Solar Energy (1)

Robert Pitz-Paal, DLR Institute of Solar Research

Outline

1. Why to deploy Solar Energy massively?
2. Photovoltaics Fundamentals
3. Market and Cost Situation for PV Technology
4. Conclusions

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1. **Why to deploy Solar Energy massively?**
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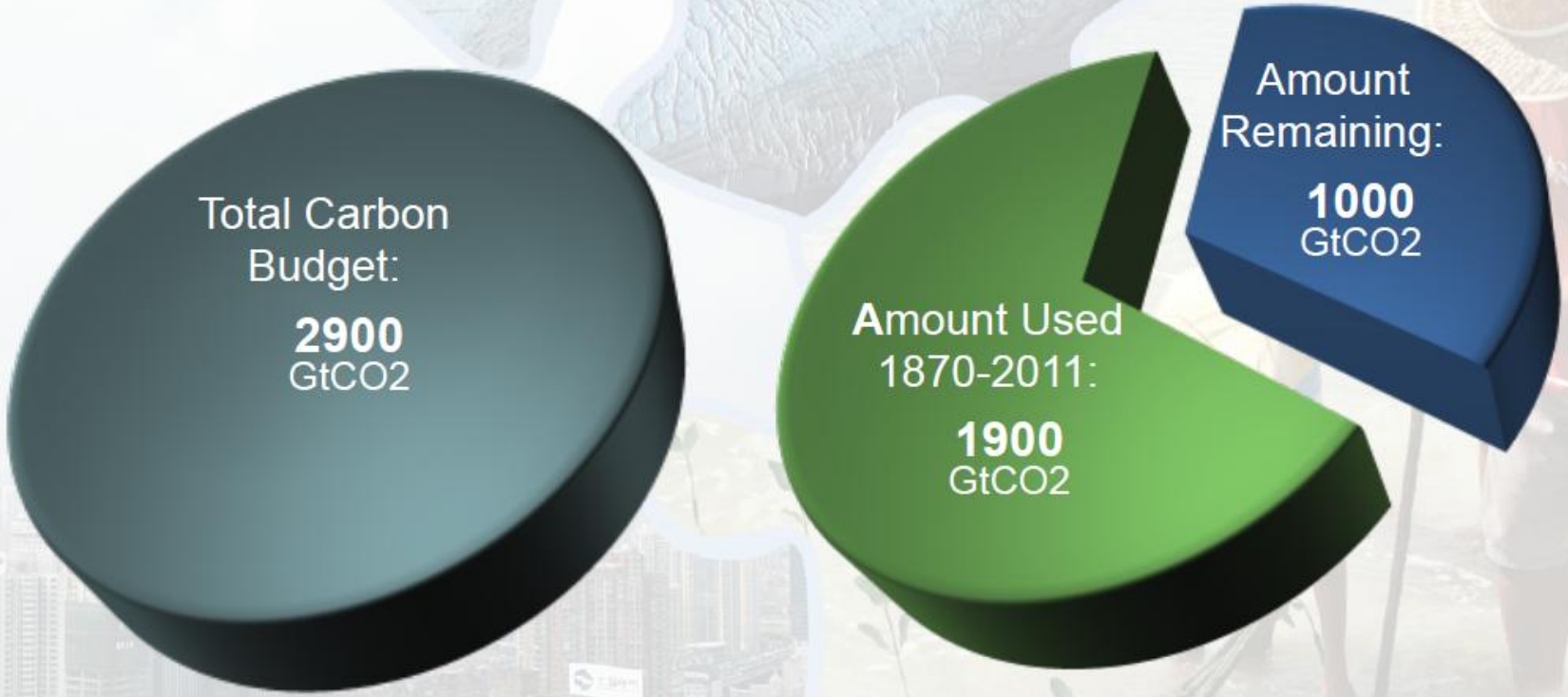
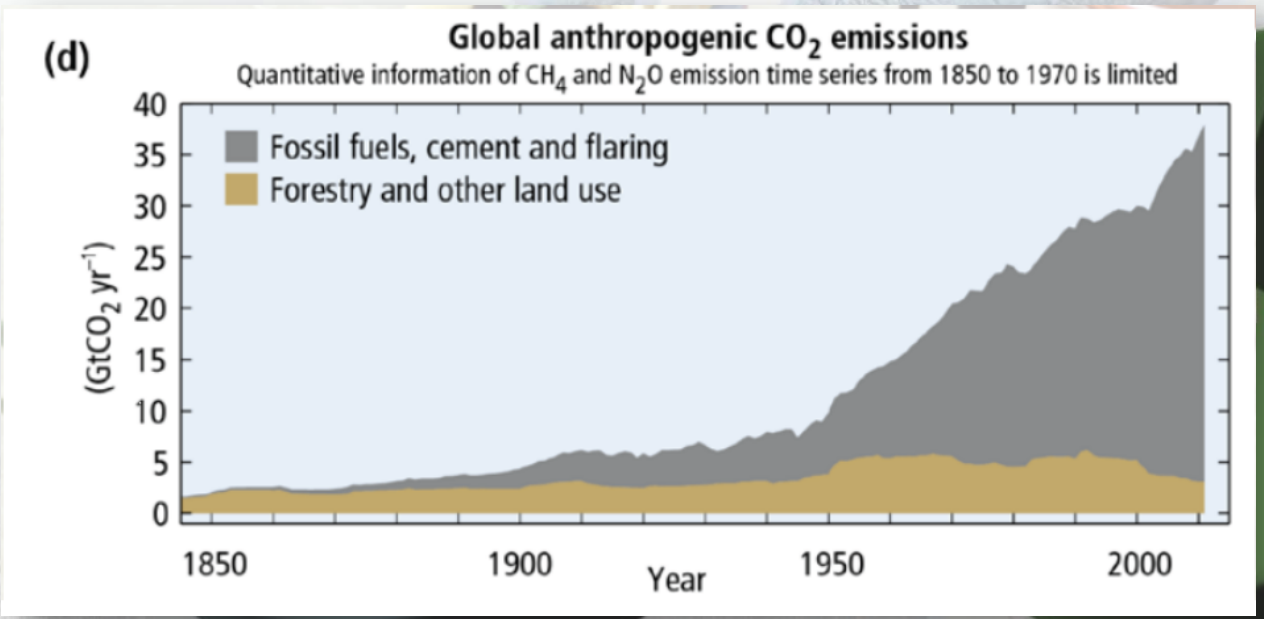
65% of our carbon budget compatible with a 2°C goal already used



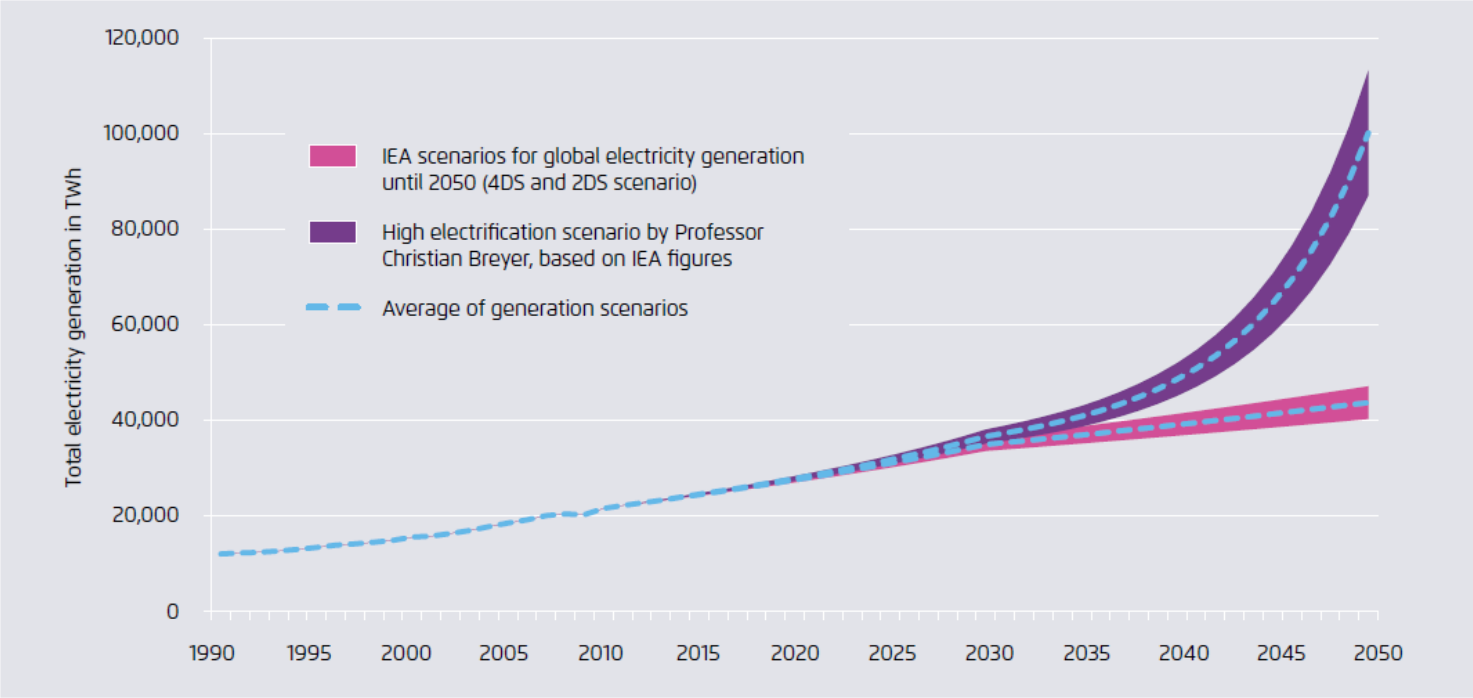
AR5 WGI SPM

65% of our carbon budget compatible with a 2°C goal already used



AR5 WGI SPM

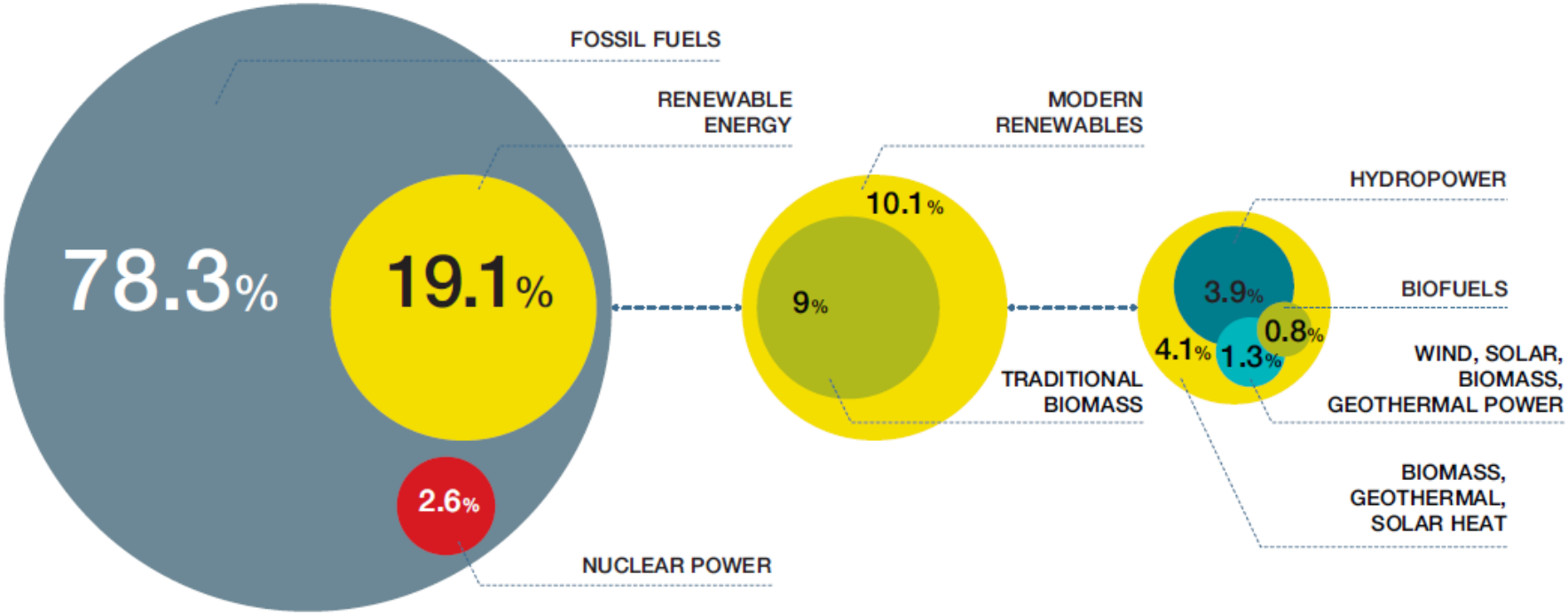
Energy demand is rising quickly: here electricity



Own illustration, data from IEA [5] [6]

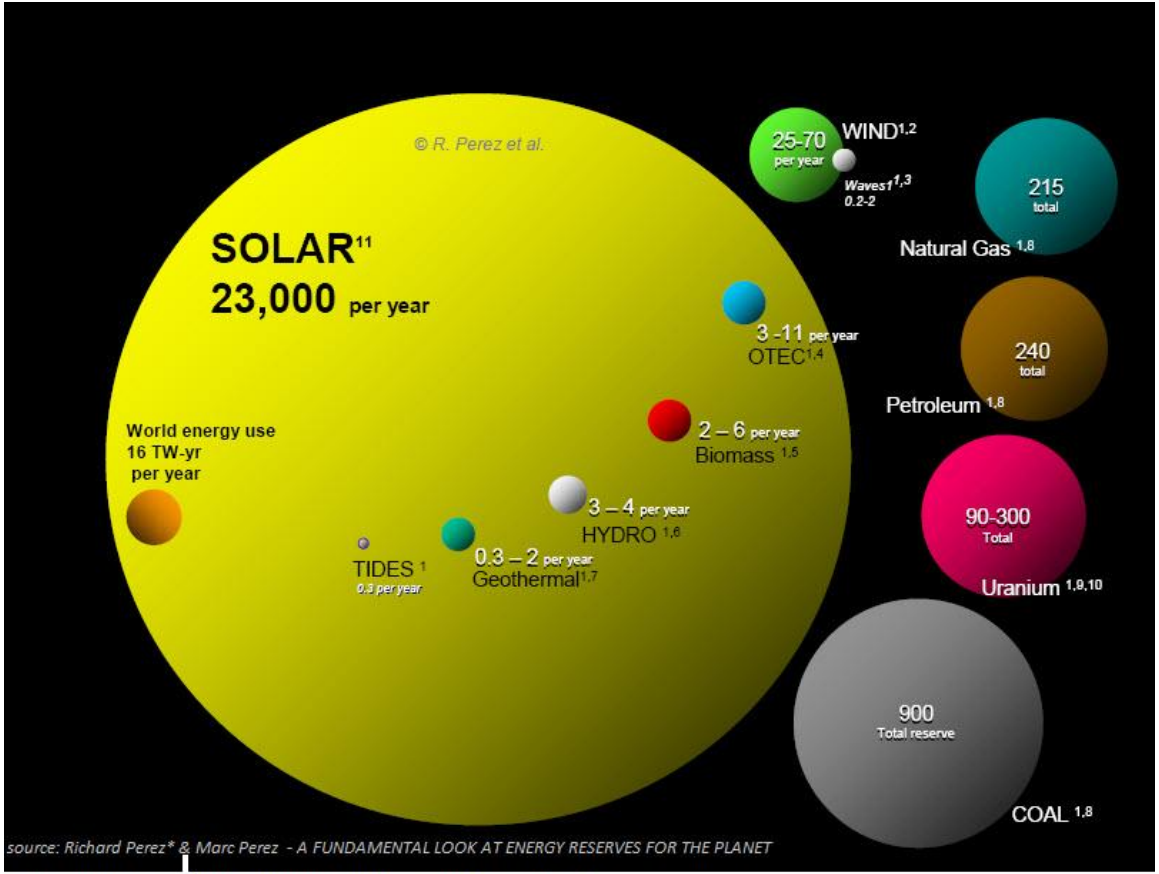
Fraunhofer ISE (2015): *Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems*. Study on behalf of Agora Energiewende

Primary Energy Use 2014



source REN21-2015.

