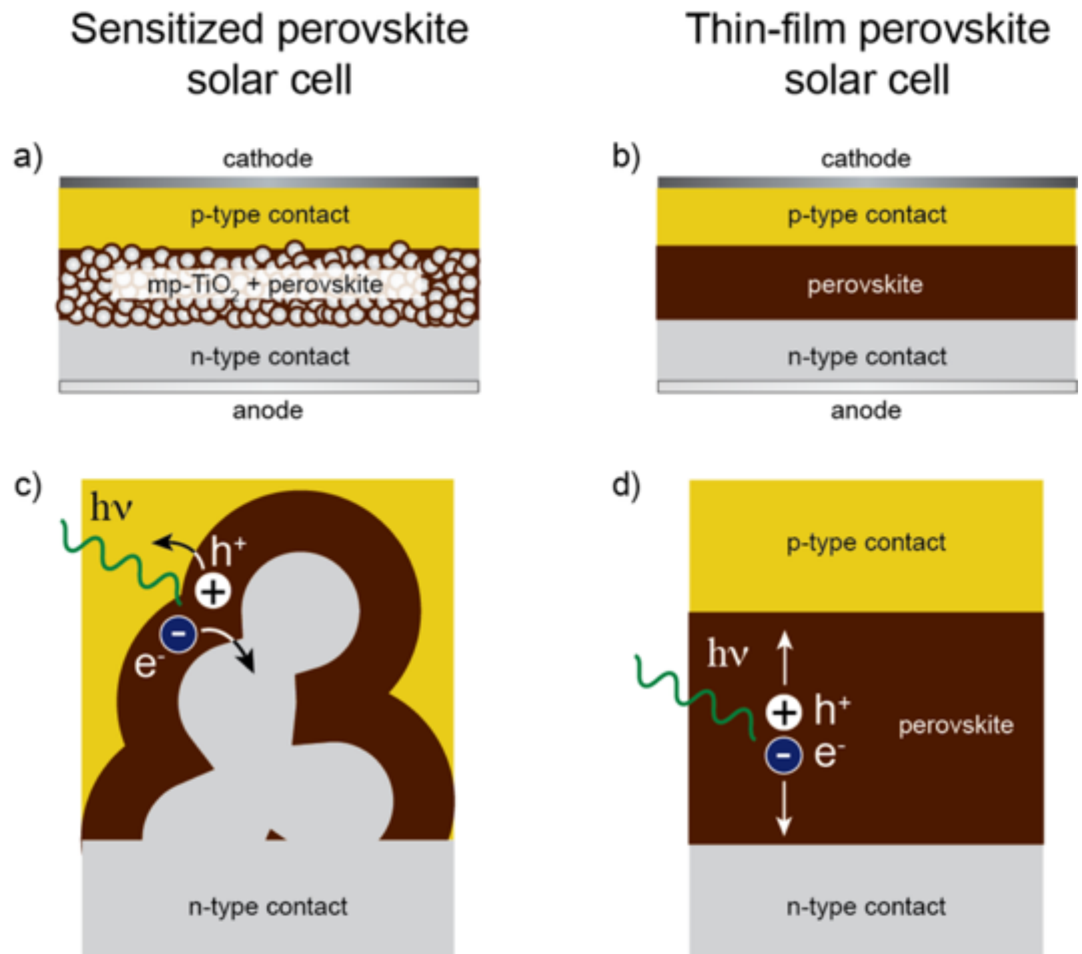


Ref.: Bjørn Petter Jelle, “Building Integrated Photovoltaics: A Concise Description of the Current State of the Art and Possible Research Pathways”, *Energies* 2016, *9*(1), 21

11.5.3. PEROVSKITE PHOTOVOLTAIC CELLS

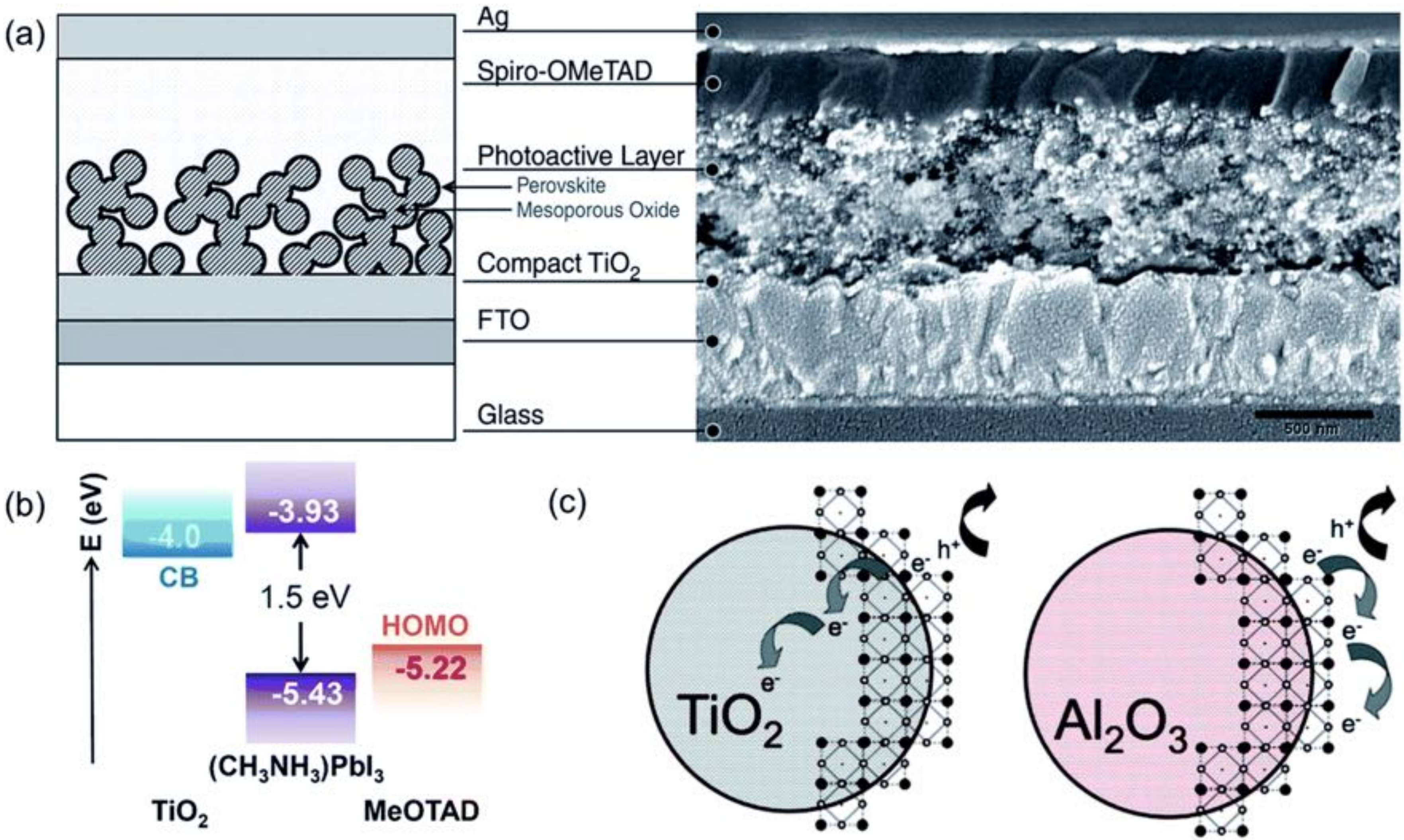


Crystal structure of $CH_3NH_3PbX_3$ perovskites (X=I, Br and/or Cl). The methylammonium cation ($CH_3NH_3^+$) is surrounded by PbX_6 octahedra.

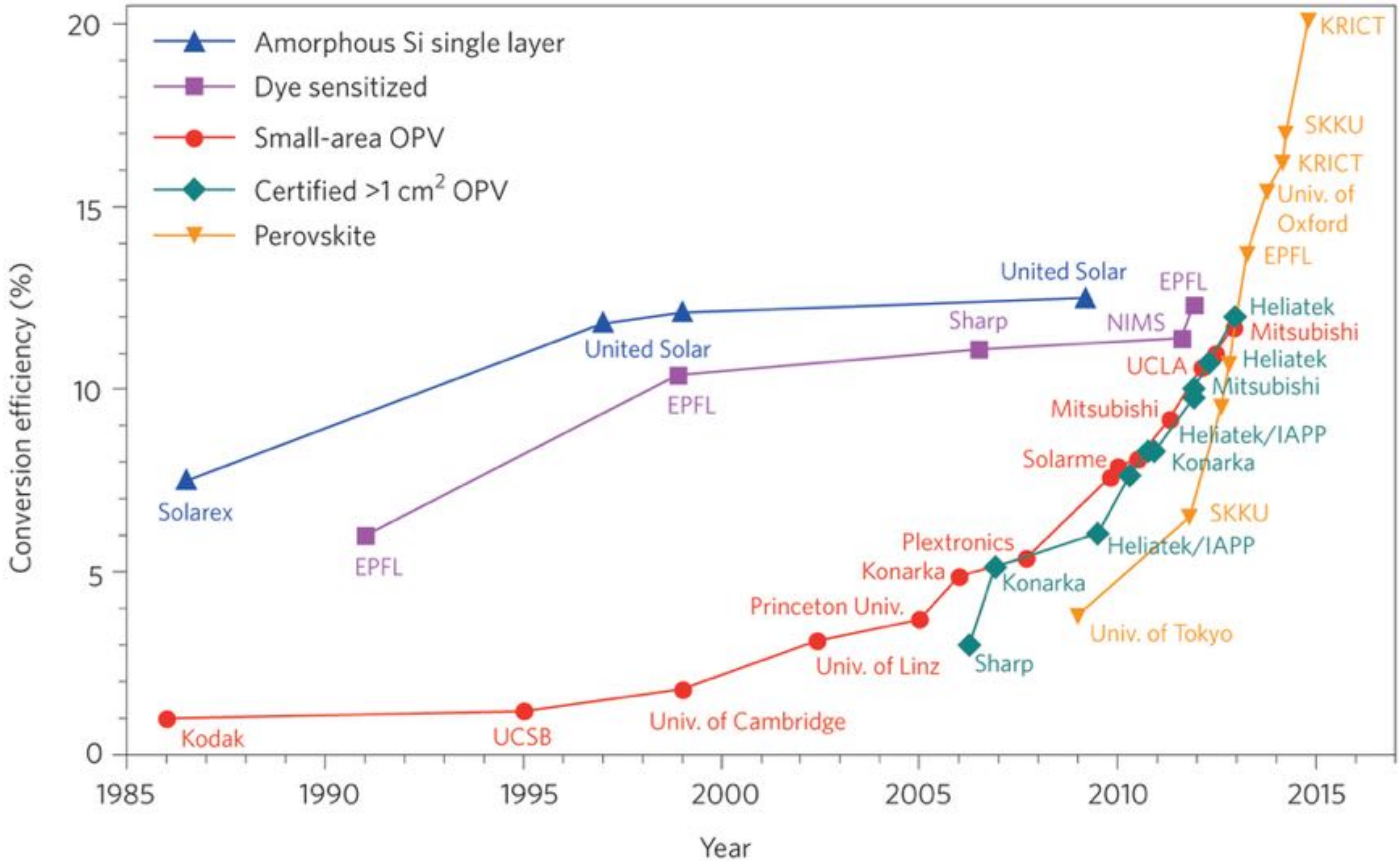


Schematic of a sensitized perovskite solar cell in which the active layer consist of a layer of mesoporous TiO_2 which is coated with the perovskite absorber. The active layer is contacted with an n-type material for electron extraction and a p-type material for hole extraction. b) Schematic of a thin-film perovskite solar cell. c) Charge generation and extraction in the sensitized architecture. d) Charge generation and extraction in the thin-film architecture. After light absorption both charge generation as well as charge extraction occurs in the perovskite layer.

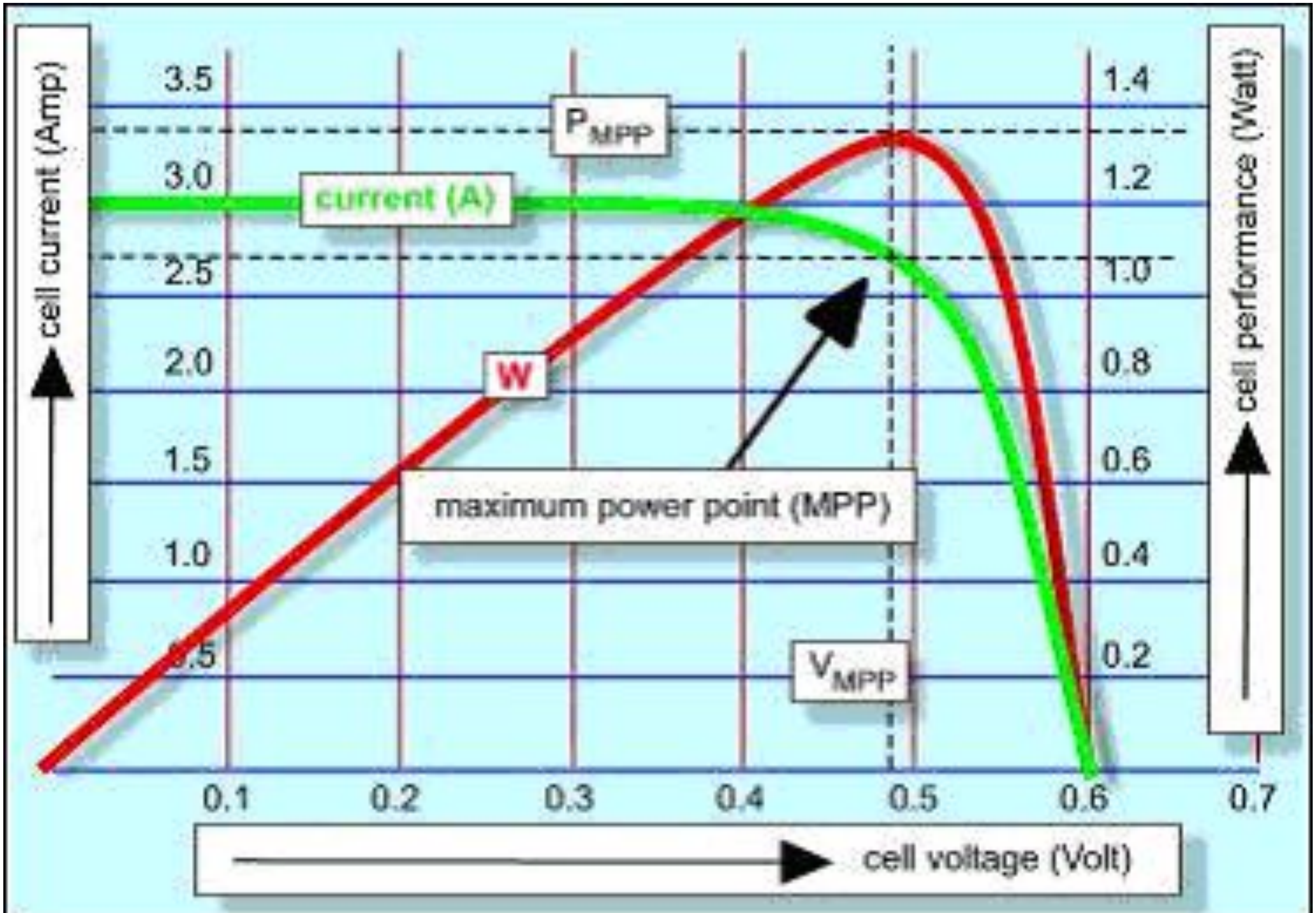
11.5.4. PEROVSKITE PHOTOVOLTAIC CELL MATERIALS