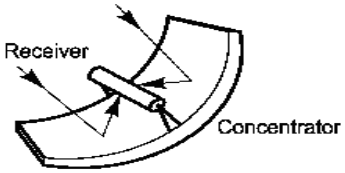
The renewable potential

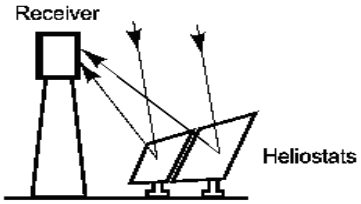


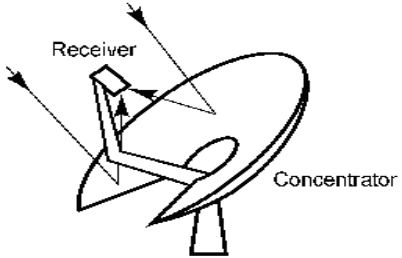
Comparing finite and renewale planetary energy reserves)Terawatt-years).
Total recoverable reserves are shown for the finate resources.

CSP versus PV

CSP

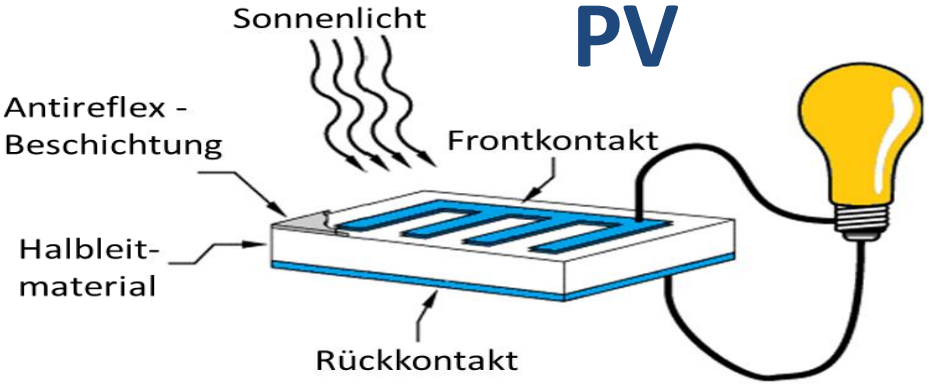






Direct Normal Irradiance (DNI) → clear sky is necessary

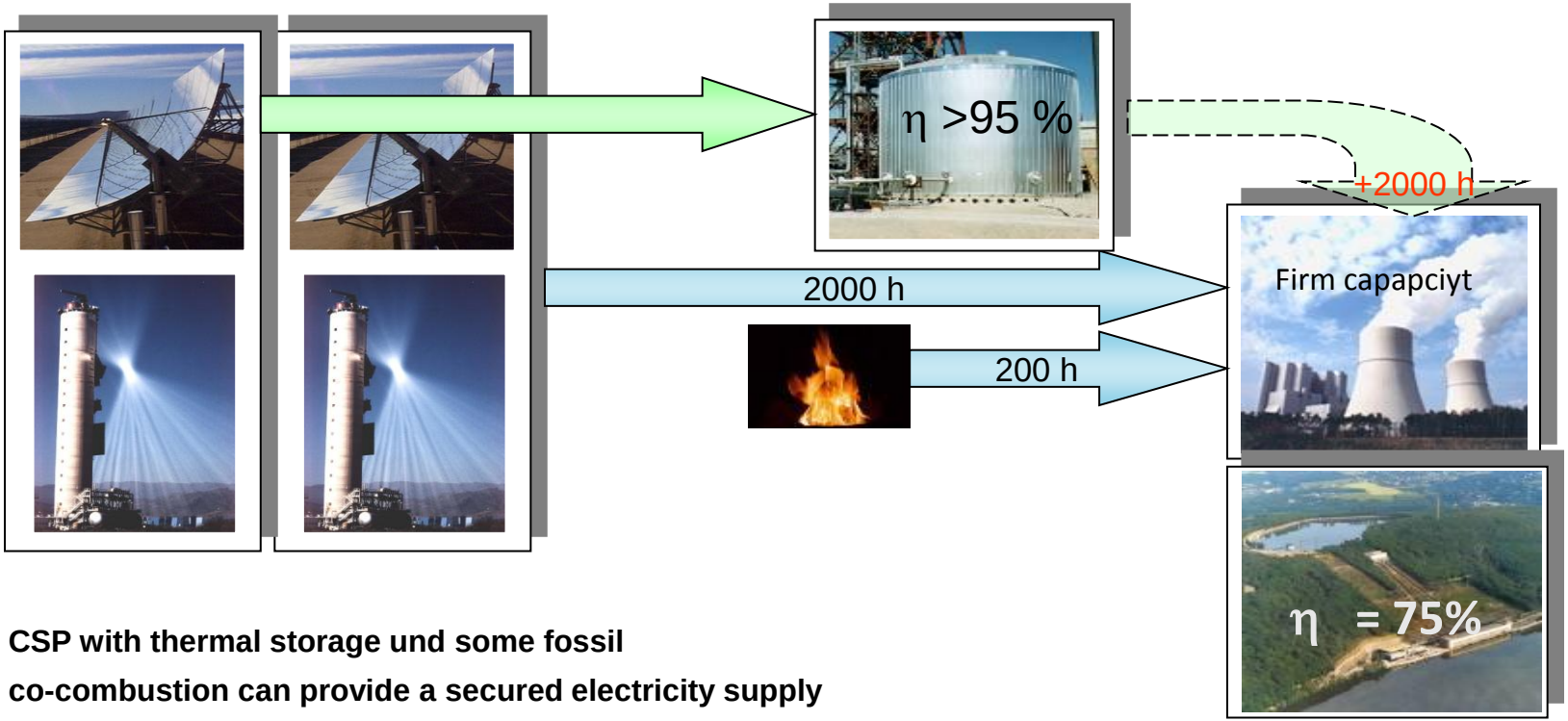
PV



DNI + diffuse radiation
→ PV-Cells als work with cloudy sky

Charakteristics		
Resource	Direct und diffuse radiation	Direct radiation
Block size	mWatt up to 100 MW	10 MW up to 100 MW
Installation:	everywhere (rooftops etc.)	Flat unused land
Capacity factor :	700 – 2000 full load hours	2000 – 7000 full load hours
Backup:	External	therm. storage + foss. Backup
Inst. Power (2015)	227 GW	5 GW
Electricity price	0,03 – 0,13 €/kWh	0,06 – 0,20 €/kWh

Thermal vs. electric storage



CSP with thermal storage und some fossil co-combustion can provide a secured electricity supply

Outline

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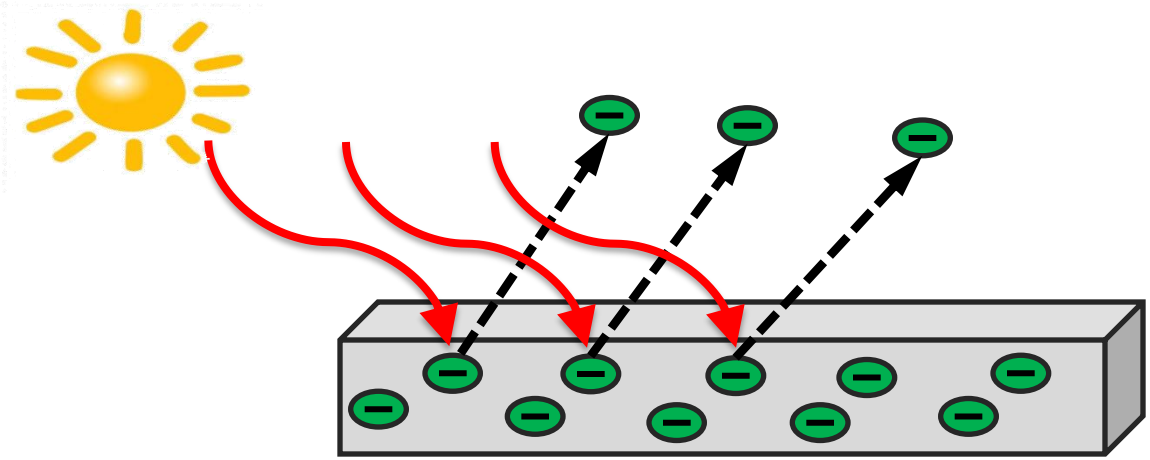
Photoelectric effect

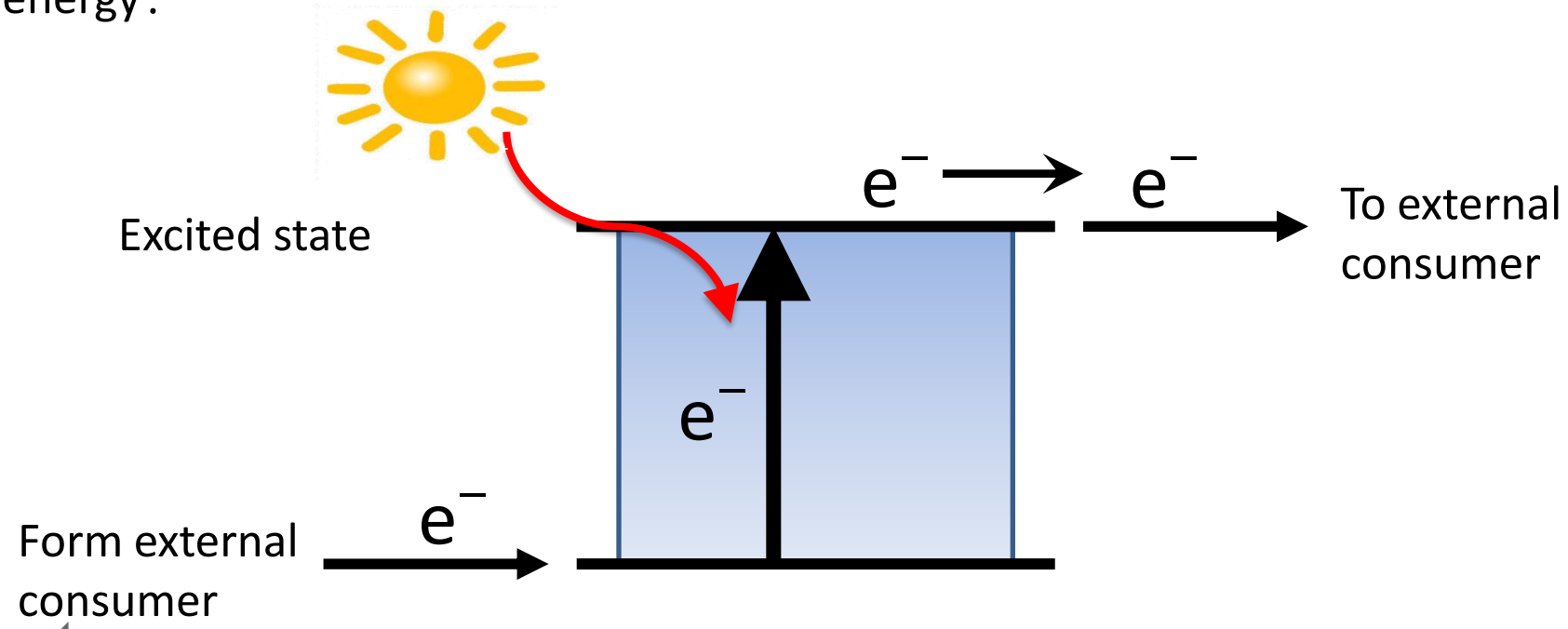
Photoelectric effect: emissions of electrons from the atom or atomic group by the action of electromagnetic radiation.

The energy distribution of the detached electrons is not determined by the intensity of the incident light, but by its frequency. The electron has the energy of the absorbed photon, which is reduced by the amount liberation energy



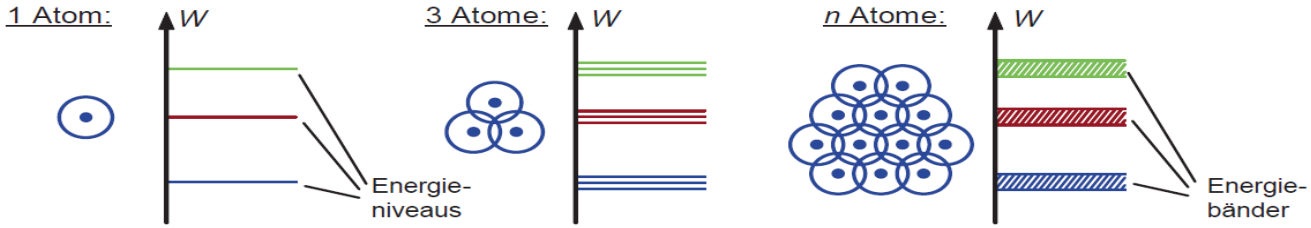
Photovoltaic effect

Photovoltaic effect: The effect of an electrical potential difference between two electrodes under light irradiation, i.e. light is directly converted into electrical energy .



Isolator - Semiconductor – Conductor

Energy bands model in solids :

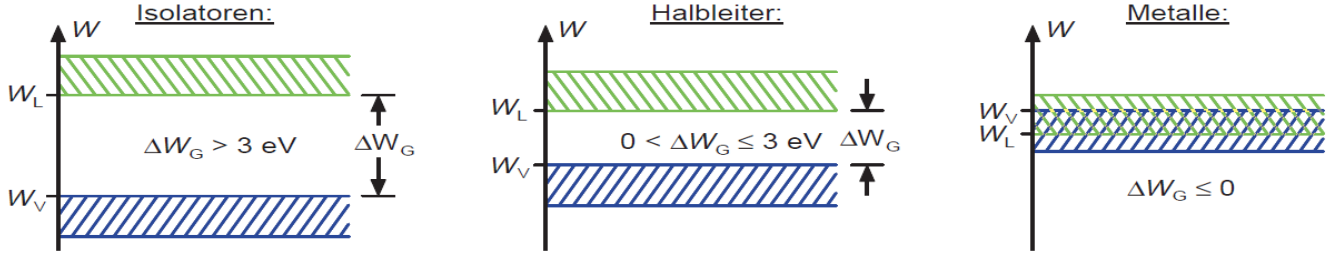


Classification of solids by their bandgap energy

Conduction band

Band gap

Valence band

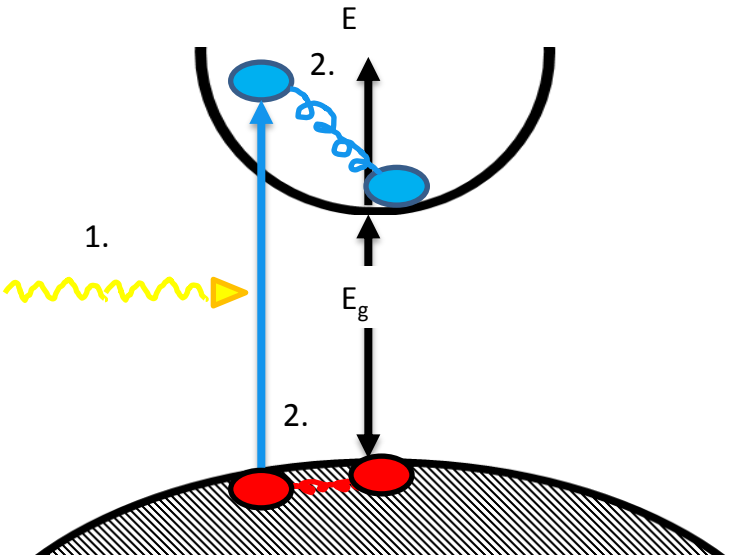


Isolator Seminconductor Conductor

Quelle: Konrad Mertens; Photovoltaik - Lehrbuch zu Grundlagen, Technologie und Praxis; HANSER, 2013

Excitation of Electrons in semiconductors

1. Absorption of light. An electron (blue) is excited with at least the bandgap energy. Generation of an electron-hole pair. (10^{-15} s)
2. The electron relaxes to the minimum band, the hole (red) to the bandmaximum. (10^{-12} s)



Electron (hole) "lives" on Band minimum (-maximum). (Up to ms range)

If no band gap were present, the excitation energy would immediately be converted into thermal energy → no metals as PV material

Quelle: Vorlesung von Prof. Dr.-Ing. Wolfgang Heering und Prof. Dr.-Ing. Uli Lemmer

Band gap energy

Planck-Einstein equation for the photon

$$E_\lambda = \frac{h\,c}{\lambda}$$

c = 2,998 * 10^8 m/s
h = 6,626 * 10^{-34} Js
1 eV = 1,602 * 10^{-19} J

Material	E_G in eV
Ge	0.7
$CuInSe_2$	1
c-Si	1.13
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 = 1.78 µm

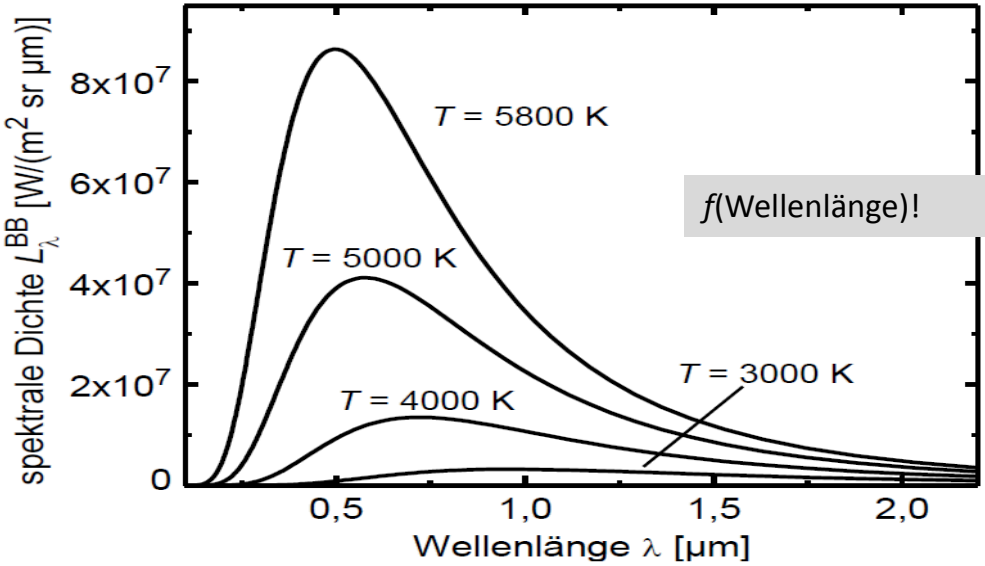
λ_G = 1.13 µm

λ_G = 0.51 µm

Quelle: Vorlesung von Prof. Dr. Aldo Steinfeld

Solar Spectrum

The solar radiation is often approximated with the radiation of a black body (BB) of 5780 or 5800 K.

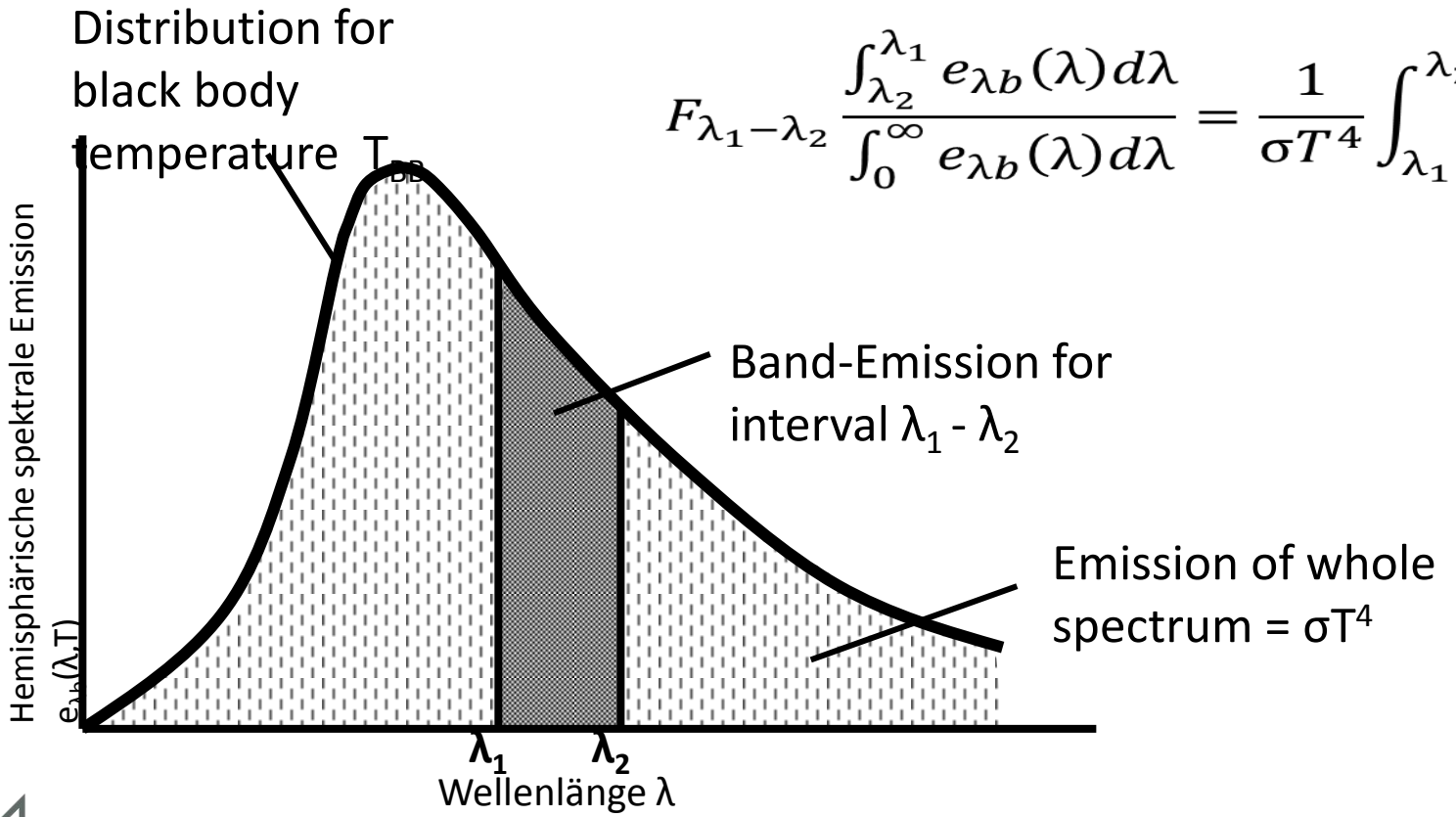


f(Wellenlänge)!

Quelle: John R. Howell; Thermal Radiation Heat Transfer; CRC Press, 2011

Fractional Function

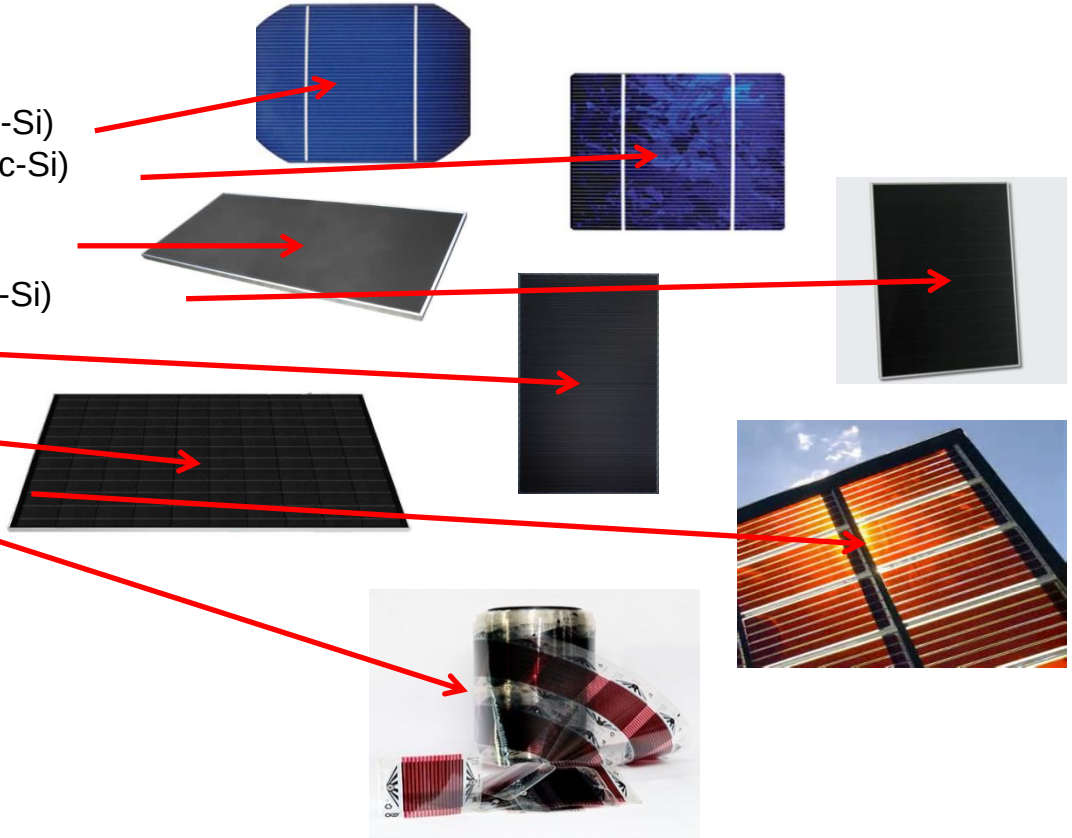
$$F_{\lambda_1-\lambda_2} \frac{\int_{\lambda_2}^{\lambda_1} e_{\lambda b}(\lambda)d\lambda}{\int_0^{\infty} e_{\lambda b}(\lambda)d\lambda} = \frac{1}{\sigma T^4}\int_{\lambda_1}^{\lambda_2} e_{\lambda b}(\lambda)d\lambda$$



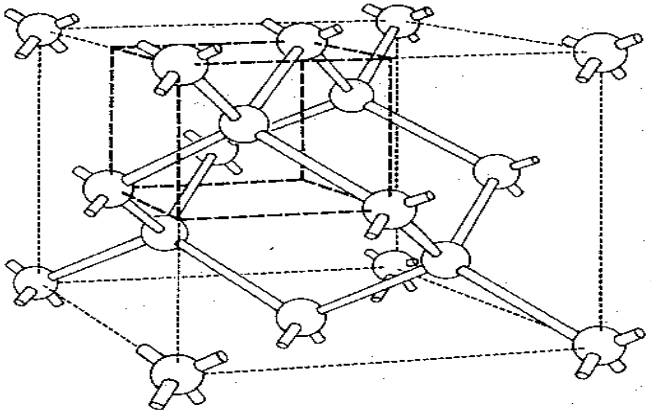
Quelle: John R. Howell; Thermal Radiation Heat Transfer; CRC Press, 2011

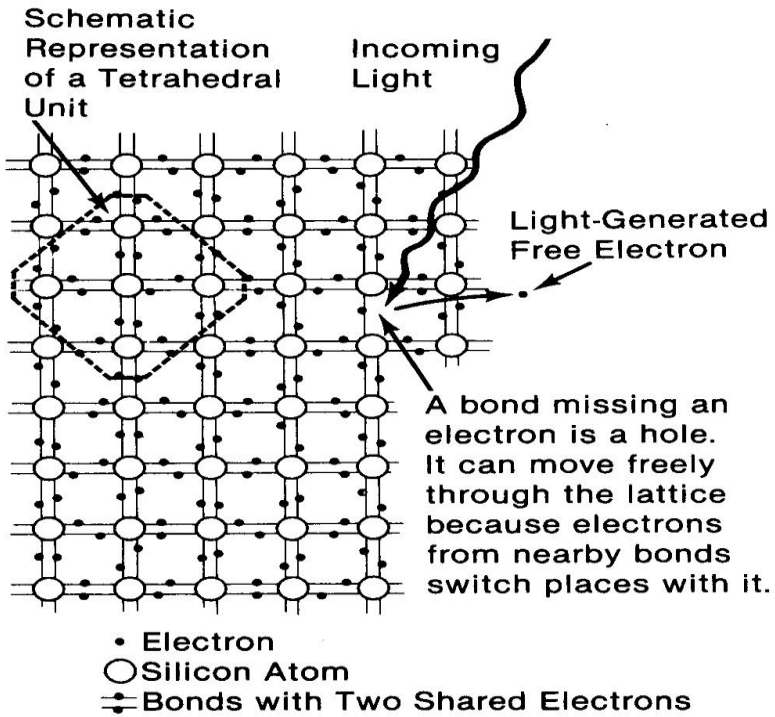
Types of solar cells

- Thick film solar cells
  - Mono crystalline silicon (c-Si)
  - Multi crystalline silicon (mc-Si)
- Thin film solar cells
  - amorphous silicon (a-Si)
  - Micro crystalline silicon (c-Si)
  - CdTe
  - GaAs
  - CIGS
- Dye solar cells (Grätzel-Zelle)
- Organic solar cells



Silicon crystal structure





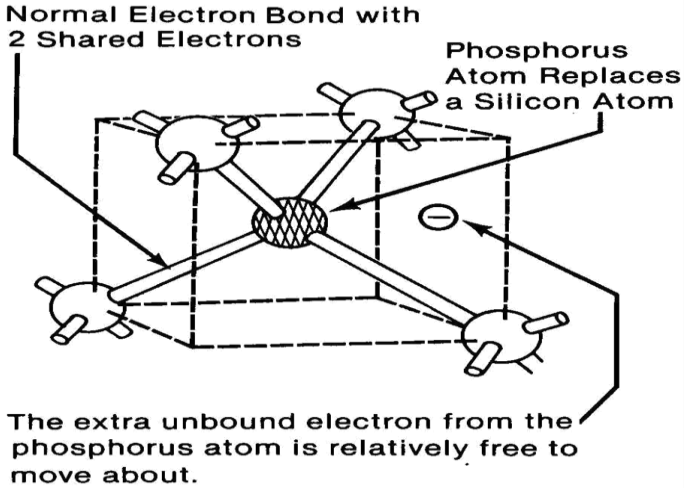
Quelle: NREL, Basic Photovoltaic Principles and Methods, 1981

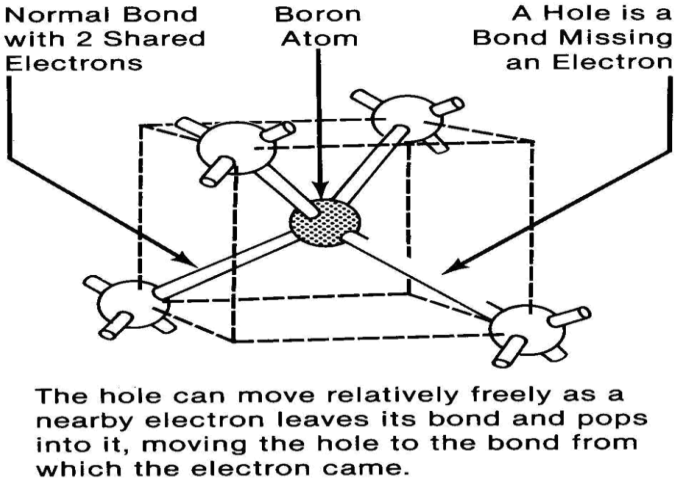
Si-atoms has 4 covalent bonds.