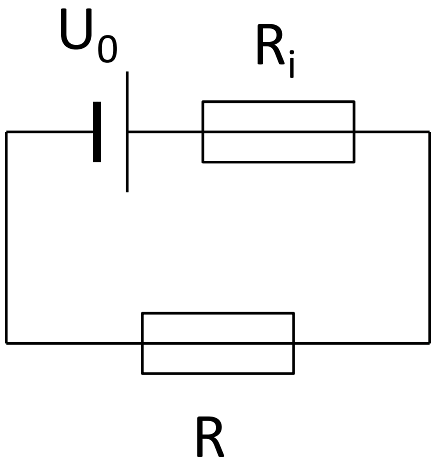
11.5.5. DEVELOPMENT OF PEROVSKITE PHOTOVOLTAIC CELLS



11.6. POWER OUTPUT



11.6.1. POWER OUTPUT MODEL



$$P = U \cdot I = R \cdot I^2$$

$$U_0 = (R + R_i) \cdot I$$

$$P = R \cdot \left(\frac{U_0}{(R + R_i)} \right)^2 = U_0^2 \cdot \frac{R}{(R + R_i)^2}$$

Pmax:

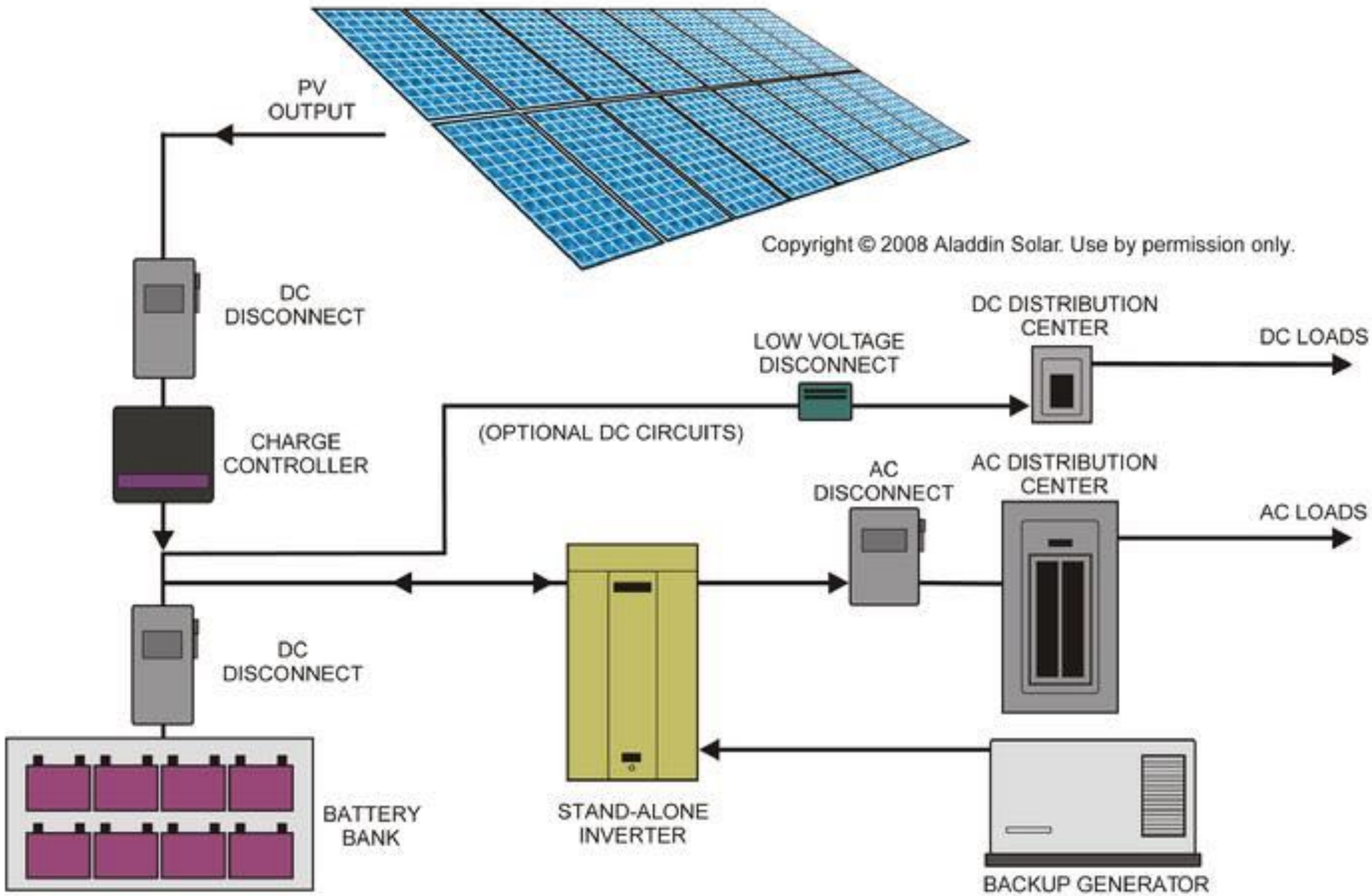
$$\frac{dP}{dR} = U_0 \cdot \frac{1}{(R + R_i)^2} - 2 \cdot R \cdot U_0 \cdot (R + R_i)^{-3} = 0$$

$$(R + R_i) - 2 \cdot R = 0$$

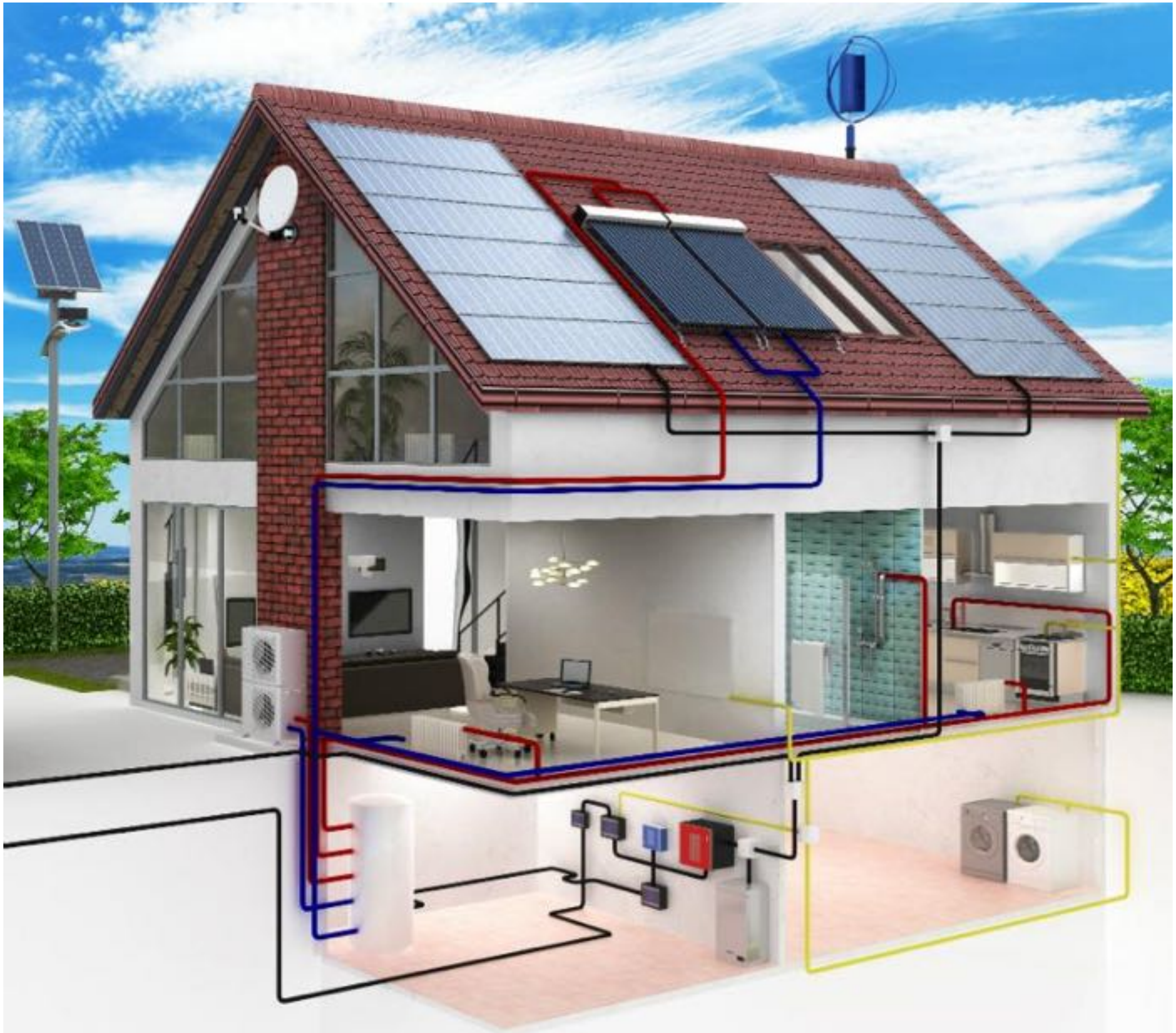
$$R = R_i$$

$$P_{max} = \frac{U_0^2}{4 \cdot R_i}$$

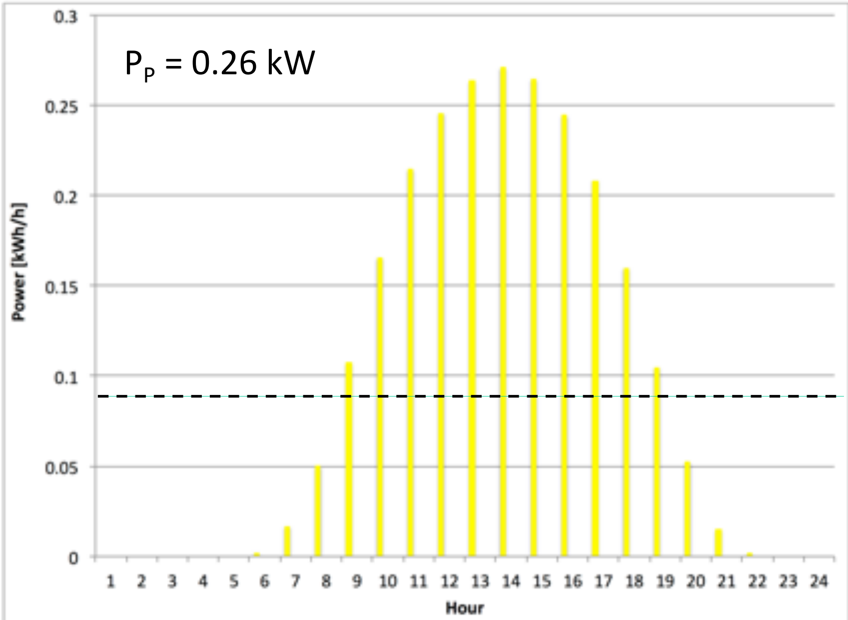
11.7.1. TYPICAL PV-STAND ALONE SYSTEM

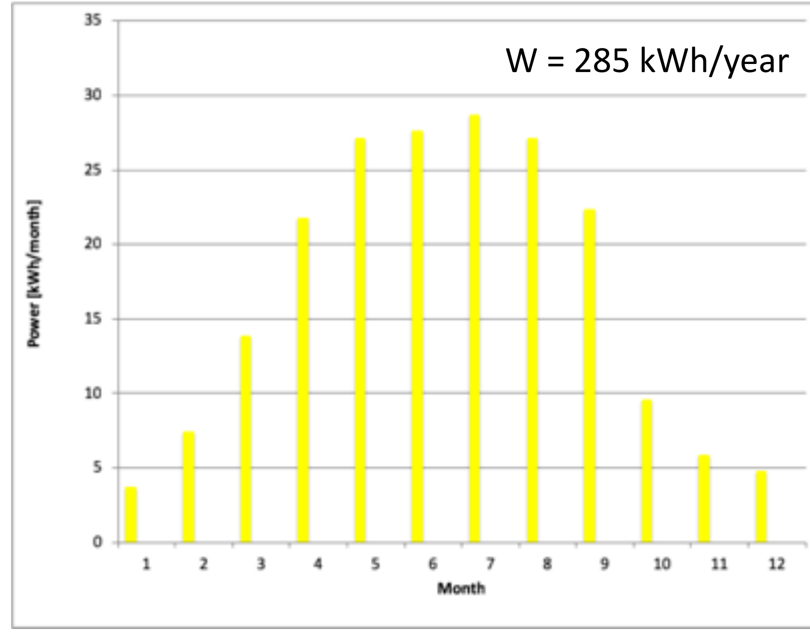


11.7.2. PV AND SOLAR THERMAL SYSTEM



11.7.3. $1m^2$ PHOTOVOLTAIC ENERGY PRODUCTION

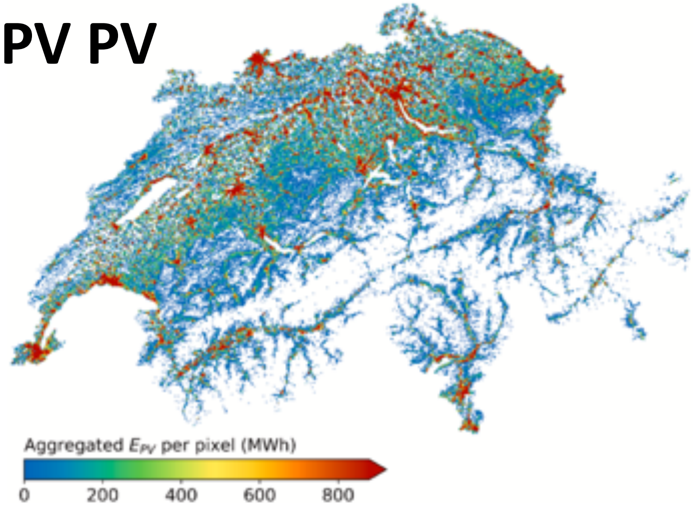


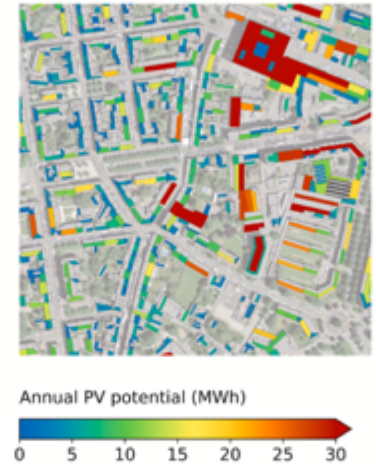


Parameter	Relationship	Value
Average power	$<P>$	$<P> = 1$ kW
Annual energy per year	$W = <P>\cdot 8760h/y$	$W = 8.76$ MWh/y
Annual solar irradiation	$1050 \leq I \leq 1550\ kWh\cdot m^{-2}\cdot y^{-1}$	$I = 1100\ kWh\cdot m^{-2}\cdot y^{-1}$
Efficiency	η	$\eta = 20\%$
PV surface area/capita	$A = W\cdot I^{-1}\cdot \eta^{-1}$	$A = 40\ m^2$
PV peak power/capita	$P_P = 1\ kW\cdot m^{-2}\cdot A\cdot \eta = 1\ kW\cdot m^{-2}\cdot I^{-1}\cdot <P>\cdot 8760h/y$	$P_P = 8$ kW
Ratio	$P_p /<P> = 1\ kW\cdot m^{-2}\cdot I^{-1}\cdot 8766h/y$	$P_p /<P> = 8$

11.7.4. ROOF AREA FOR PV PV

55% of the total Swiss roof surface is available for the installation of PV panels, yielding an annual technical rooftop PV potential of 24 ± 9 TWh.