Incident photons excite electrons from valence band to conduction band

Electrons & wholes move in the crystal lattice until they recombine .

Silicon lattice doping





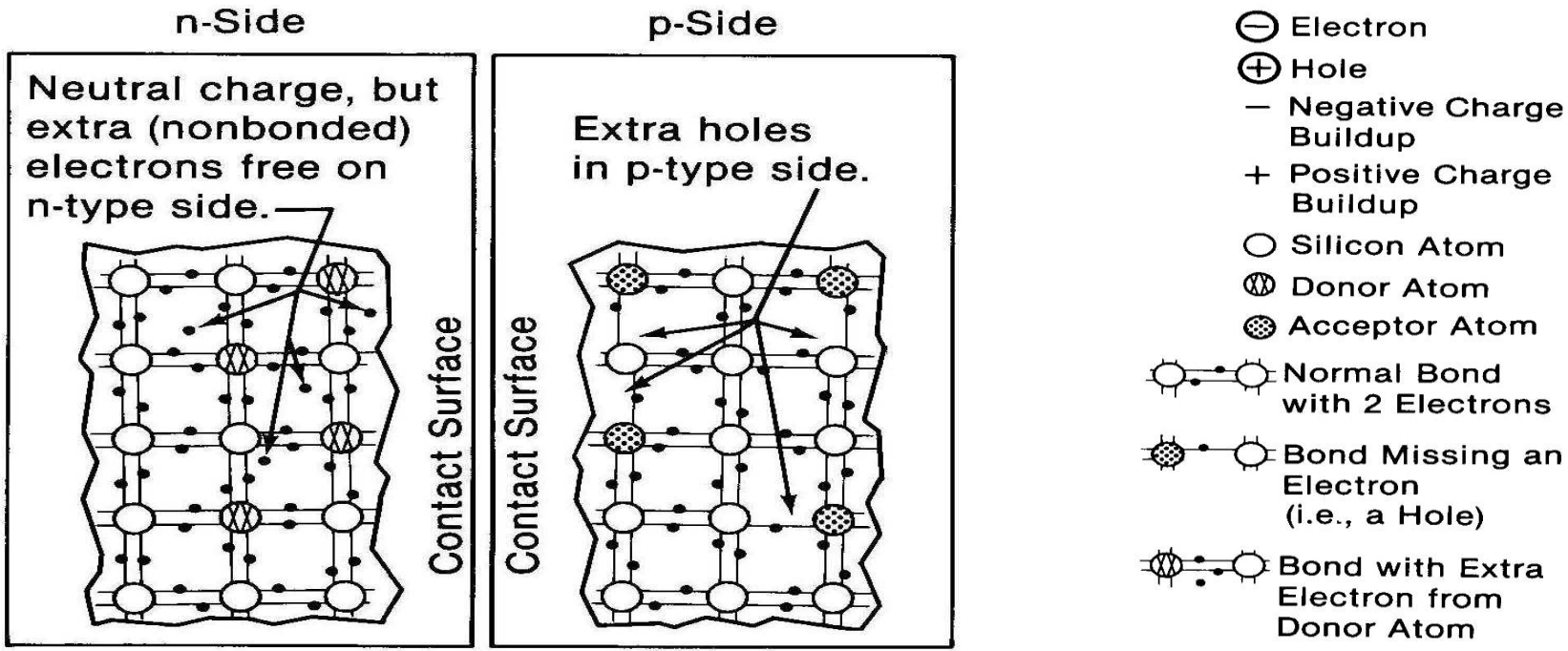
The semiconductor material is contaminated with atoms of another element group to provide n-type and p-type crystals.

Excess electrons (or holes) move freely in n-type crystals (or p-type crystals).

IMPORTANT: Both doped materials are electrically neutral!

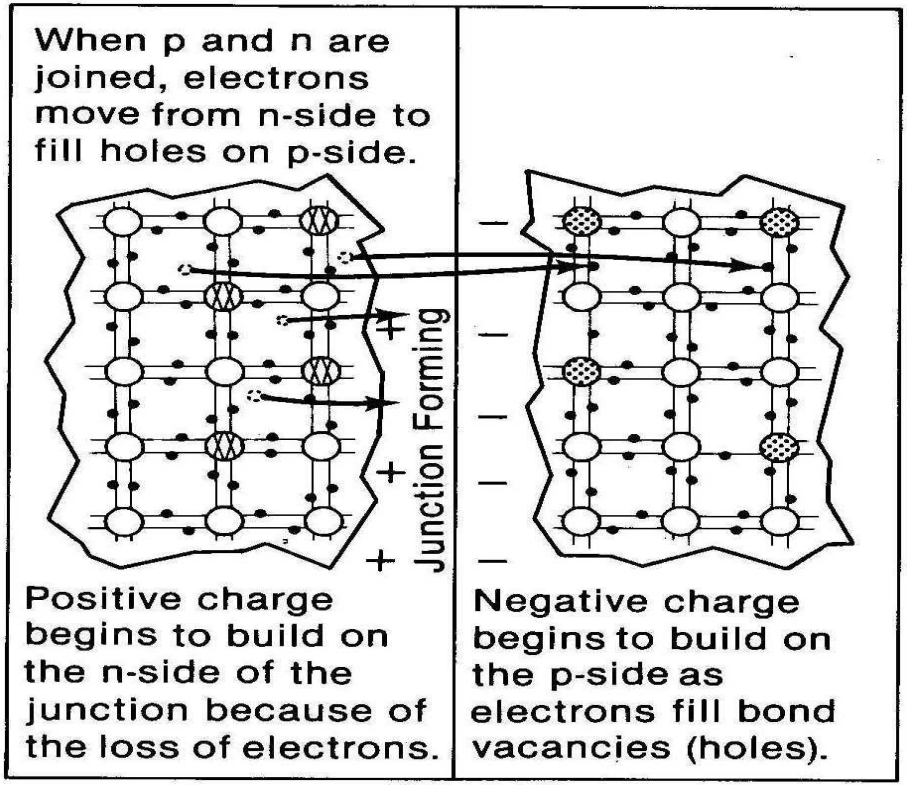
Quelle: NREL, Basic Photovoltaic Principles and Methods, 1981

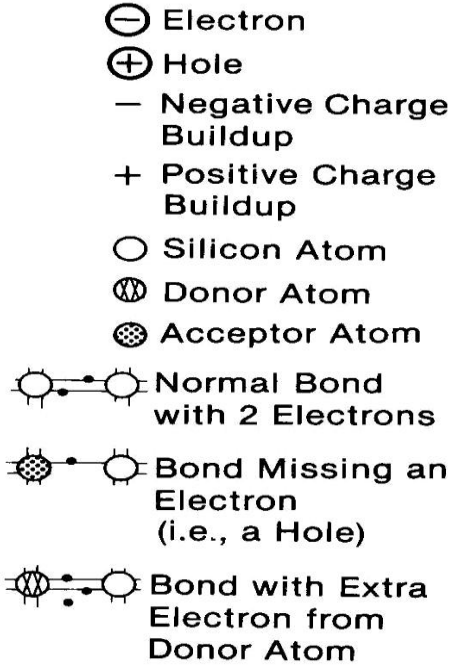
pn-junction – 1/4



Quelle: NREL, Basic Photovoltaic Principles and Methods, 1981

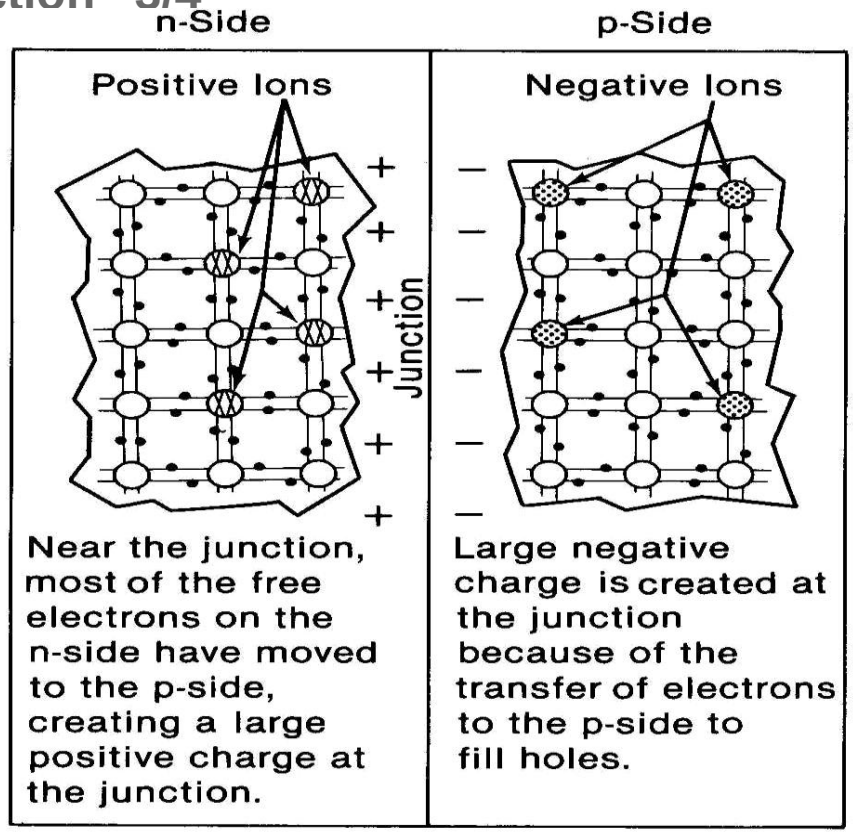
pn-junction– 2/4

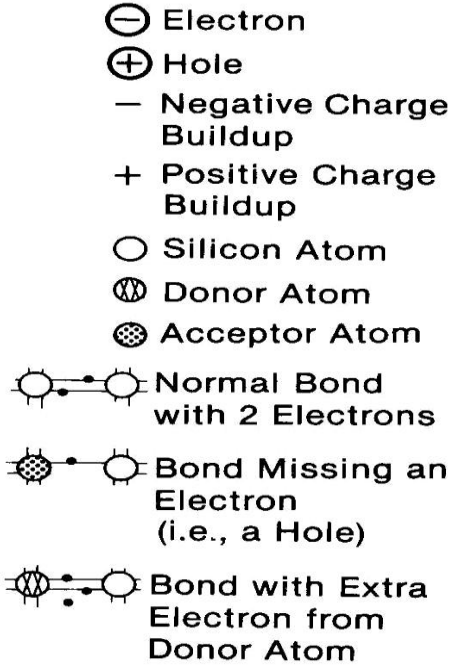




Quelle: NREL, Basic Photovoltaic Principles and Methods, 1981

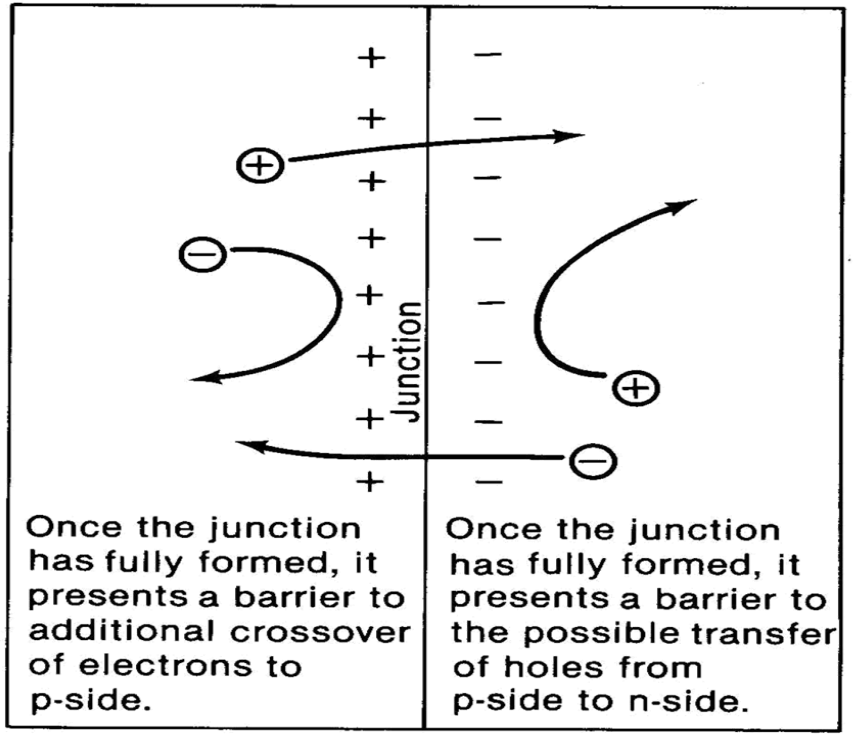
pn-junction– 3/4

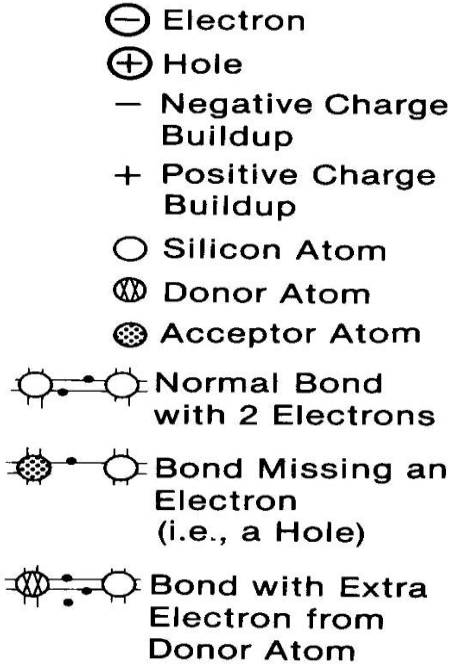




Quelle: NREL, Basic Photovoltaic Principles and Methods, 1981

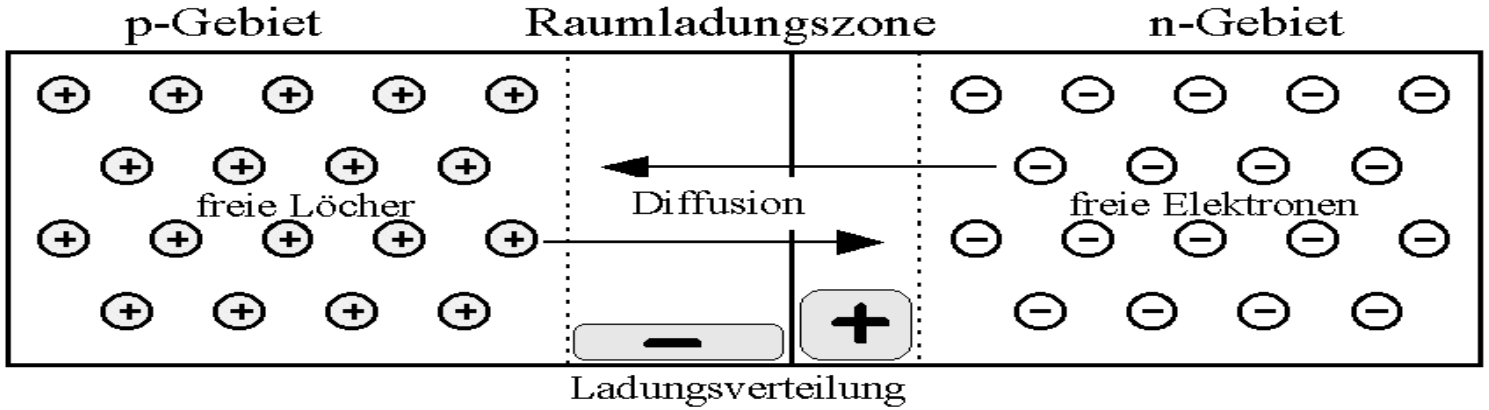
er pn-junction – 4/4



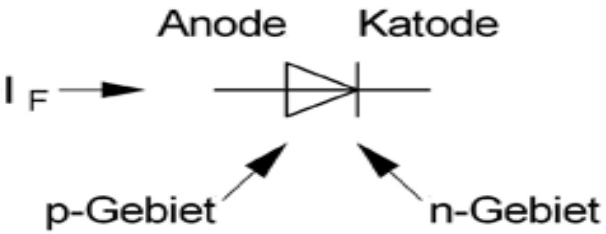


Quelle: NREL, Basic Photovoltaic Principles and Methods, 1981

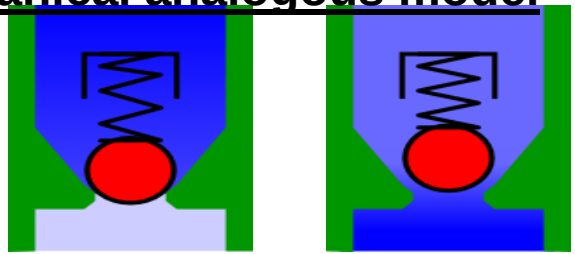
PN-diode: Space charge region



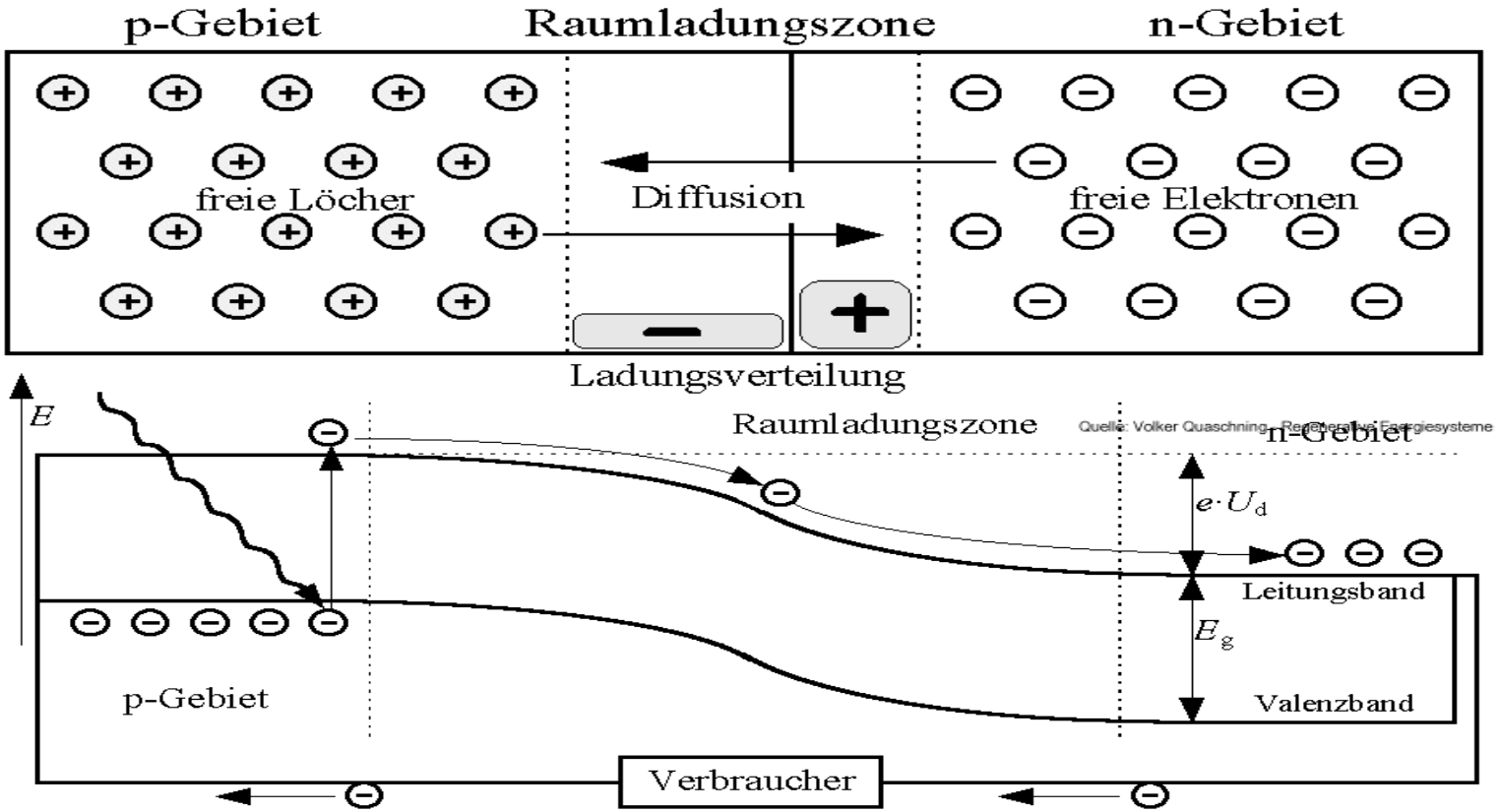
Quelle: Volker Quaschning - Regenerative Energiesysteme



Mechanical analogous model



Energy Band Modell

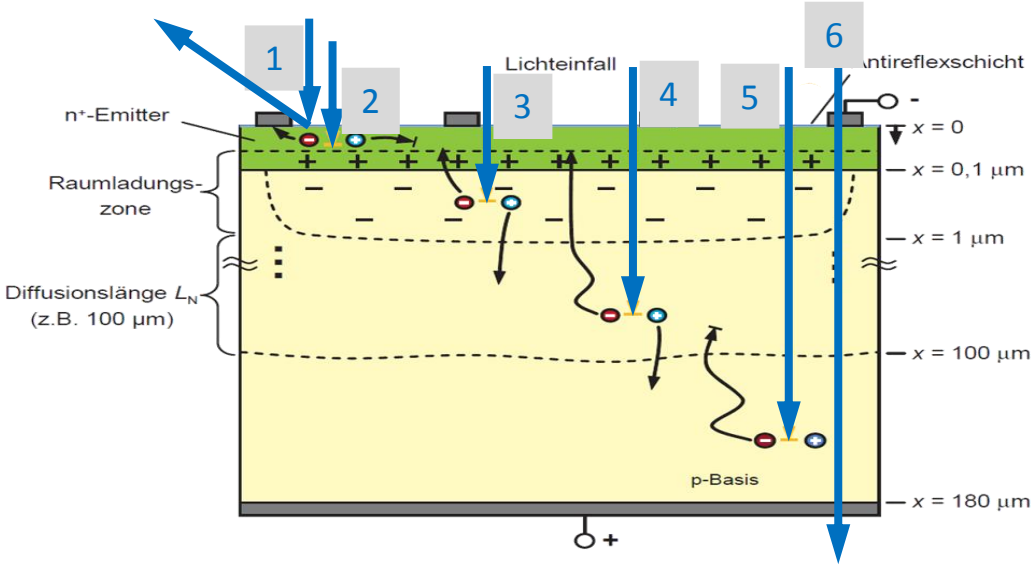


Quelle: Volker Quaschning - Regenerative Energiesysteme

Absorption – practical application – 1/6

Reflection on the surface

Let us first consider Photon 1. It is reflected in spite of the antireflection layer and does not contribute to energy conversion.



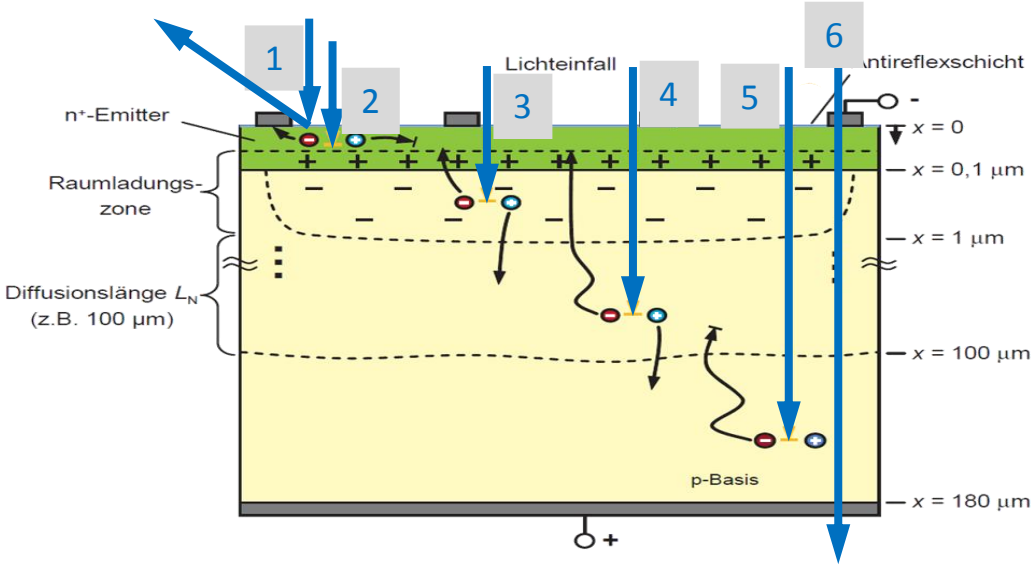
Quelle: Konrad Mertens; Photovoltaik - Lehrbuch zu Grundlagen, Technologie und Praxis; HANSER, 2013

Absorption – practical application – 2/6

Absorption in the emitter

Let us consider Photon 2. It is absorbed within the highly doped emitter.

Due to the high doping, the diffusion length is extremely small, so the generated hole most probably recombines before reaching the space charge zone.

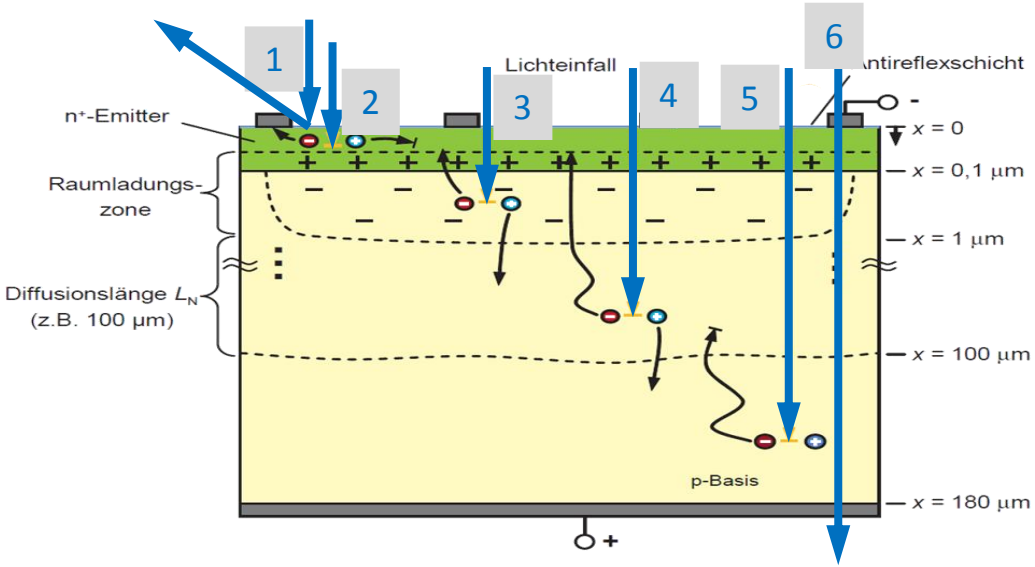


Quelle: Konrad Mertens; Photovoltaik - Lehrbuch zu Grundlagen, Technologie und Praxis; HANSER, 2013

Absorption – practical application – 3/6

Absorption in the space charge zone

The absorption of the photon 3 takes place here within the space charge zone. The field prevailing in the space charge zone separates the generated electron-hole pair and drives the two charge carriers in different directions. The electron is driven to the n-domain and then to the minius contact of the solar cell.