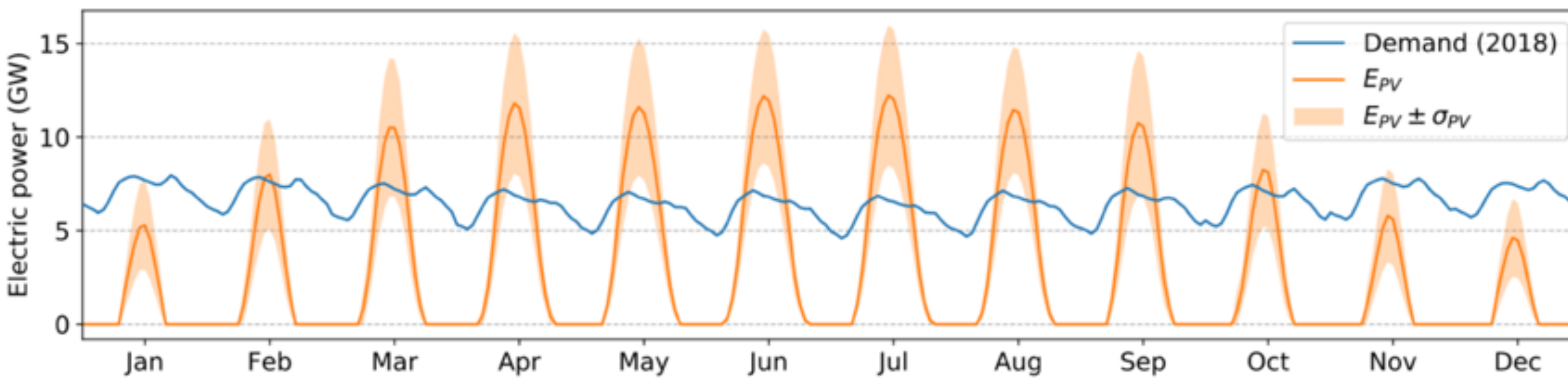


Table 12
Comparison of the results presented in 6 studies of technical RPV potential in Switzerland. To obtain comparable results, the entries labelled with * are computed from values quoted in the respective publications as explained in [67].

Study	A_{PV} (km^2)	Suitable roofs (%)	G_t (kWh/m^2)	η_{sys} (%)	E_{PV} (TWh)
IEA [28]	251*	55	1,088*	10	15.04
Assouline et al. [26]	328	60.5*	662*	13.6	17.86
Assouline et al. [27]	252	60.5*	786*	13.6	16.29
Sonnendach [22,64]	439*	71.6*	1243*	13.6	53.09*
Buffat et al. [20]	485	70.1*	1176*	10.3	41.20*
Present study	267	56.4	1186	13.8	24.58

Ref.: Alina Walcha, Roberto Castello, Nahid Mohajeri, Jean-Louis Scartezzini, “Big data mining for the estimation of hourly rooftop photovoltaic potential and its uncertainty“, Applied Energy 262 (2020) 114404

11.7.5. FLOATING PHOTOVOLTAICS

South Korea's giant floating solar flowers offer hope for unpopular large-scale projects

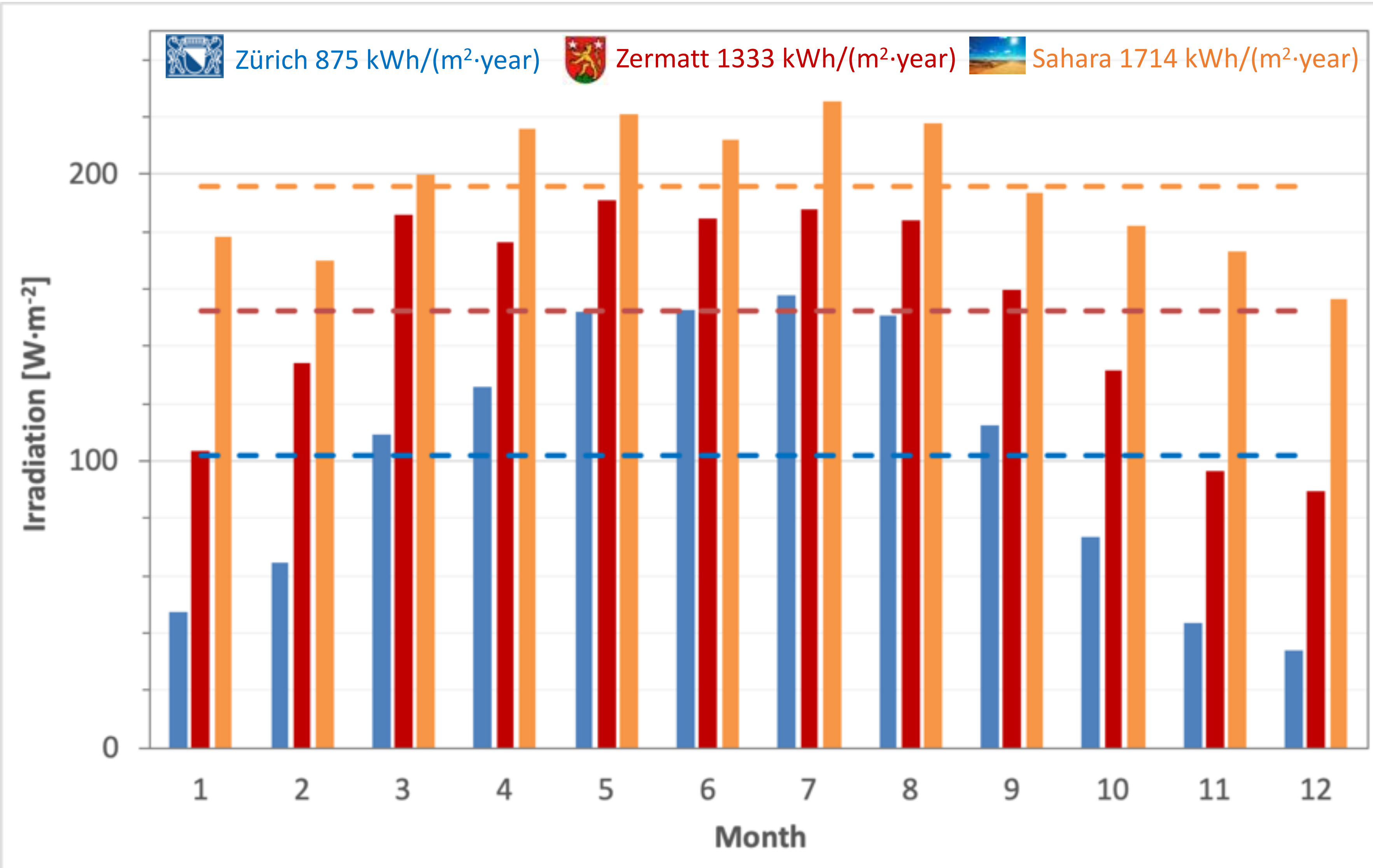
Ref: https://colorsofindia.media/world/japan/south-koreas-giant-floating-solar-flowers-offer-hope-for-unpopular-large-scale-projects/

$3.65\ km^2$
$1200\ kWh\cdot m^{-2}\cdot y^{-1}$
$W_{PV} = 4380\ GWh\cdot y^{-1}\cdot 20\% = 876\ GWh\cdot y^{-1}$
$W_{Hyd} = 2300\ GWh\cdot y^{-1}$, $\langle P_{Hyd}\rangle = 263\ MW$

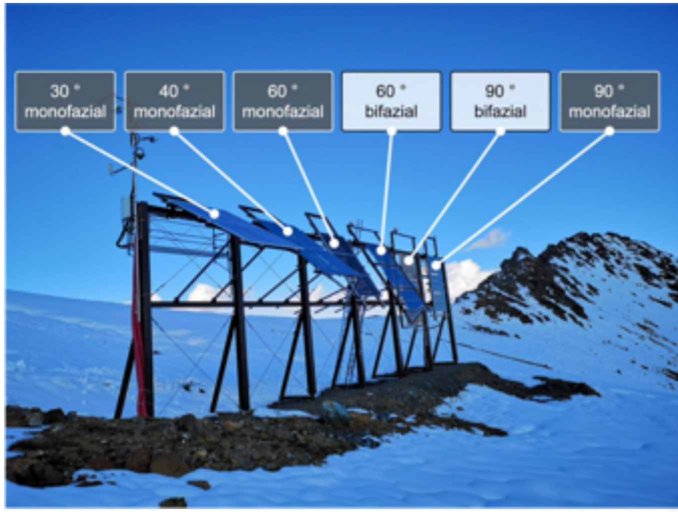
with PV +40% Electricity
area not used
Grid connection already exists
$\langle P_{PV}\rangle = 100\ MW$, $P_P = 800\ MW$

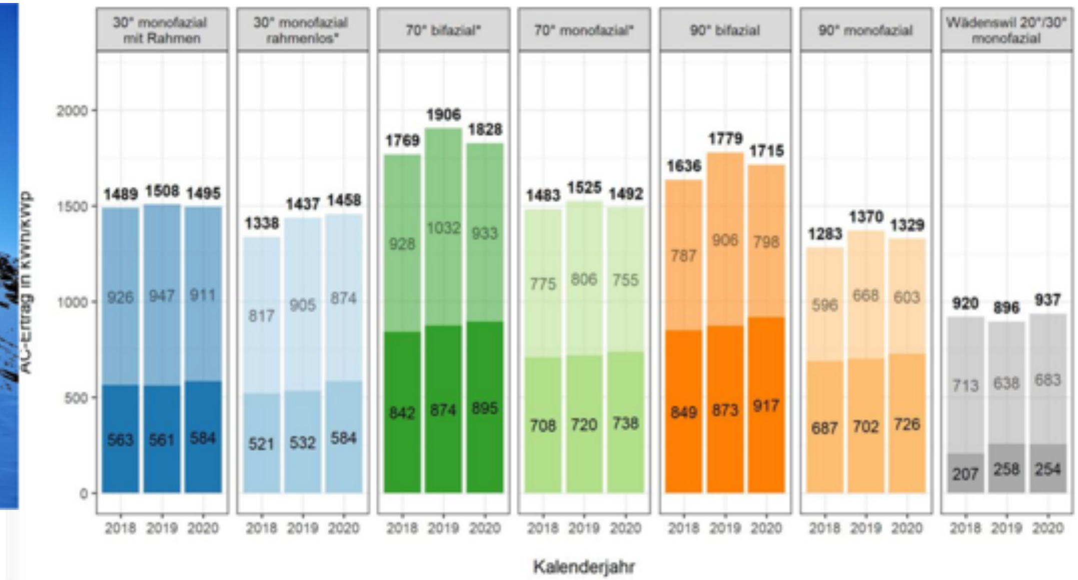
Ref.: Rafael M. Almeida, Rafael Schmitt, Steven M. Grodsky, Alexander S. Flecker, Carla P. Gomes, Lu Zhao, Haohui Liu, Nathan Barros, Rafael Kelman & Peter B. McIntyre , "Floating solar power: evaluate trade-offs", Nature Vol 606, 9 June 2022 , pp. 246-249