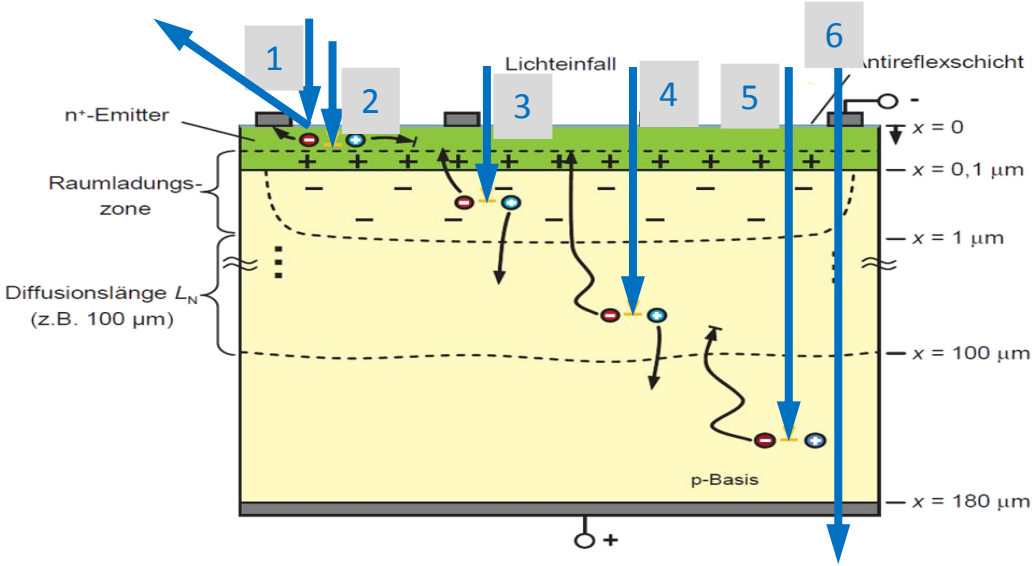


Quelle: Konrad Mertens; Photovoltaik - Lehrbuch zu Grundlagen, Technologie und Praxis; HANSER, 2013

Absorption – practical application – 4/6

Absorption within the diffusion length of the electrons

Photon 4 is only absorbed deep into the solar cell. The generated electron is not in an electric field but diffuses "aimlessly" through the crystal. If it happens to arrive near the n-side it can flow to the contact.

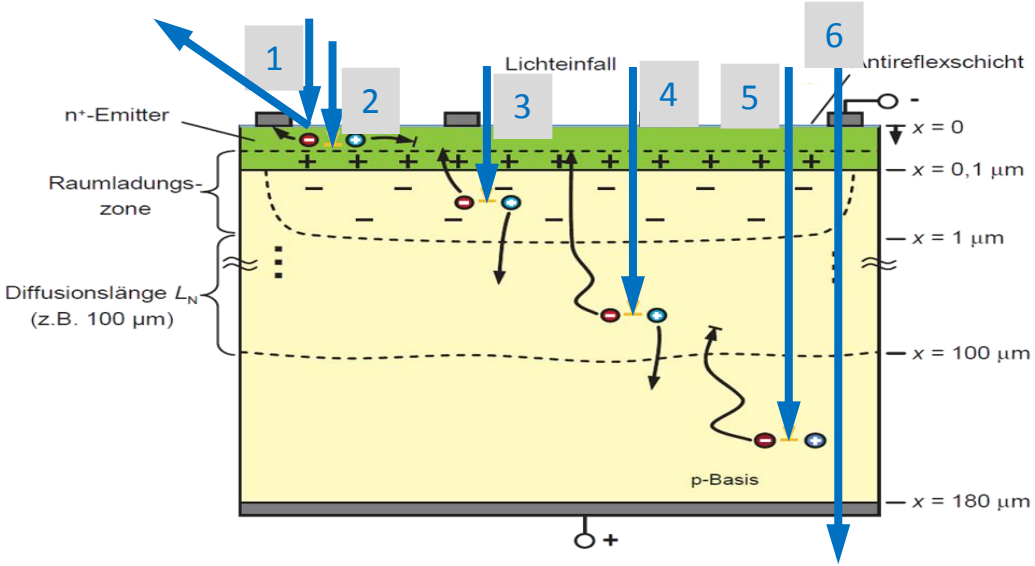


Quelle: Konrad Mertens; Photovoltaik - Lehrbuch zu Grundlagen, Technologie und Praxis; HANSER, 2013

Absorption – practical application – 5/6

Absorption outside the diffusion length of the electrons

A real loser is Photon 5, which is absorbed only in the lower region of the solar cell. The electron diffuses through the p-base, but recombines with a hole before it could reach the space charge zone.

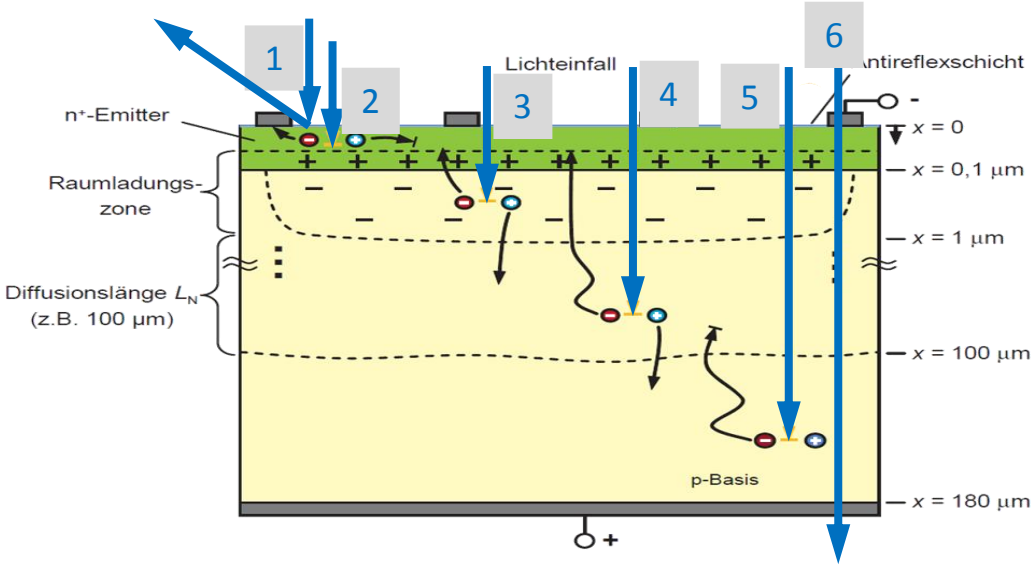


Quelle: Konrad Mertens; Photovoltaik - Lehrbuch zu Grundlagen, Technologie und Praxis; HANSER, 2013

Absorption – practical application – 6/6

Transmission

Finally, photon 6 is not absorbed at all in the thickness of the solar cell and transmitted without having formed an electron-hole pair.



Quelle: Konrad Mertens; Photovoltaik - Lehrbuch zu Grundlagen, Technologie und Praxis; HANSER, 2013

Shockley-Queisser Limit – 1/2

Theoretical limit for photovoltaic cells, calculated in 1961 by William Shockley and Hans Queisser.

Part of the limitation is the spectral efficiency

$$\eta_\lambda = \frac{\Delta W_G}{E_{solar} * h * c} * \int_0^{\lambda_G} E_\lambda(\lambda) * \lambda * d\lambda$$

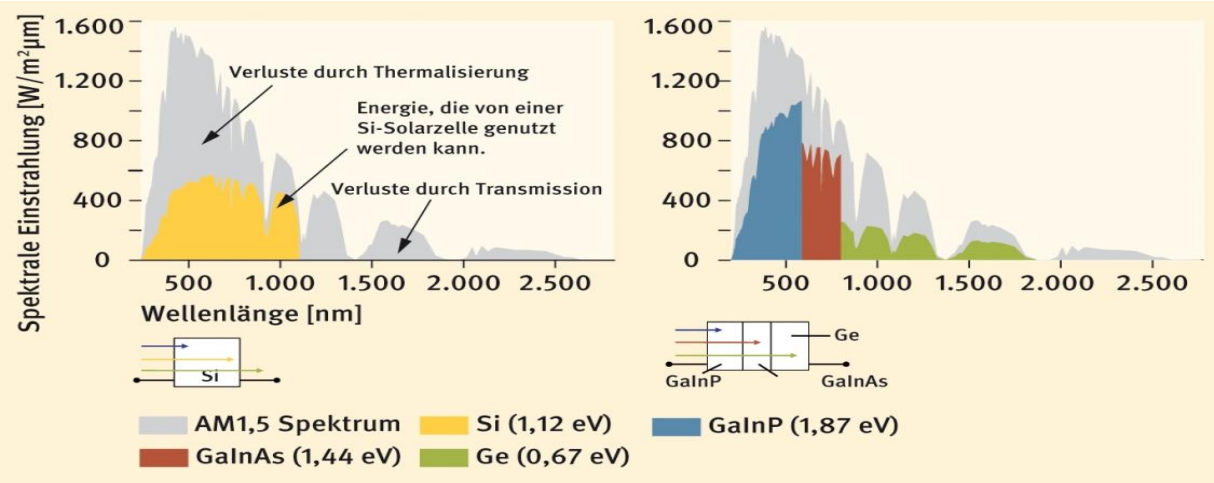
spectral loss of silcon PV cell

[1]: Heinrich Häberlin; Photovoltaik – Strom aus Sonnenlicht für Verbundnetz und Inselanlagen; VDE Verlag, 2010
Grafik: Konrad Mertens; Photovoltaik - Lehrbuch zu Grundlagen, Technologie und

Multijunction PV-Cells

- Multiple pn junctons with tuned bandgaps, which absorb the irradiation over a broader spectrum → higher efficiency
- Shockley-Queisser Limit only valid for a single pn-junction [1]
  - 1-jct. (Shockley-Queisser Limit): 30%
  - 2-jct.: 42%
  - 3-jct.: 49%
  - ∞-jct.: 68%

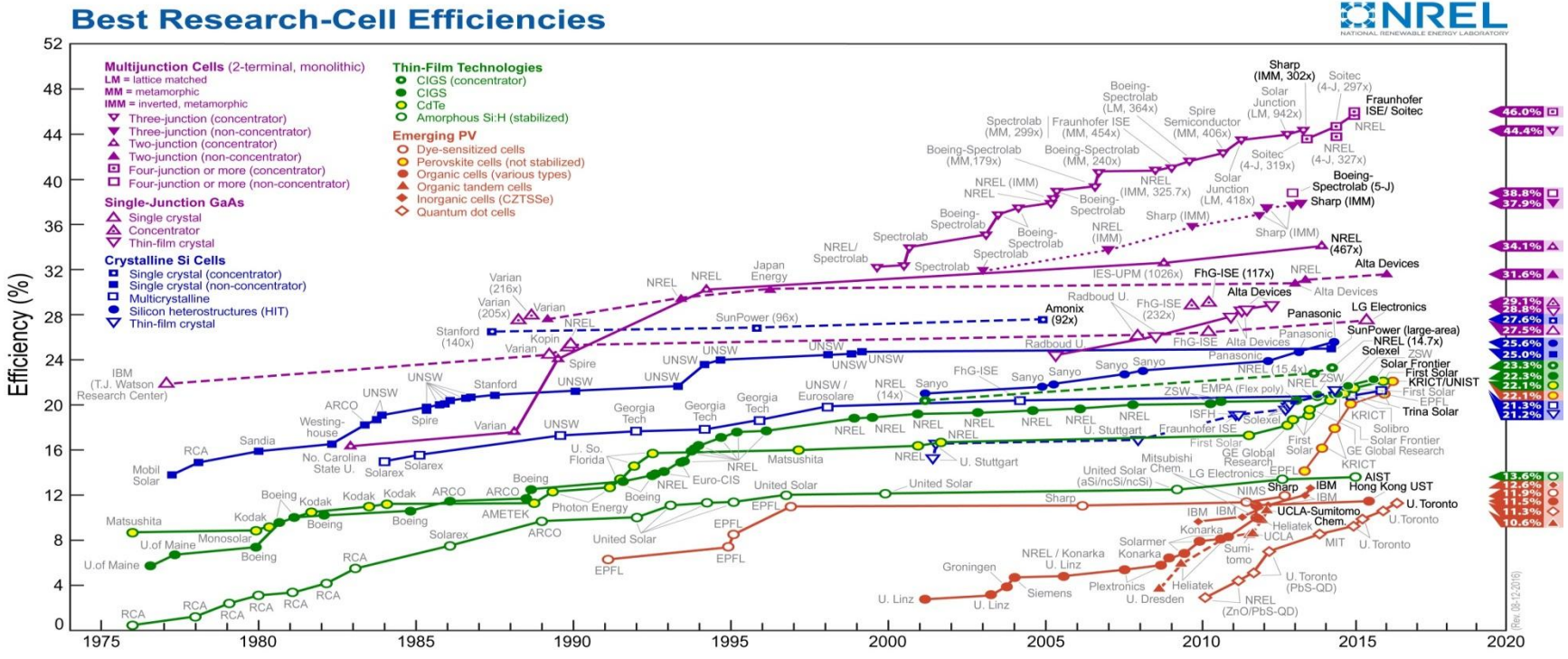
- Higher cost per area for multi-junction cells



[1]: Alexis De Vos; Detailed Balance Limit of the Efficiency of Tandem Solar Cells; *J. Phys. D*; 13 (1980) 839-46
Grafik: http://www.bine.info/publikationen/publikation/energie-von-tausend-

Wirkungsgrad

$$\eta = \frac{P_{el}}{P_{solar}} = \frac{P_{MPP}}{E_{solar} * A_{cell}} = \frac{FF * U_L * I_K}{E_{solar} * A_{cell}}$$



Grafik: http://www.nrel.gov/ncpv/images/efficiency_chart.jpg , letzter Zugriff 09.11.2016