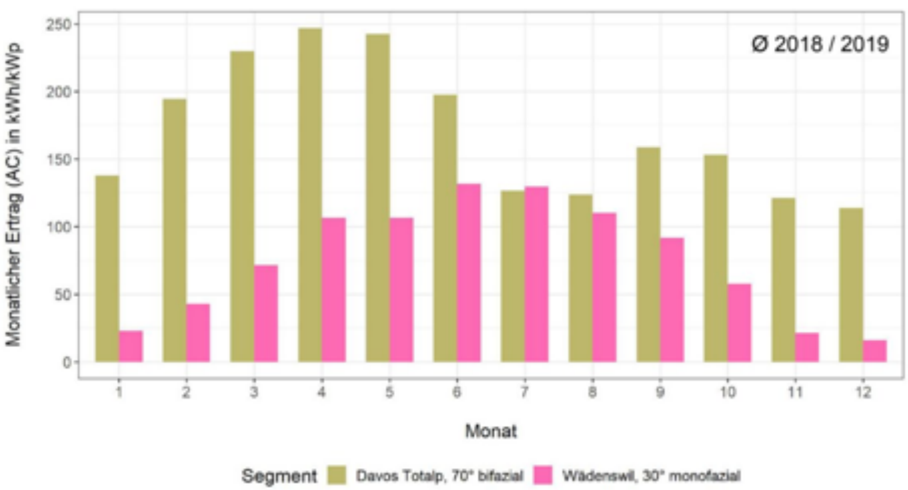
11.7.6. Monthly Solar Irradiation

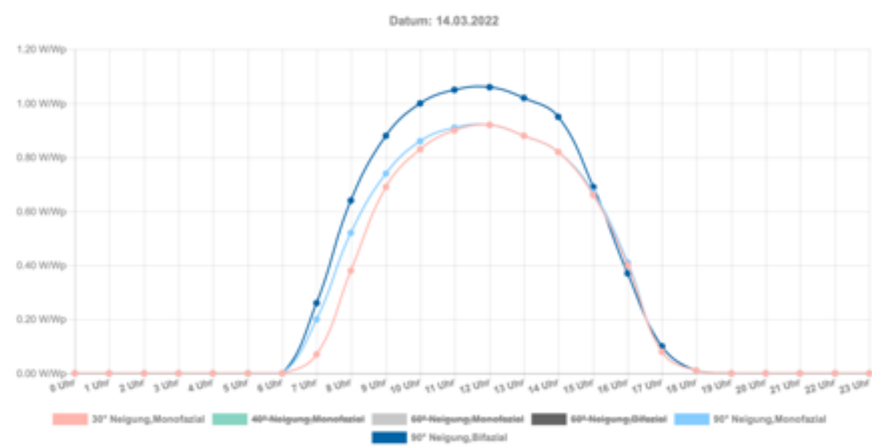


11.7.7. ALPINE SOLAR POWER



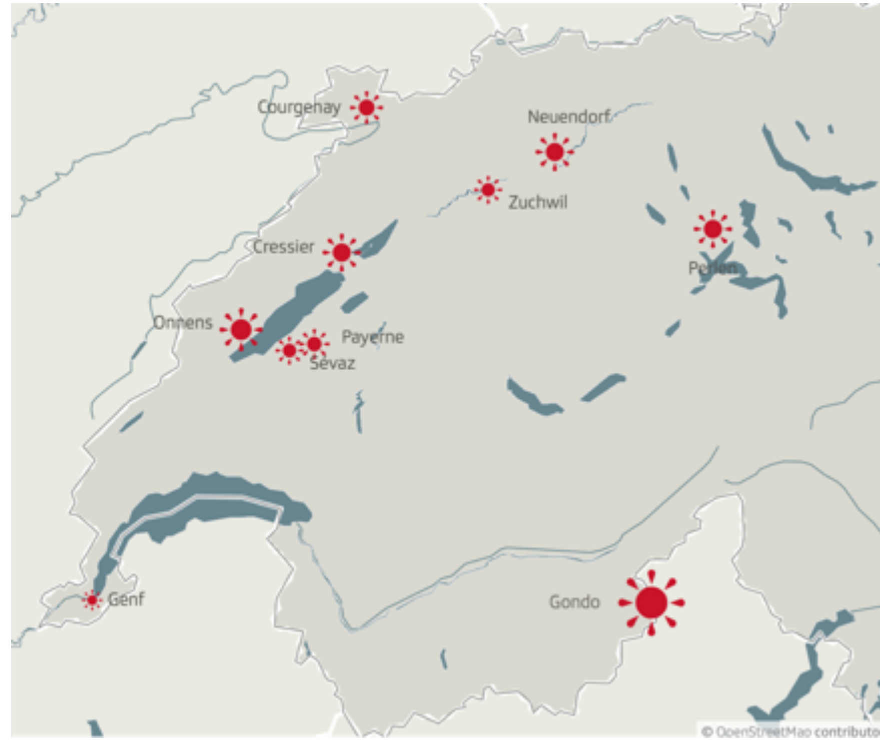






Ref.: Fabian Carigiet, Danilo Grunauer, Franz P. Baumgartner, “PERFORMANCE ANALYSIS OF PV MODULES INSTALLED IN THE ALPINE REGION”, 38th European Photovoltaic Solar Energy Conference and Exhibition (38th EUPVSEC), online Sept 2021

11.7.8. GONDO SOLAR



Gondosolar

Total area: 100'000 m^2

Number of solar panels 4500

Energy production: 23.3 $GWh \cdot y^{-1}$

Peakpower: 13 MW_{p}, Avg. power: 2.66 MW

Comissioning: 2030

Projected cost: 42 Mio. CHF

Cost: 3200 CHF/kW_p

Operation time: 60 years

Battery (day/night): 52 MWh

Cost (PV): 0.06 CHF/kWh

Cost (PV+Battery): 0.17 CHF/kWh

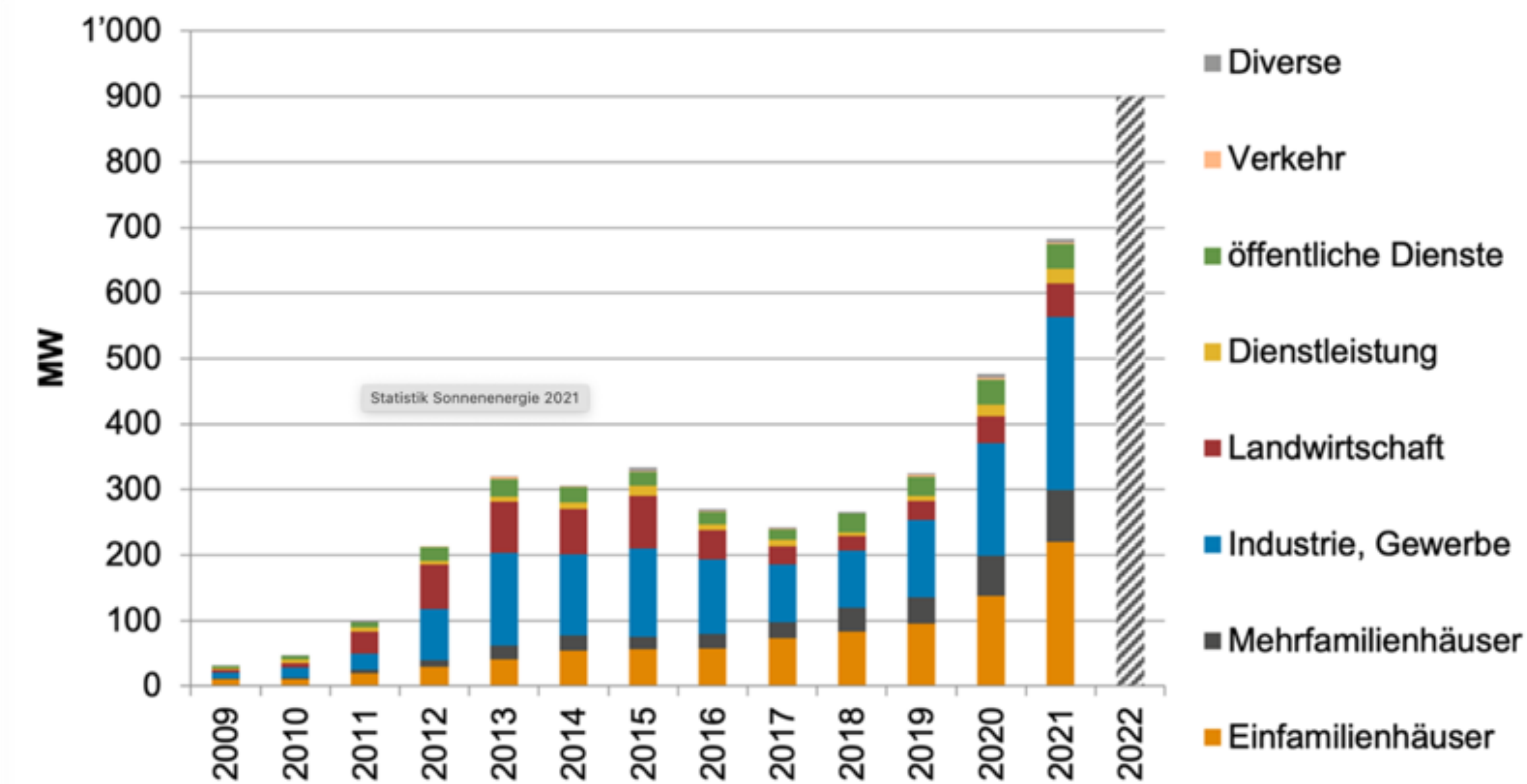
400 x Gondosolar

20 GWh Battery

(2 TWh saisonal Storage)

= 1 x

11.7.9. SWISSOLAR: ANNUAL PV INSTALLATIONS IN SWITZERLAND



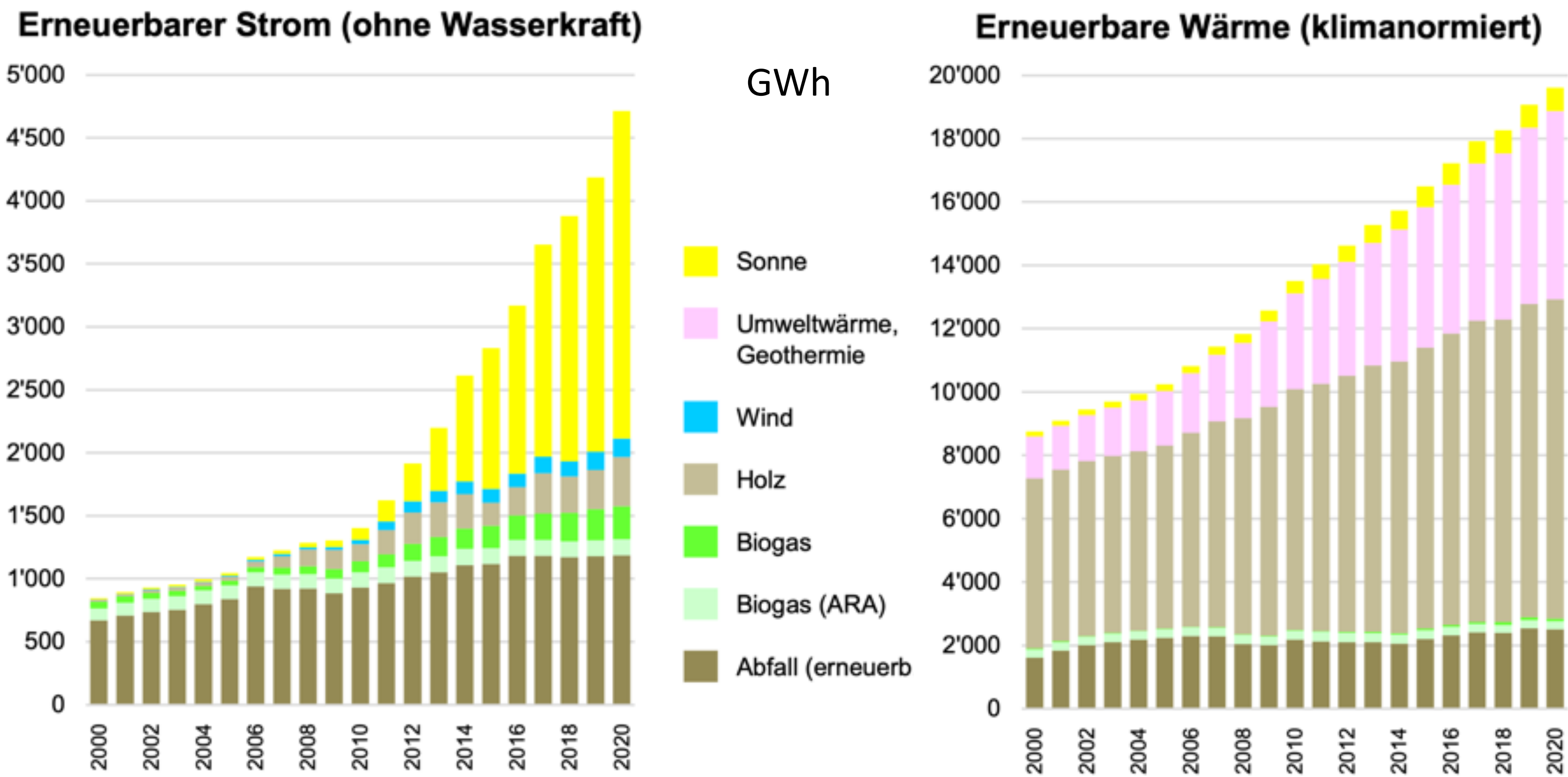
Jährlich neu installierte Leistung von Photovoltaikanlagen in der Schweiz. Gut erkennbar ist das rasche Wachstum nach 2010, ausgelöst durch die kostendeckende Einspeisevergütung (KEV). 2016 und 2017 wurden nur noch Kleinanlagen gefördert, während ab 2018 die Energiestrategie 2050 wirksam wurde. Datenquelle: Statistik Sonnenenergie 2021 sowie Schätzung Swissolar für 2022. Die gesamte installierte Leistung lag zum Jahresende bei 3655 MW_P, die Jahresproduktion lag bei 2842 Gigawattstunden (GWh).

Fläche = 18.275 km^2 (bei η = 20%) prod. 2842 $GWh \cdot y^{-1}$ d.h. 150 km^2 prod. **23.3 $TWh \cdot y^{-1}$**

Ref.: https://www.swissolar.ch/services/medien/news/detail/n-n/der-schnelle-zubau-der-photovoltaik-setzt-sich-fort/

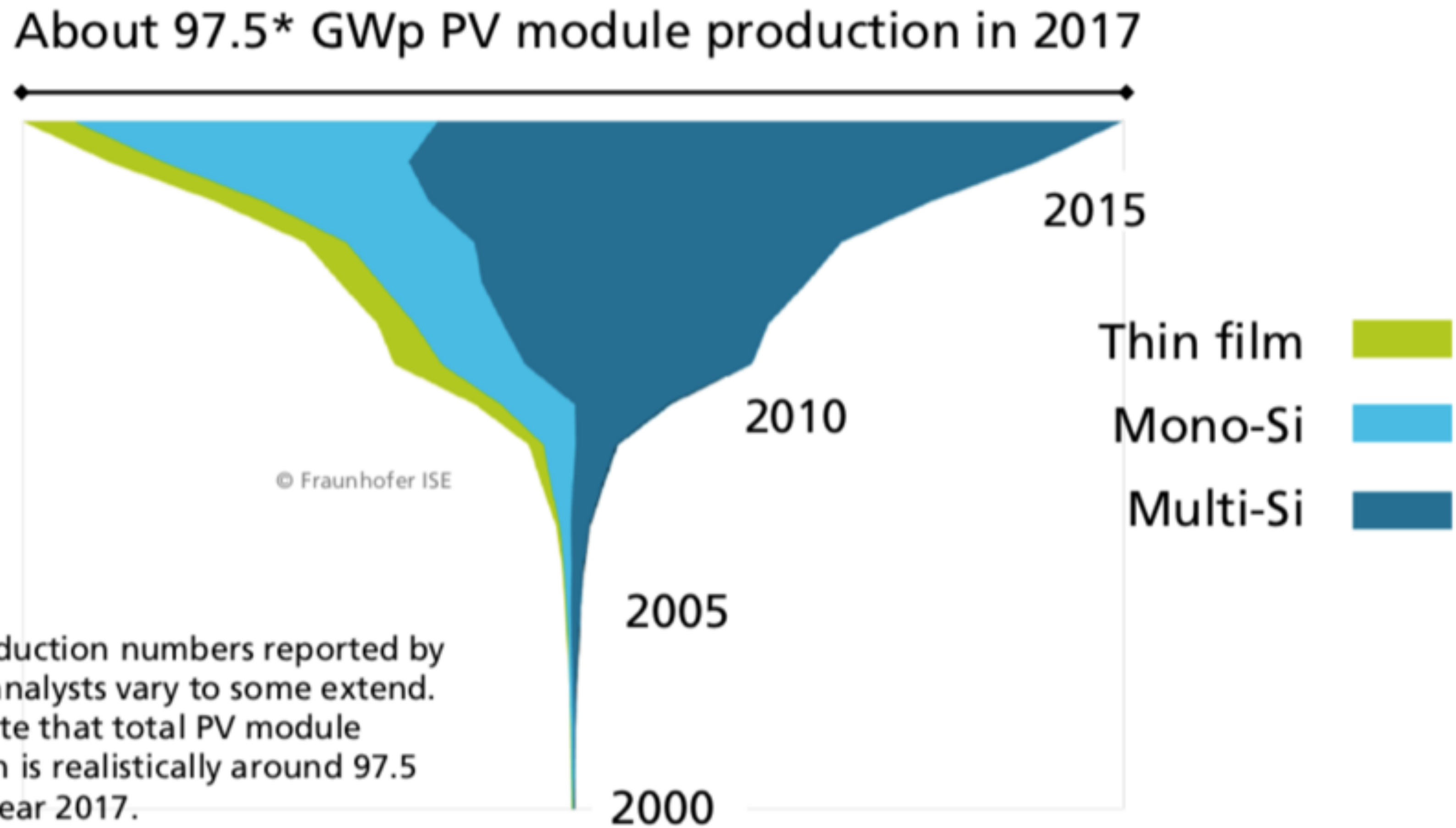
11.7.10. RENEWABLE ENERGY IN SWITZERLAND