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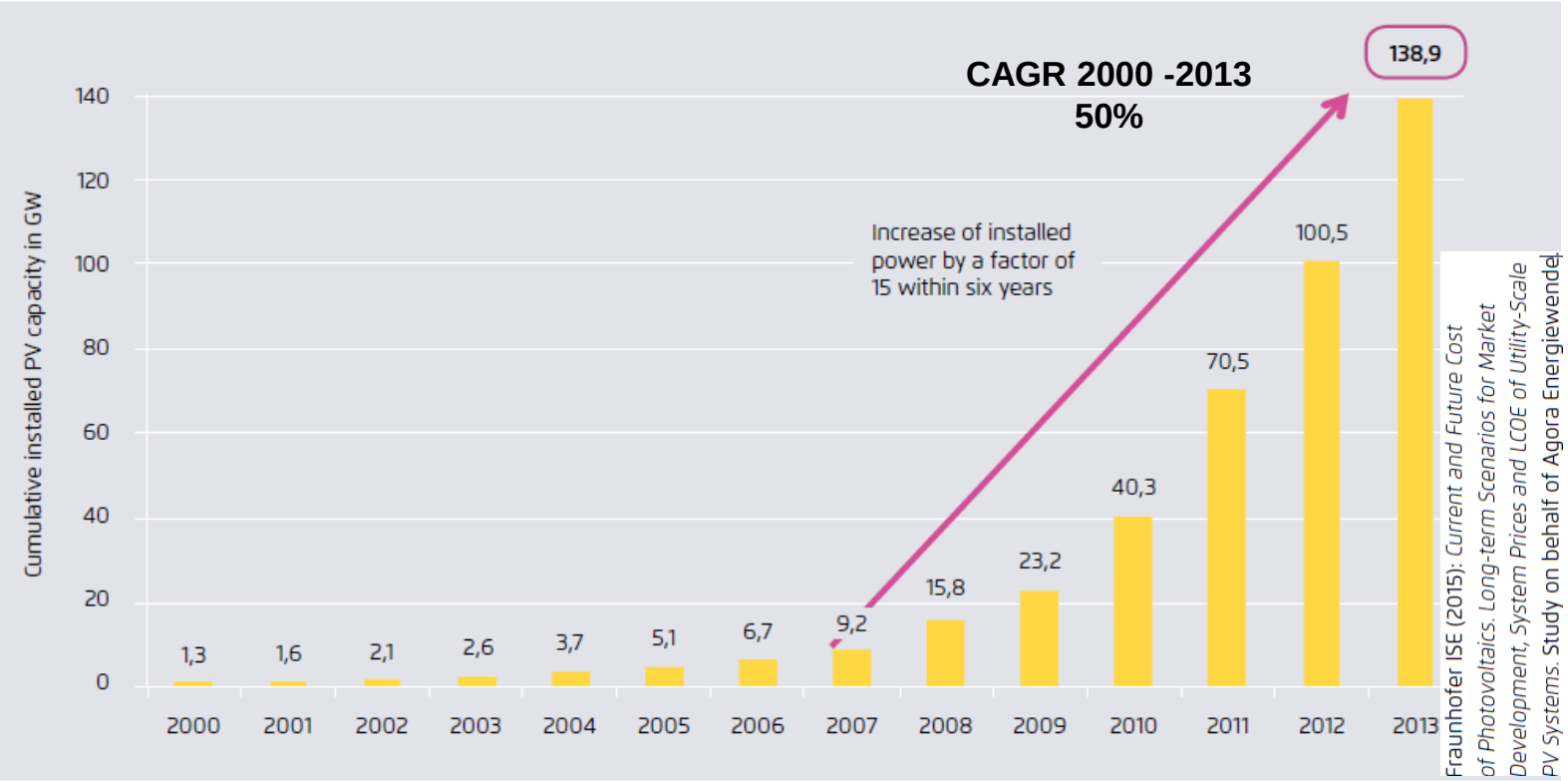
4. Conclusions

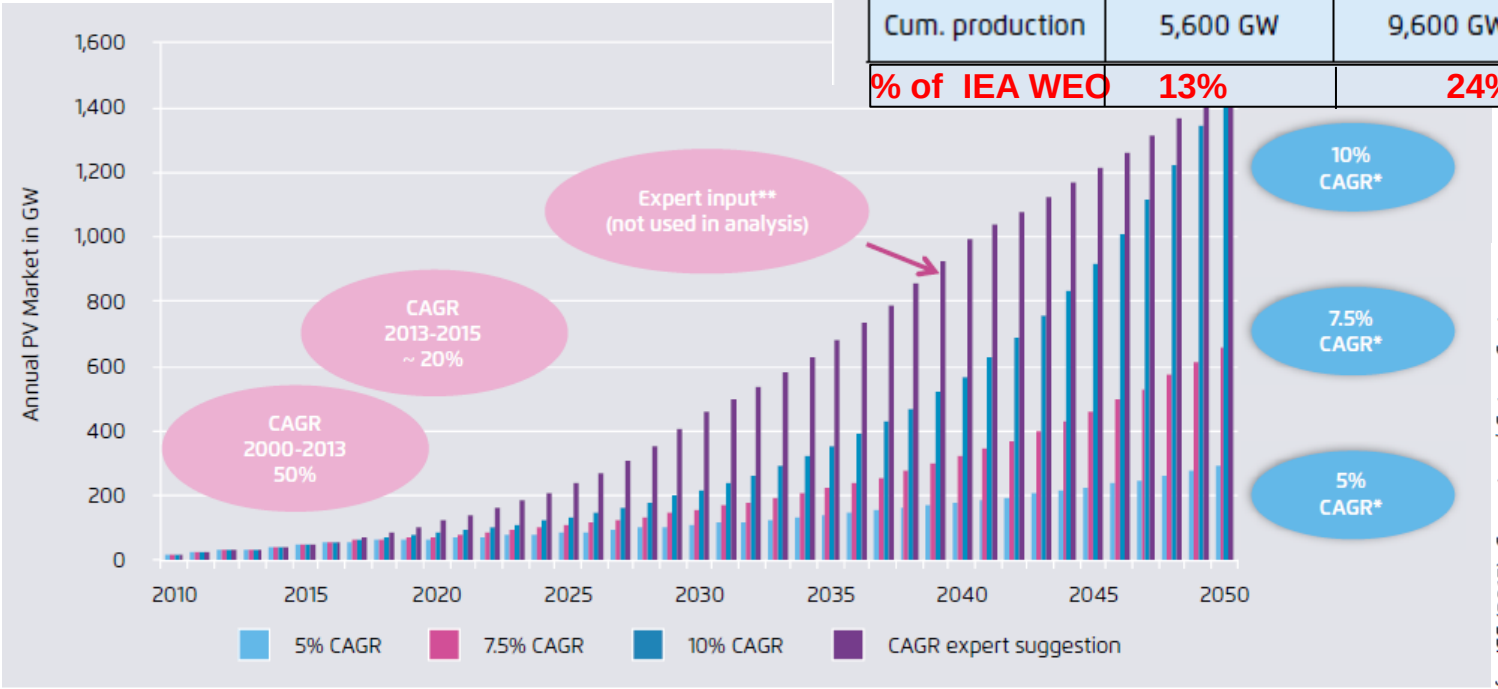
Global PV capacity



Fraunhofer ISE (2015): *Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems*. Study on behalf of Agora Energiewende.

Scenarios for global PV deployment

Scenario	5% CAGR	7.5% CAGR	10% CAGR
Installed in 2050	4,300 GW	7,900 GW	14,800 GW
Cum. production	5,600 GW	9,600 GW	16,700 GW
% of IEA WEO	13%	24%	44%



Own illustration

* CAGR = Compound Annual Growth Rate; ** Suggested market growth by year: 2014-2020: ~20 %; 2020-2030: 14 %; 2030-2040: 8 %; 2040-2050: 4 %; Considered by applying the S-curve approach to all scenarios

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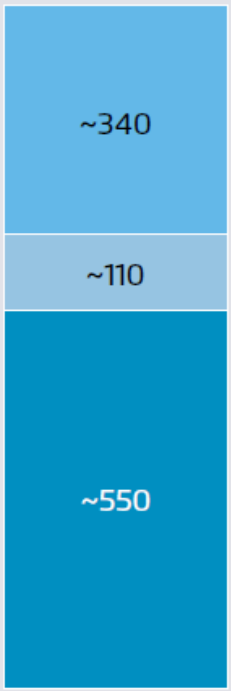
Cost structure of PV systems

Total: ~1000 €/kWp



Balance of System cost

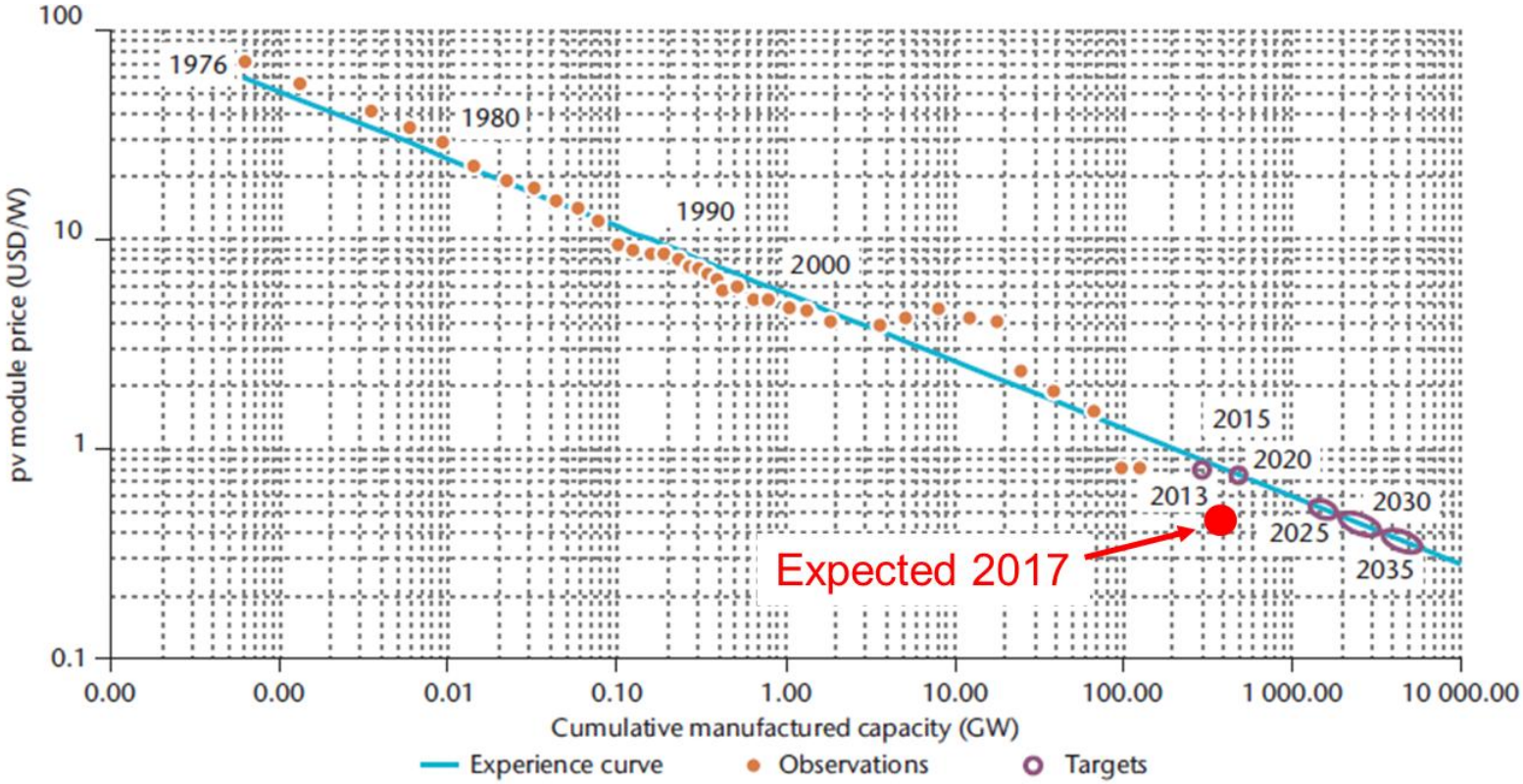
Module and inverter:
~ 660 EUR/kWp
[world market]

"BOS" (="Any other components")

- Mounting system
- Installation
- Cable (DC)
- Infrastructure
- Transformer
- Grid connection
- Planning and documentation

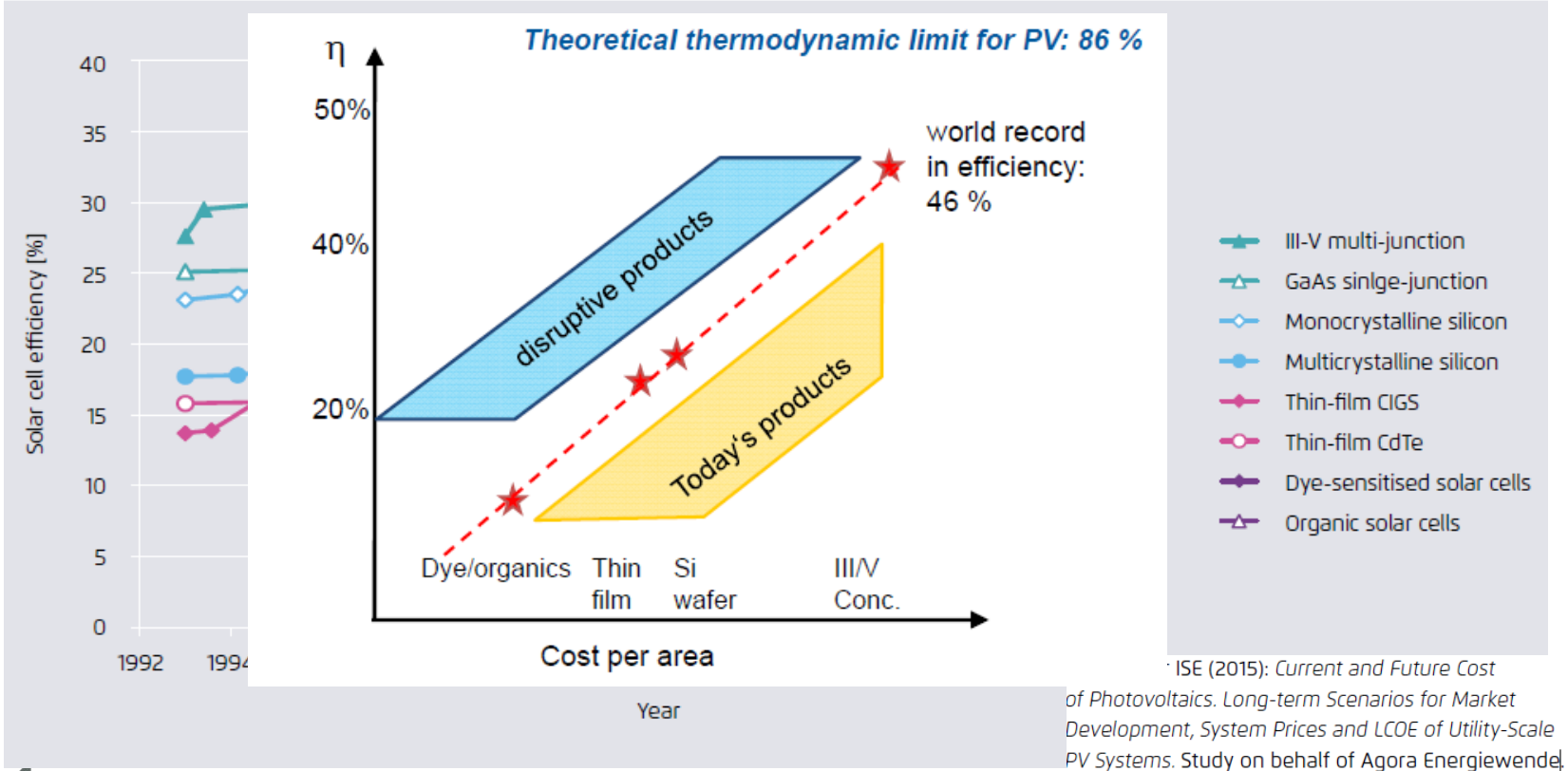
Fraunhofer ISE (2015): *Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems*. Study on behalf of Agora Energiewende

Learning rate for PV modules



Notes: Orange dots indicate past module prices; purple dots are expectations. The oval dots correspond to the deployment starting in 2025, comparing the 2DS (left end of oval) and 2DS hi-Ren (right end).

The efficiency of a solar cell is one key driver for cost reduction

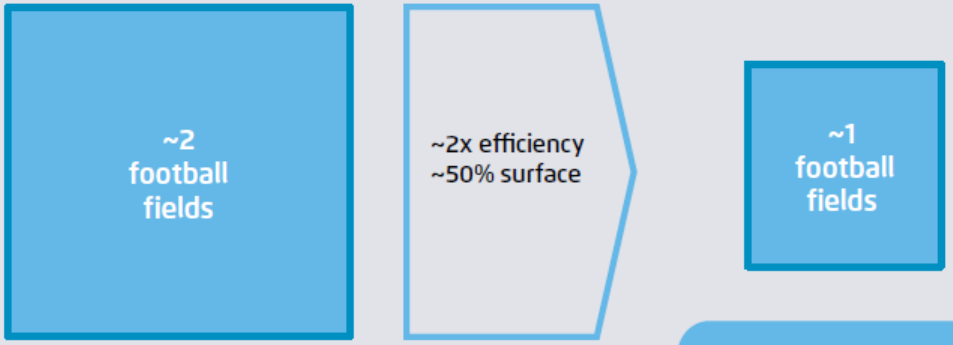


ISE (2015): *Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems.* Study on behalf of Agora Energiewende.

Cell effciency has a major impact on BOS cost

Today:
(~15% module efficiency)

2050:
(~30% module efficiency)



Effect of higher module efficiency:

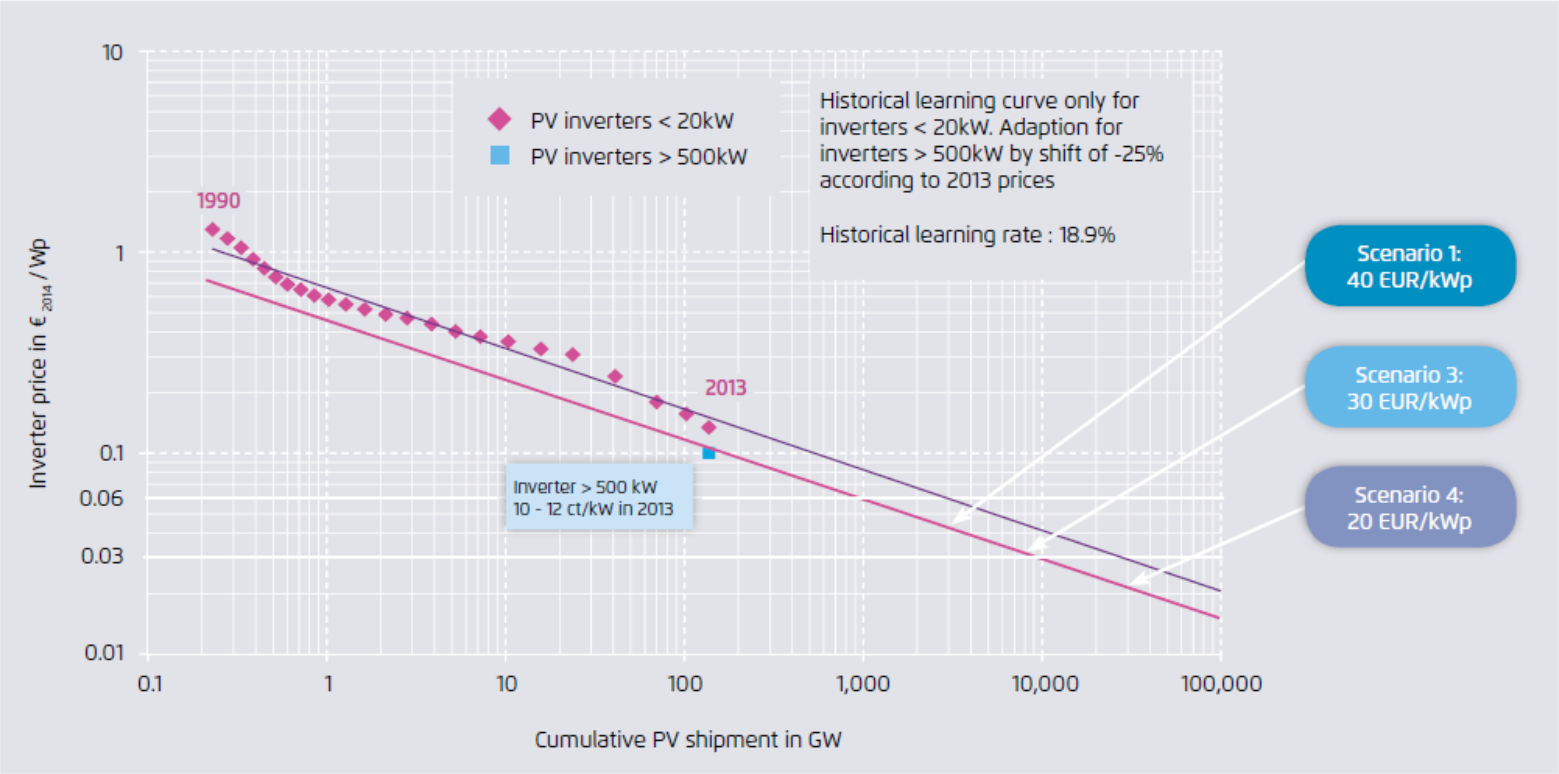
- Less modules to install
- Less weight to transport
- Less structures to build
- Less surface to use

Fraunhofer ISE (2015): *Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems.* Study on behalf of Agora Energiewende

Own illustration

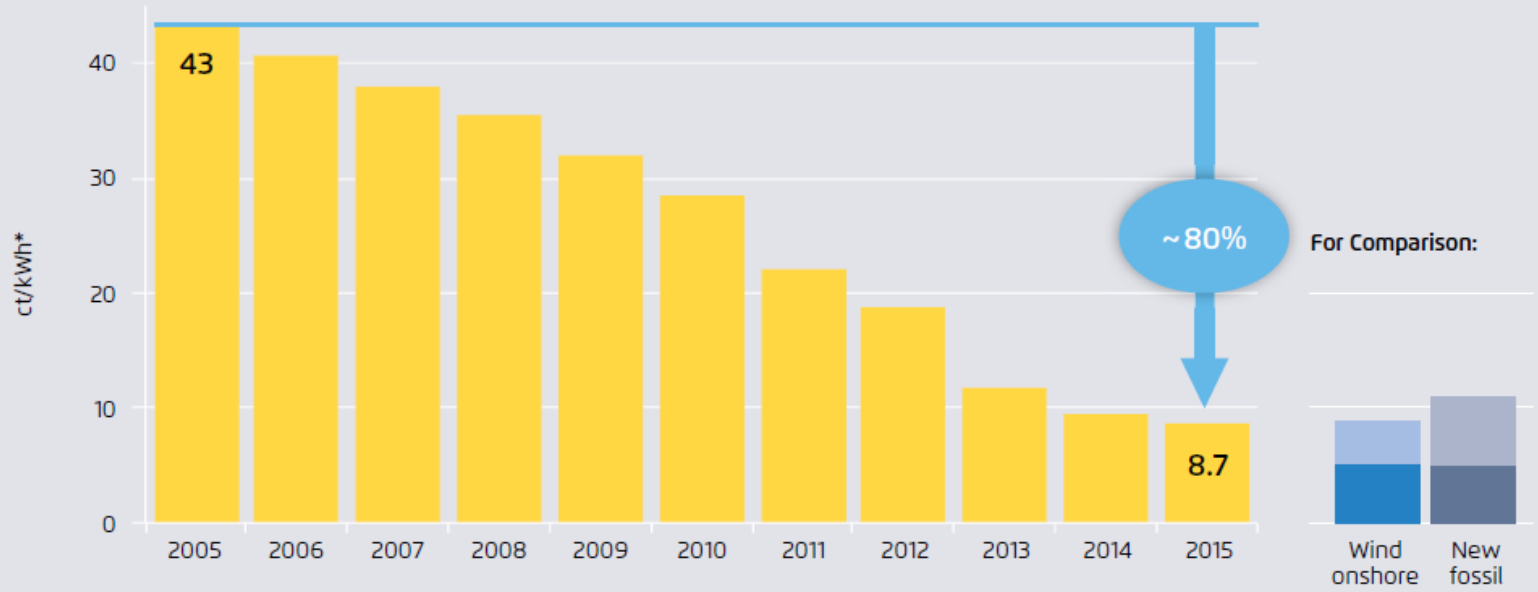
* Football field (Fifa) = 7140 m²

Learning curve for inverter



Fraunhofer ISE (2015): *Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems.* Study on behalf of Agora Energiewende

Historical development of German feed-in tariff



*Nominal values, Feed-in tariff applicable at first of January each year, value 2015 excl. adjustment of 0,4 ct/kWh for direct marketing

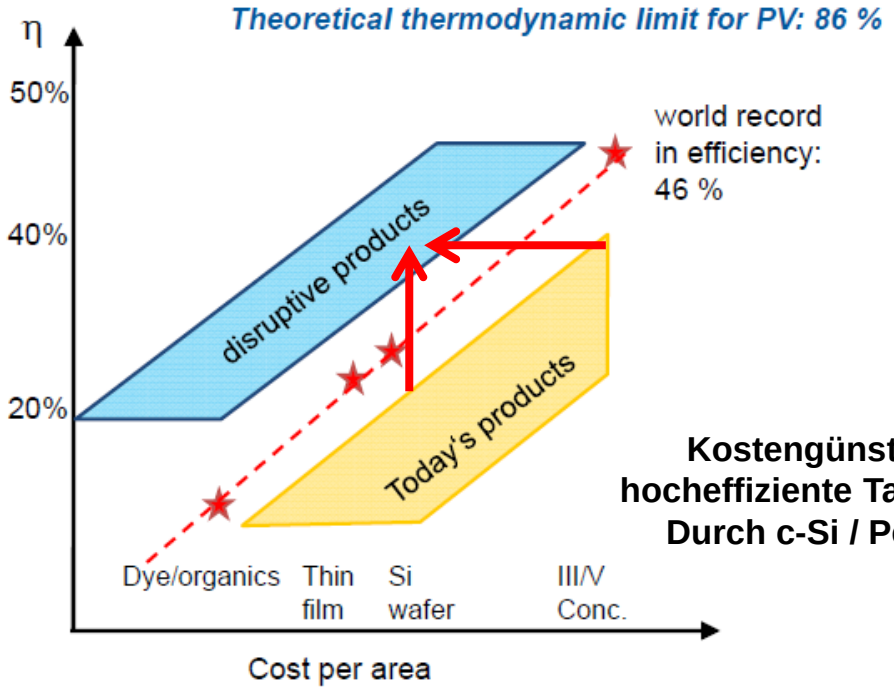
Fraunhofer ISE (2015): *Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems*. Study on behalf of Agora Energiewende

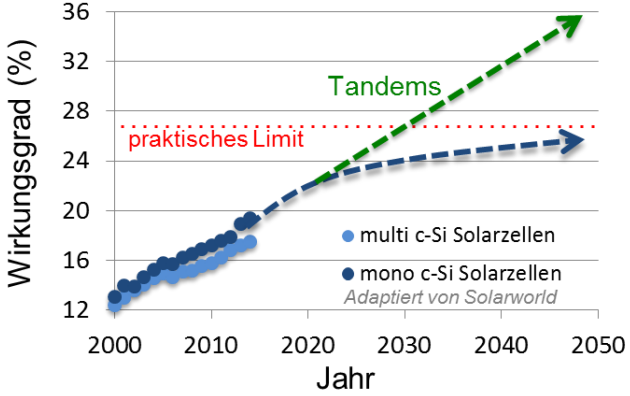
Expected cost development of PV electricity

* Real values EUR 2014; full load hours based on [27], investment cost bandwidth based on different scenarios of market, technology and cost development; assuming 5% (real) weighted average cost of capital.

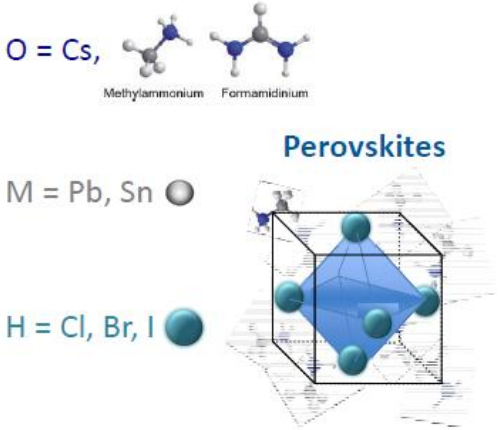
Fraunhofer ISE (2015): *Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems*. Study on behalf of Agora Energiewende

PV research in Germany addresses disruptive concepts

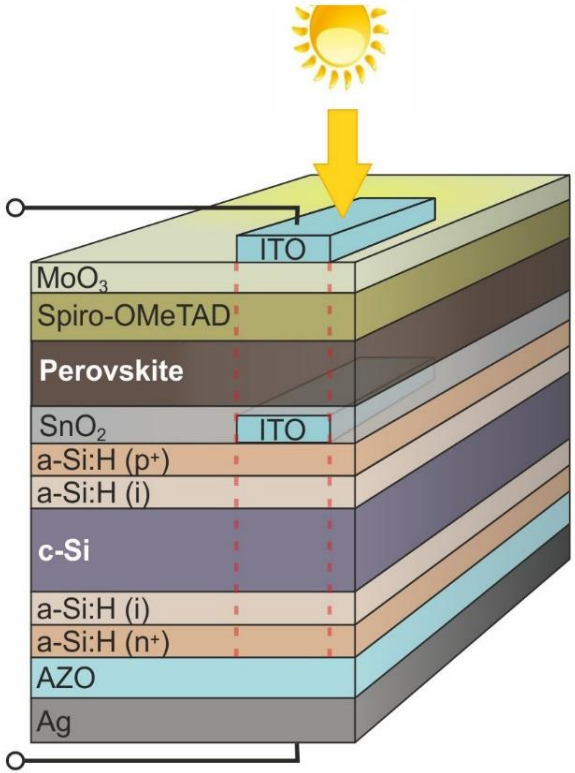




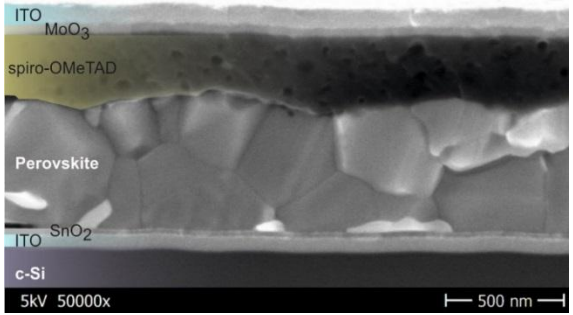
Kostengünstige und hocheffiziente Tandemzellen Durch c-Si / Pervoskite



Perovskit: A tandem partner for SI and CIGS



Efficiency: 19.9 %



Target :
Efficiency > 30 %
stabile – environmentally friendly - scalable

S. Albrecht et al., Energy & Env. 2016

Outline

1. Why to deploy Solar Energy massively?
2. Photovoltaics Fundamentals
3. Market and Cost Situation for PV Technology
4. **Conclusions**

Conclusions

- PV Cells use the photoelectric effect to excite electrons and convert light into electricity
- The energy (wavelength) of the photon needs to be sufficient to overcome the bandgap in a semiconductor material
- PV cells consist of a junction of differently doped semi-conductors to separate the excited charge carriers
- PV electricity has reduced its cost dramatically over the last 20 years and is today one of the lowest cost electricity producer
- This is driven but scaled automated manufacturing and efficiency improvements in the semiconductor
- Further cost reduction is expected