Schweizerische Statistik der erneuerbaren Energien. Ausgabe 2021 (PDF, 2.8 MB, 01.10.2022) ID



Ref.: https://www.bfe.admin.ch/bfe/de/home/versorgung/statistik-und-geodaten/energiestatistiken/teilstatistiken.exturl.html/aHR0cHM6Ly9wdWJkYi5iZmUuYWRtaW4uY2gvZGUvcHVibGljYX/Rpb24vZG93bmxvYWQvMTExMTI=.html

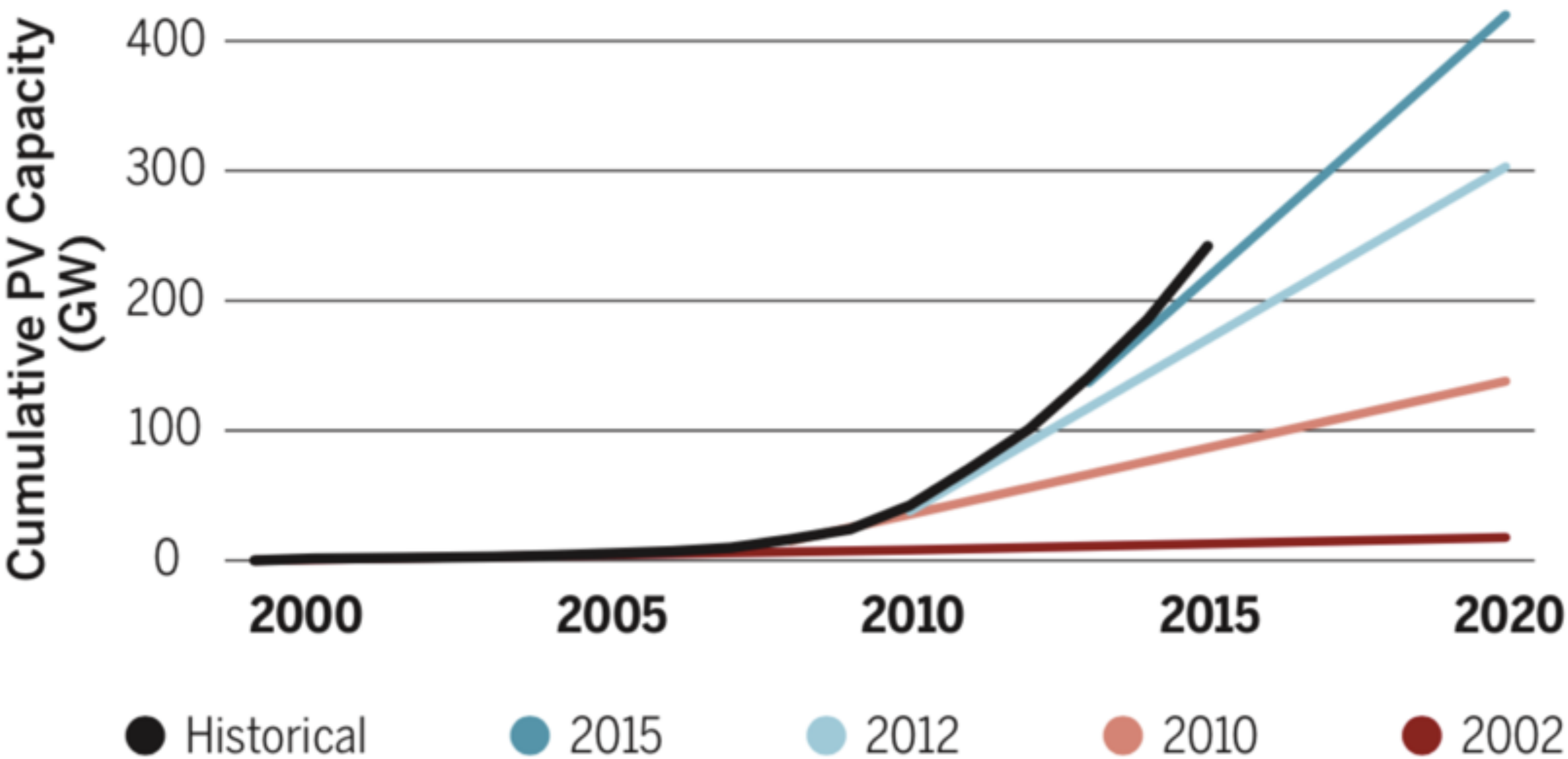
11.8.1. ANNUAL PRODUCTION OF PV PEAK POWER (GW_P)



*2017 production numbers reported by different analysts vary to some extend. We estimate that total PV module production is realistically around 97.5 GWp for year 2017.

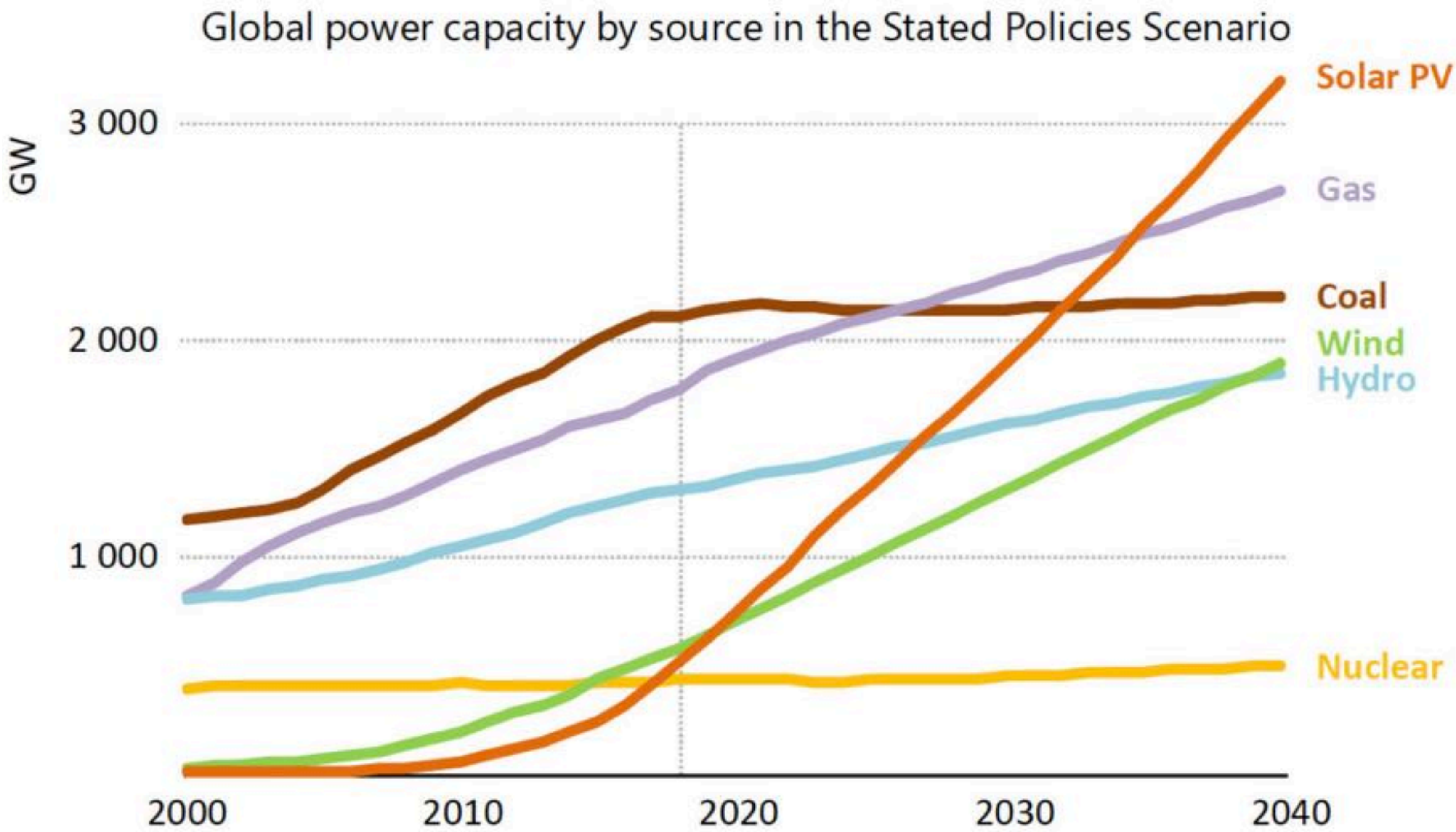
11.8.2. IEA PROJECTION OF CUMULATIVE INSTALLATALLED PV

Projected (labeled by year of IEA publication) versus actual (labeled as "historical"). See supplementary materials for data sources and discussion.



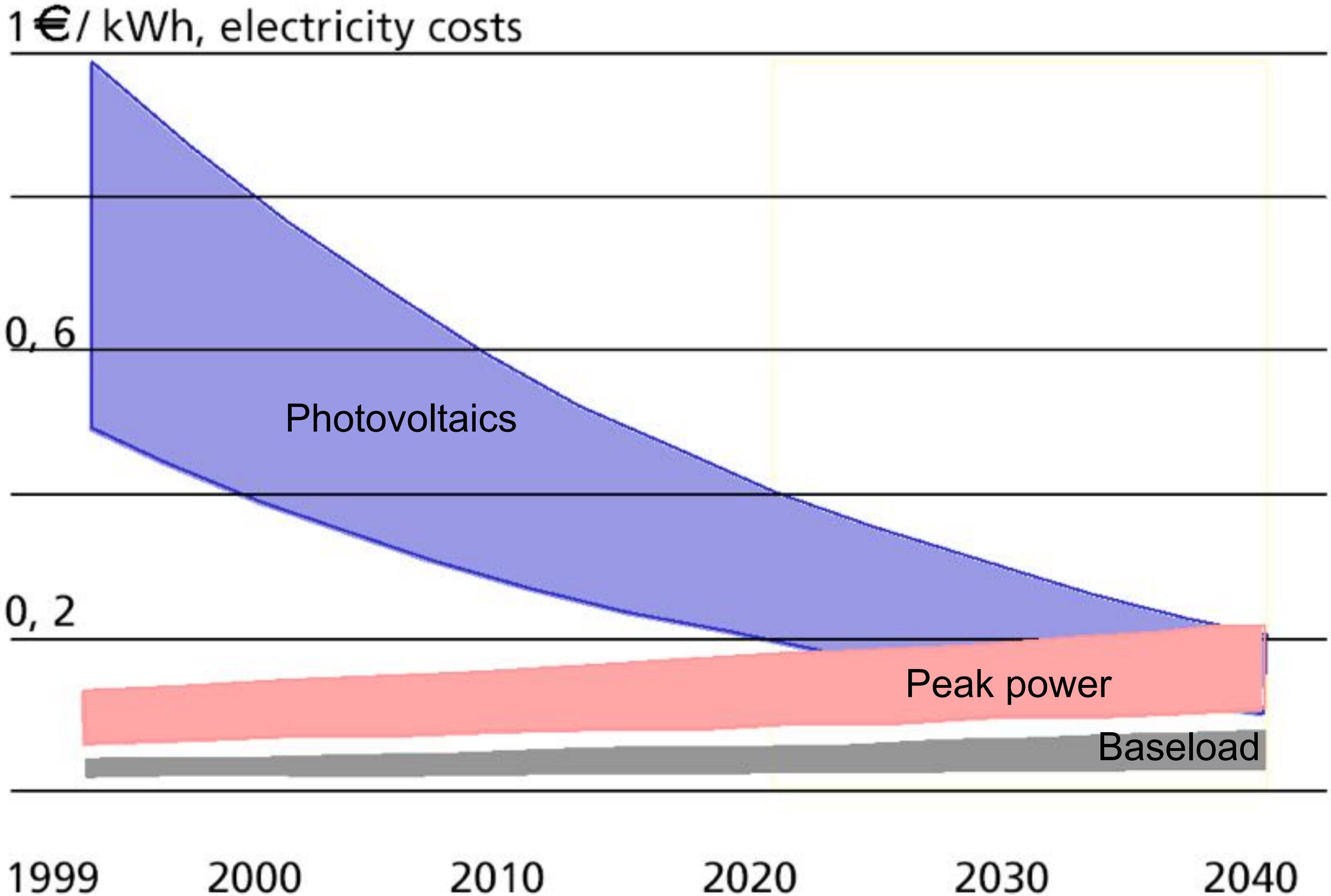
Ref.: Nancy M. Haegel, Robert Margolis, Tonio Buonassisi, David Feldman, Armin Froitzheim, Raffi Garabedian, Martin Green, Stefan Glunz, Hans-Martin Henning, Burkhard Holder, Izumi Kaizuka, Benjamin Kroposki, Koji Matsubara, Shigeru Niki, Keiichiro Sakurai, Roland A. Schindler, William Tumas, Eicke R. Weber, Gregory Wilson, Michael Woodhouse, Sarah Kurtz, "Terawatt-scale photovoltaics: Trajectories and challenges Coordinating technology, policy, and business innovations", SCIENCE 356 ISSUE 6334 (2017), pp. 141 - 143

11.8.3. POWER CAPACITY

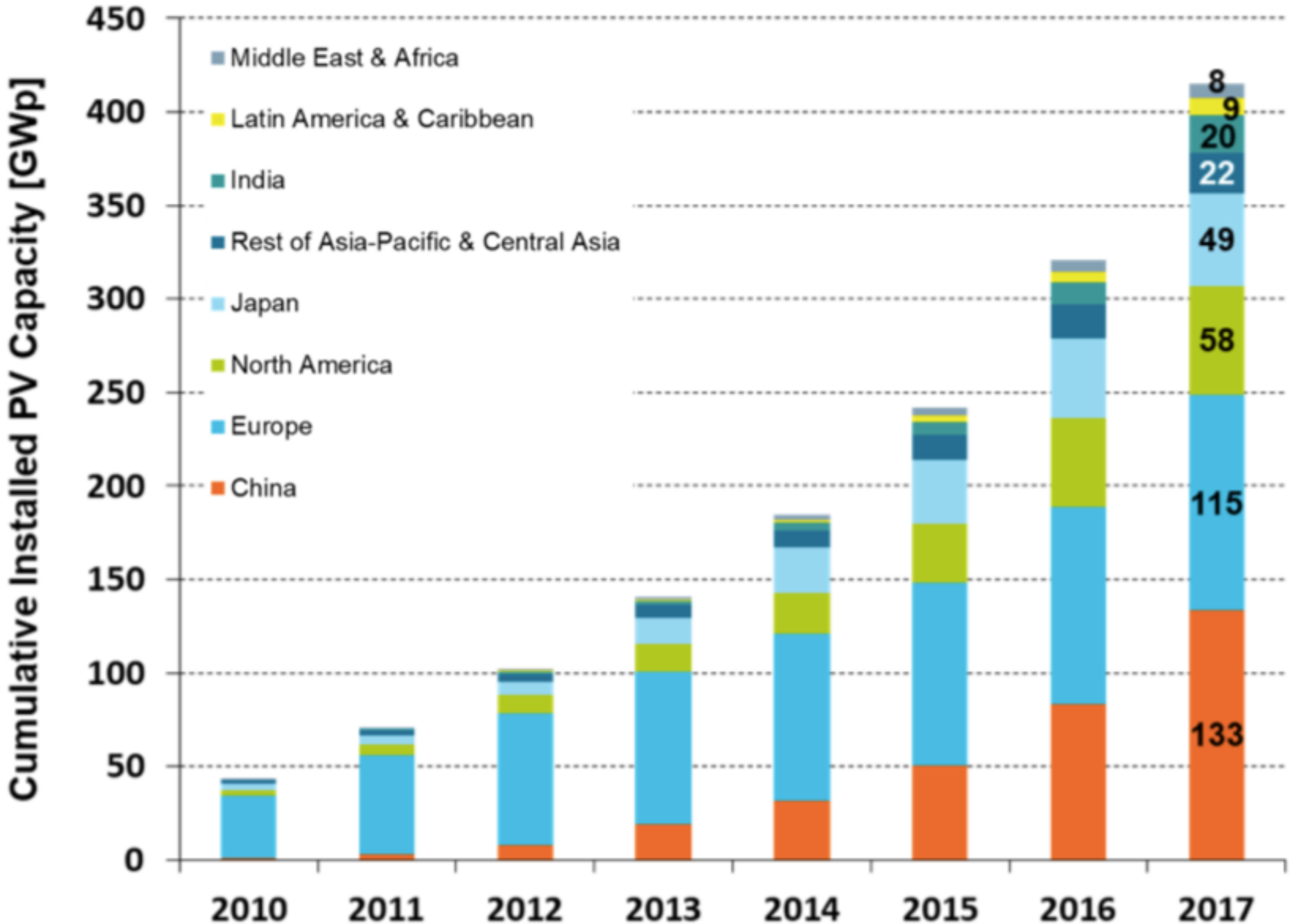


Ref.: IEA World Energy Outlook: Solar Capacity Surges Past Coal and Gas by 2040, 14. 11. **2019** | Sonal Patel

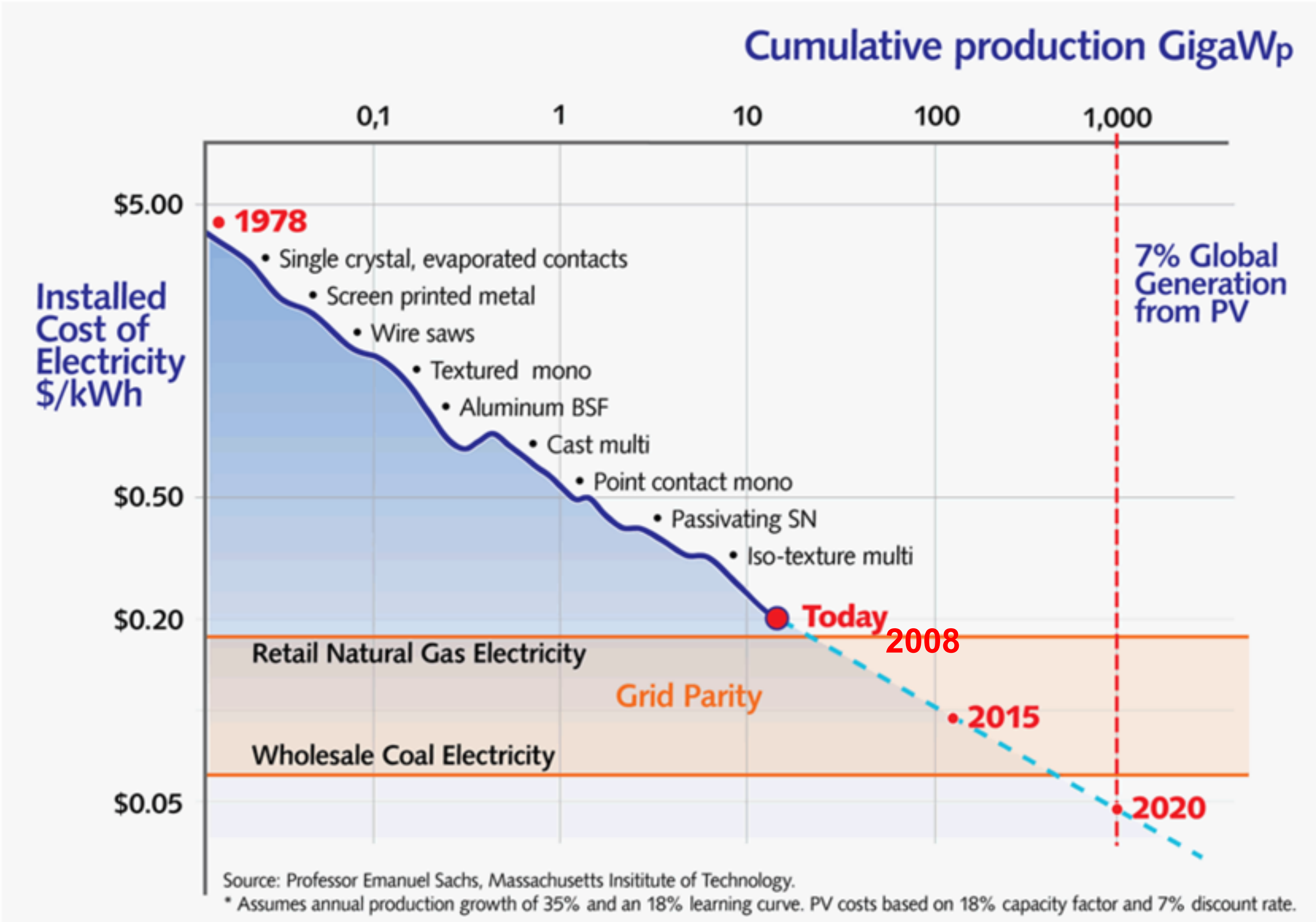
11.8.4. COST OF ELECTRICITY



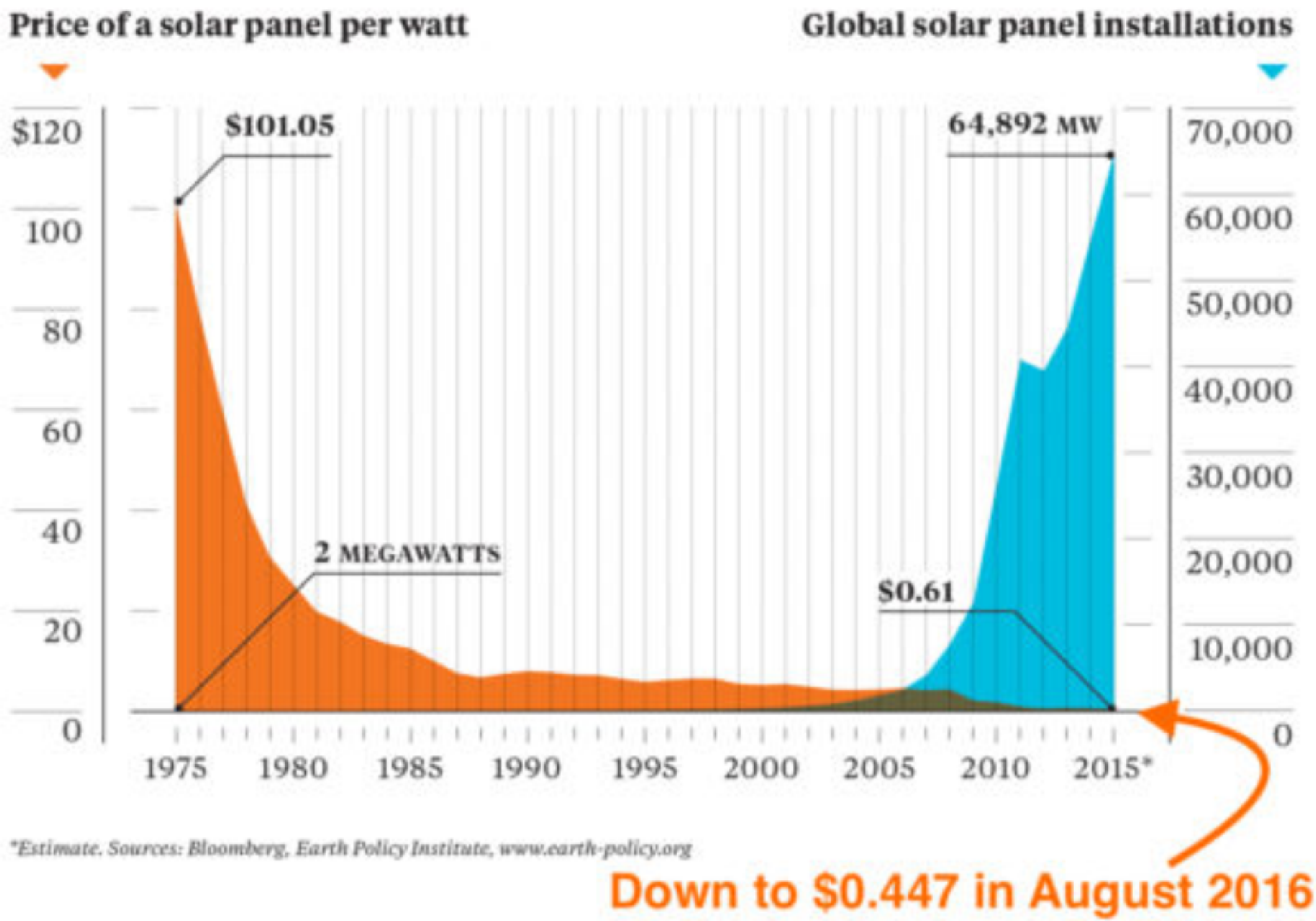
11.8.5. GLOBAL ANUAL INSTALLATIONS PER REGIONS 2010 - 2017



11.8.6. DEVELOPMENT OF THE COST OF PV



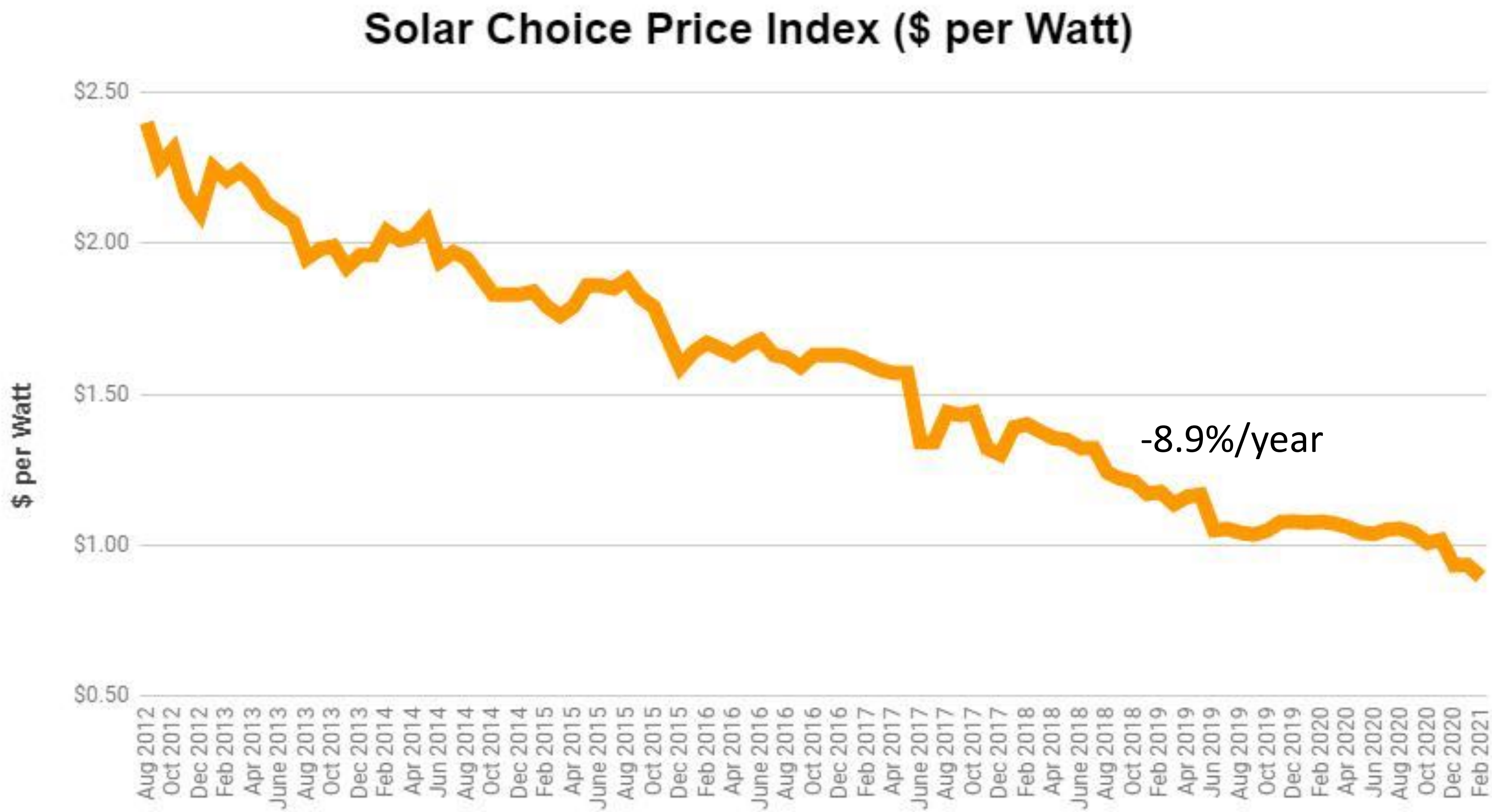
11.8.7. GLOBAL INSTALLATION VS. COST PER WATT OF PV



Ref.: http://cleantechnica.com/2016/08/17/10-solar-energy-facts-charts-everyone-know/

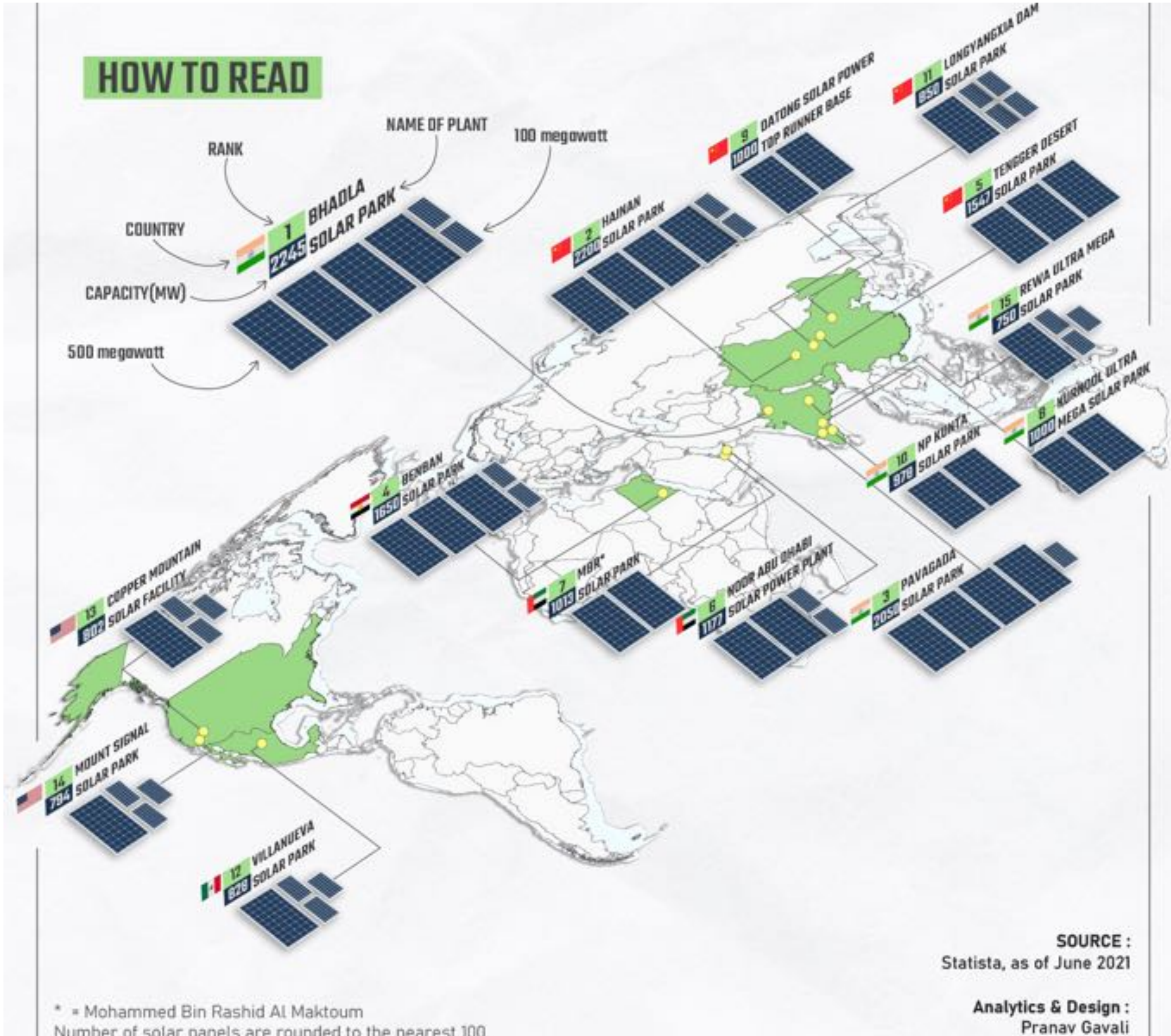
11.8.8. Photovoltaic

Cost: 750 CHF/kW_P
(offers <400 CHF/kW_p)
PV still working after 30 years.
The cost of installation increases the cost of photovoltaics to ≈1200 CHF/kW_p

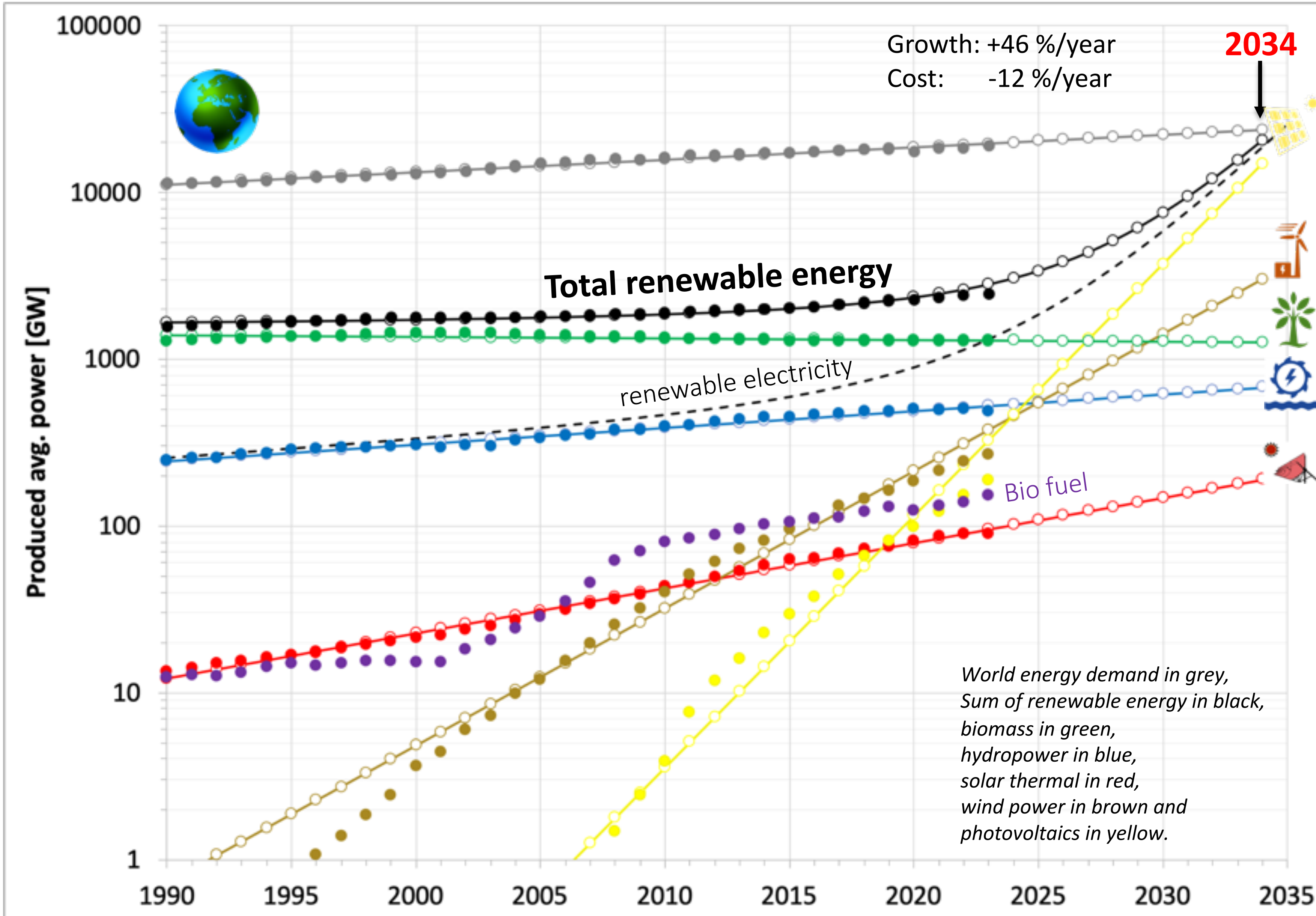


Ref.: https://www.solarchoice.net.au/blog/solar-power-system-prices

11.8.9. WORLD LARGEST PHOTOVOLTAIC ENERGY PRODUCTION

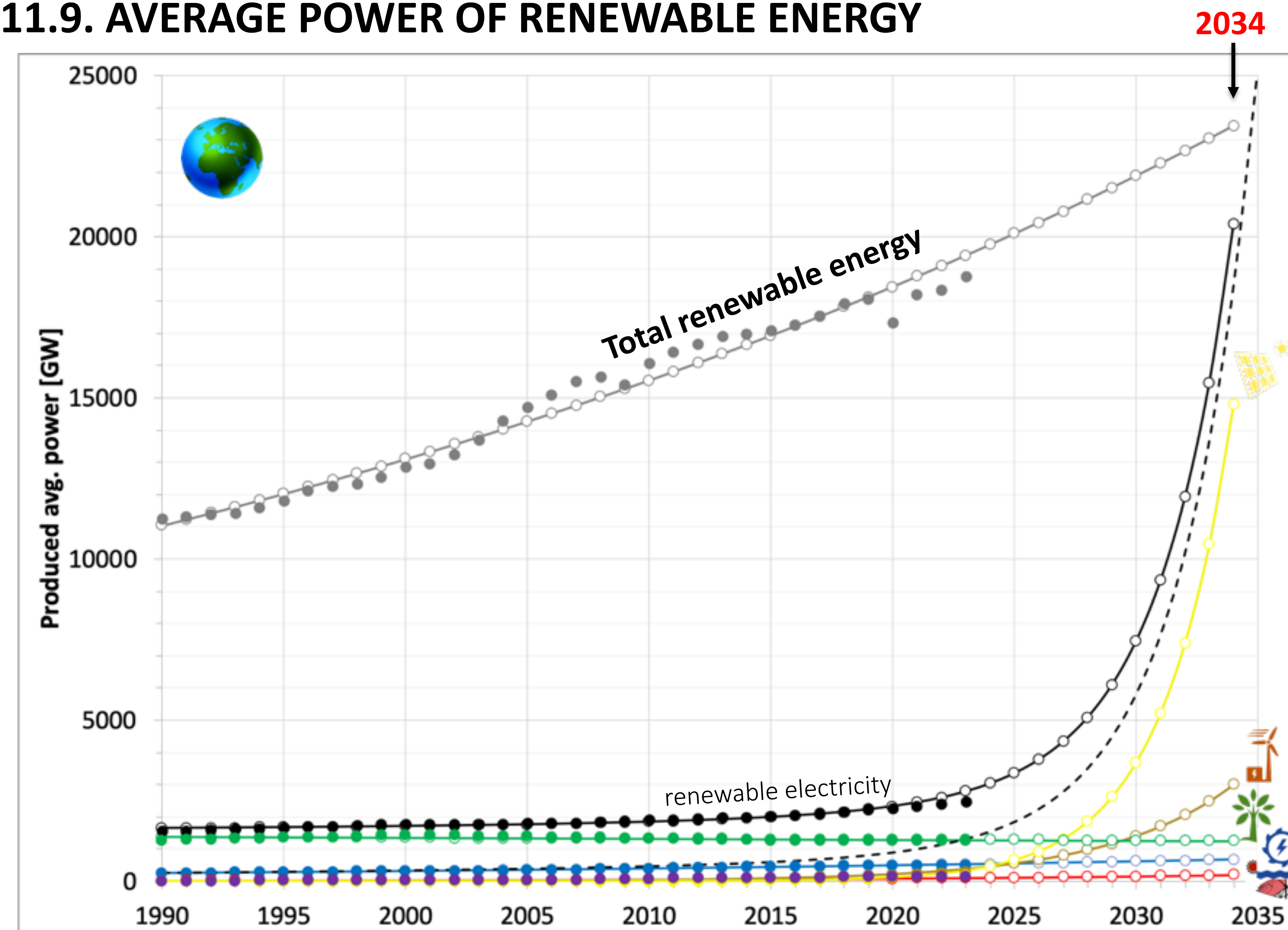


11.9. AVERAGE POWER OF RENEWABLE ENERGY



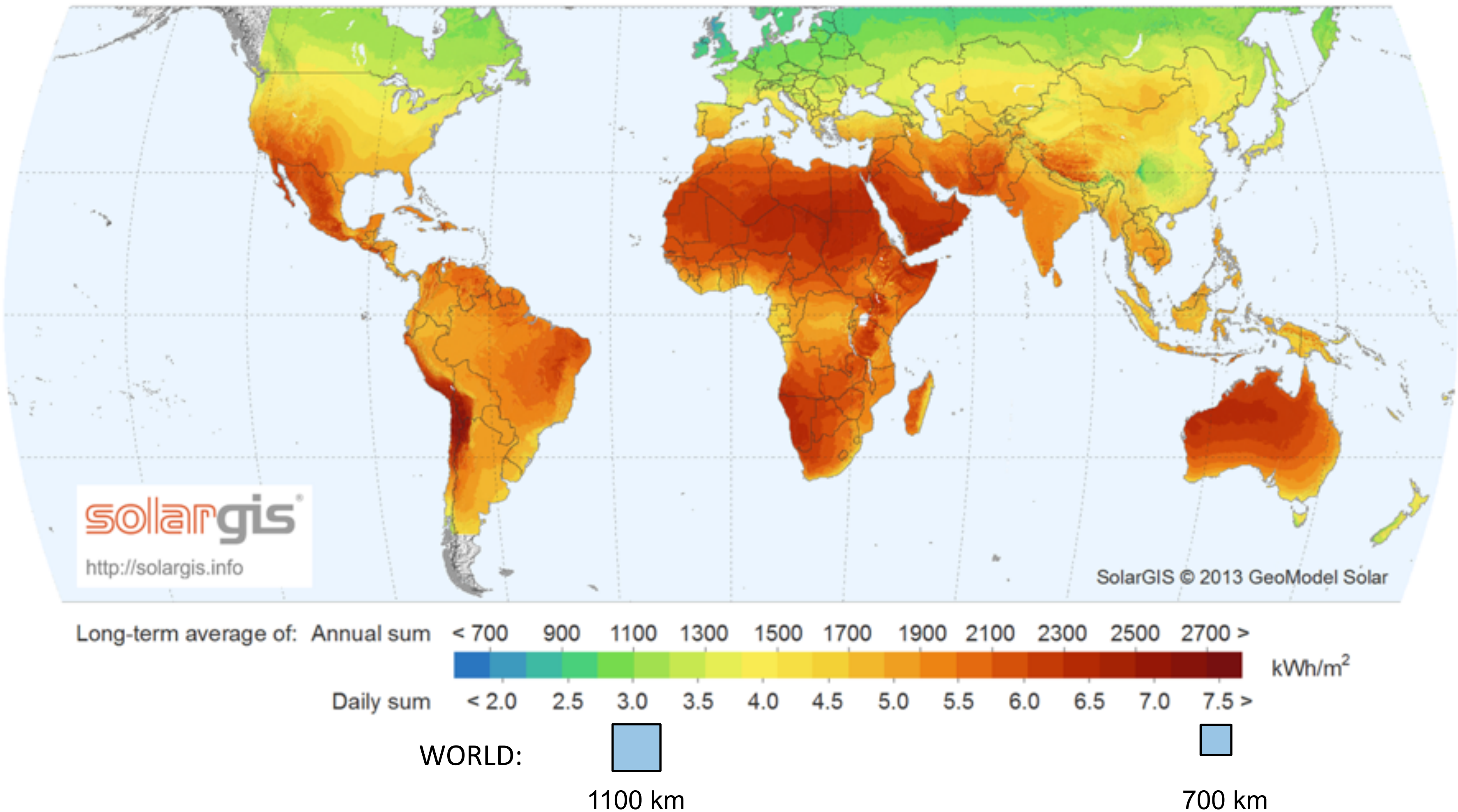
Ref.: https://ourworldindata.org/energy

11.9. AVERAGE POWER OF RENEWABLE ENERGY



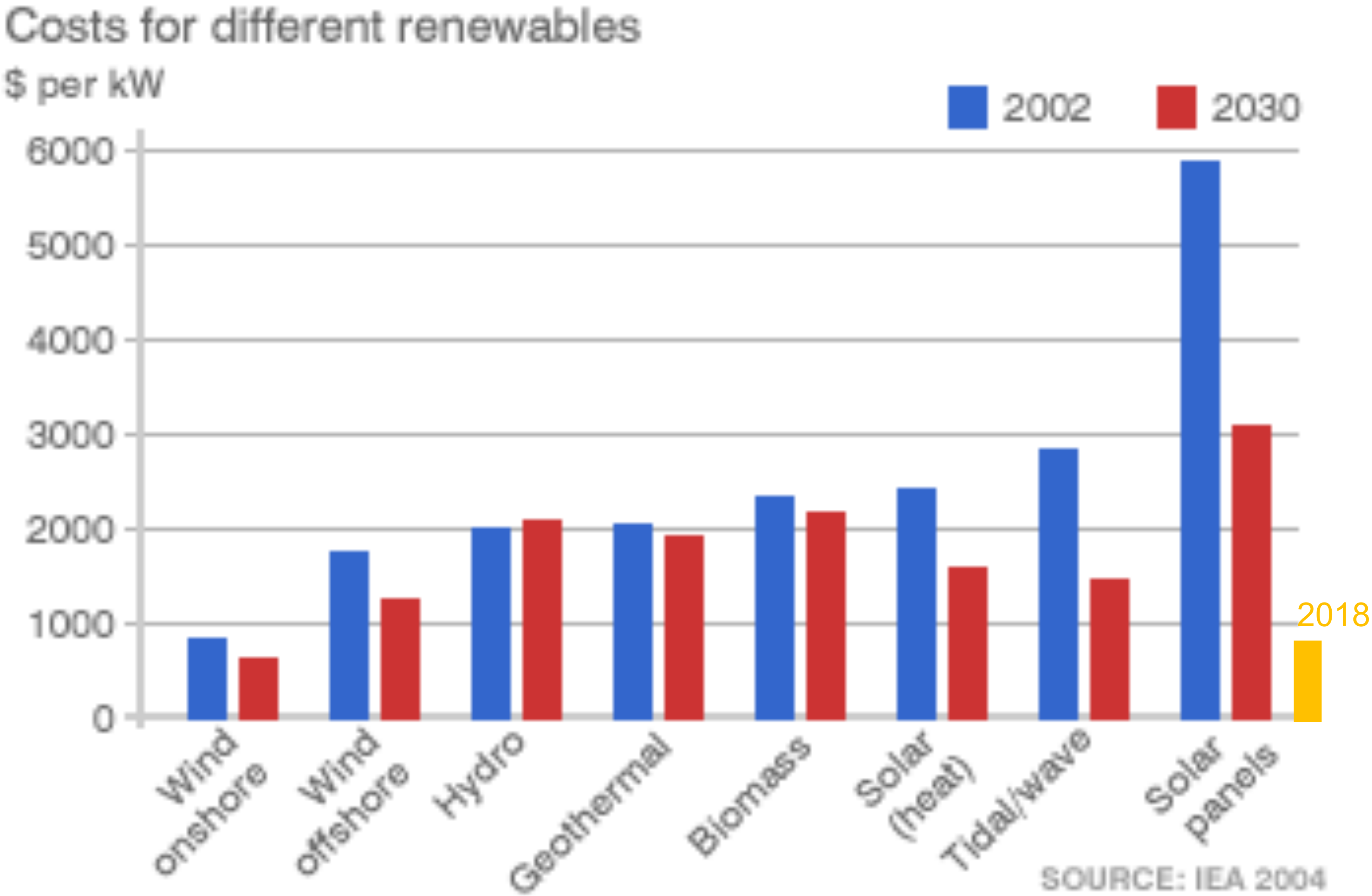
Ref.: https://ourworldindata.org/energy

11.9.1. SOLAR IRRADIATION



in CH: 166 m^2 PV per capita

11.9.2. CAPEX OF RENEWABLE ENERGY CONVERTERS



11.9.3. COST MODEL OF RENEWABLE ENERGY

$$\mathrm{COST} = \mathrm{OPEX} + \mathrm{CAPEX}$$

$$(\mathrm{CAPEX} - C_{\mathrm{back}})\cdot Z - C_{\mathrm{back}})\cdot Z - C_{\mathrm{back}})\cdot Z ... - C_{\mathrm{back}} = 0$$

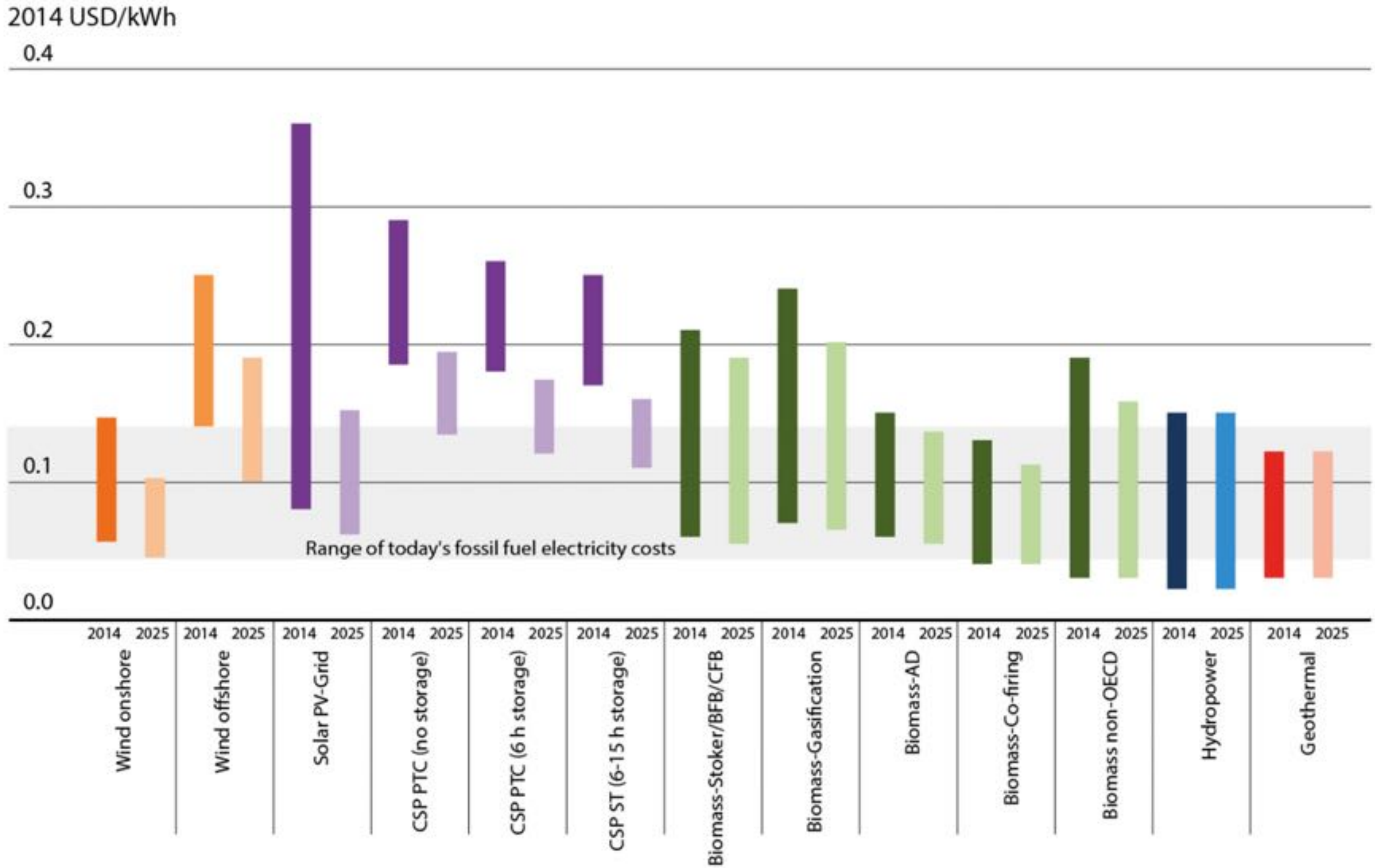
C_{back}: annual pay back
Z: annual interest
n: lifetime in years

$$C_{back} = CAPEX \frac{Z \cdot (1+Z)^n}{(1+Z)^n - 1}$$

C_E: Cost of energy
Ey: annual energy
C_C: Cost of energy input

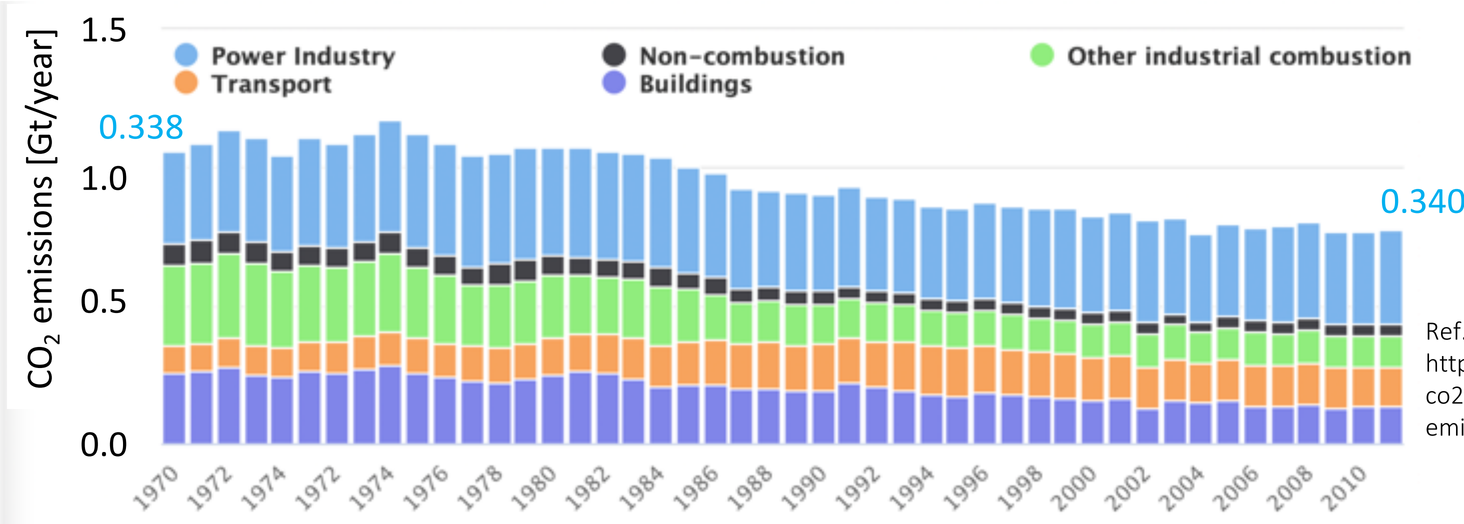
$$C_E = \frac{C_{back} + OPEX}{E_y} + \frac{C_C}{E_y}$$

11.9.4. COST OF RENEWABLE ENERGY



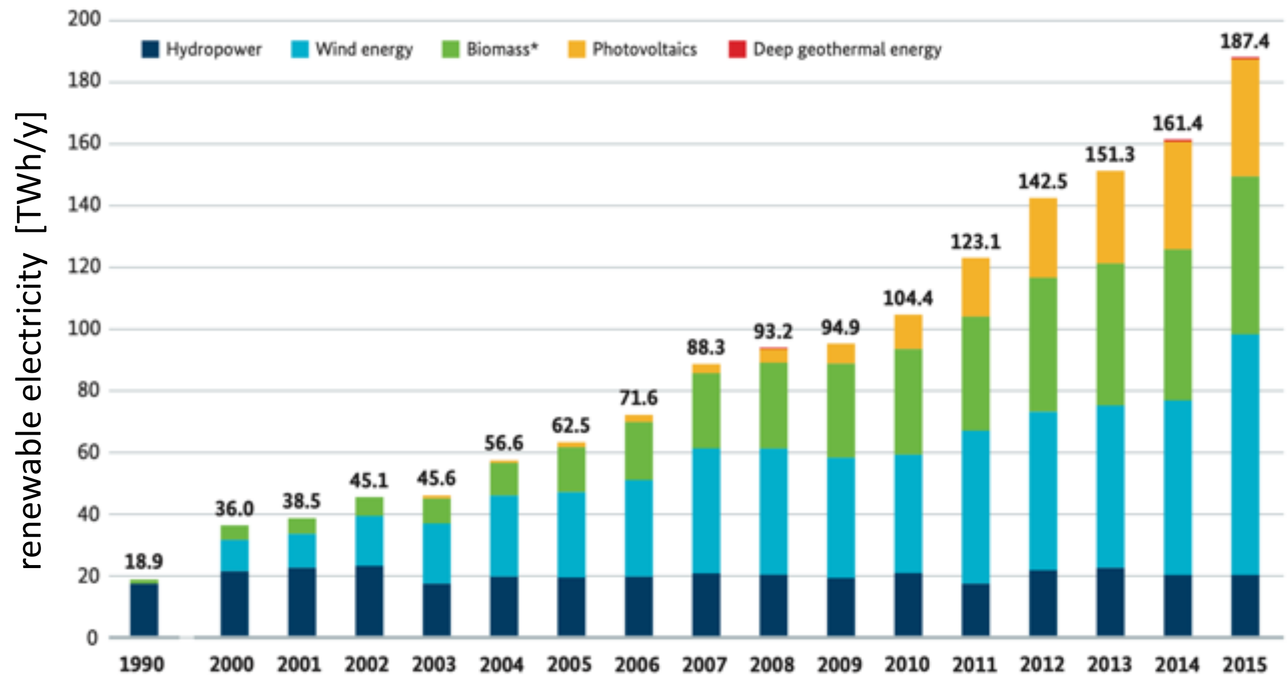
Ref.: https://www.irena.org/costs/Charts/Power-Generation-Summary

11.9.5. CO_2 EMISSION AND RENEWABLE ENERGY PRODUCTION



Ref.: https://www.worldometers.info/co2-emissions/germany-co2-emissions/

123.1 TWh corresponds to 0.181 Gt CO_2



Ref.: https://www.bmwi.de/Redaktion/EN/Downloads/Infografiken/development-of-electricity-generation-from-renewables-in-germany.pdf?__blob=publicationFile&v=2

EXERCISE

1) What measurement can you do to distinguish between a metal, semiconductor and a insulator?

2) What energy corresponds to a visible photon?

3) Calculate the size of the PV in order to cover the electricity demand for a house (2 kW).

4) Calculate the estimated growth rate per year for the installed peak power of PV.

5) Calculate the surface area of PV necessary to cover the world energy consumption.