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Nizhniy Novgorod 21.9.2016

Direct production of electrical energy from solar radiation:
Commercial inorganic photovoltaic solar cells and more in detail development of organic solar cells

1. Overview renewable energy and electricity

2. Inorganic photovoltaic solar cells mainly based on silicon

3. Organic and related photovoltaic solar cells

   Three different types of organic solar cells

4. Summary

Photovoltaik plant house D. Wöhrle

1/3 of electrical energy consumption from this plant

1. Overview renewable energy and electricity

Do we need renewable energies like solar radiation?

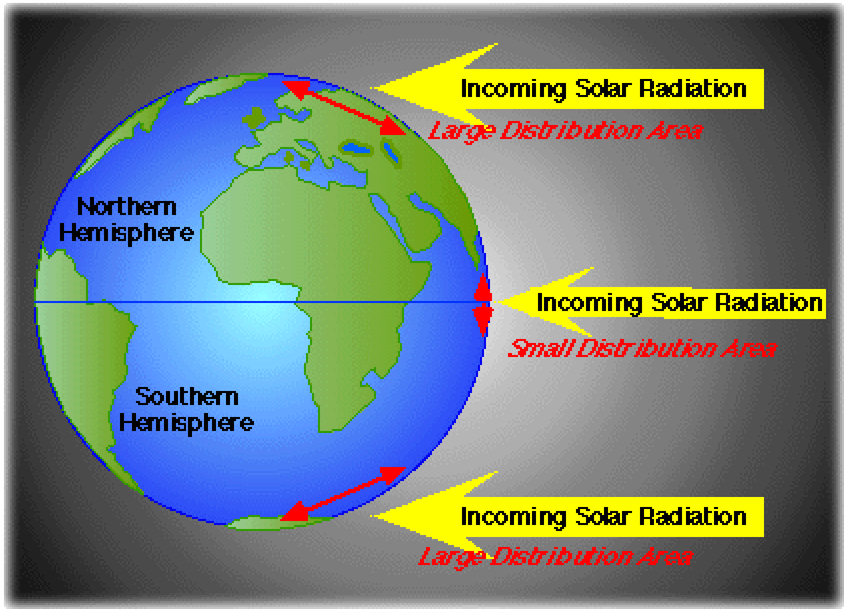
1. Limited natural resources:
   Petroleum and natural gas available for around 45-65 years.
2. Global warming
   Mainly caused by human activities (green house effect, CO_2).
   Global surface temperature in 21th century may increase 1,7-4.5 ^oC resulting in great climate change.

One solution is to use of renewable energies:
solar, wind, hydropower, biomass, etc.

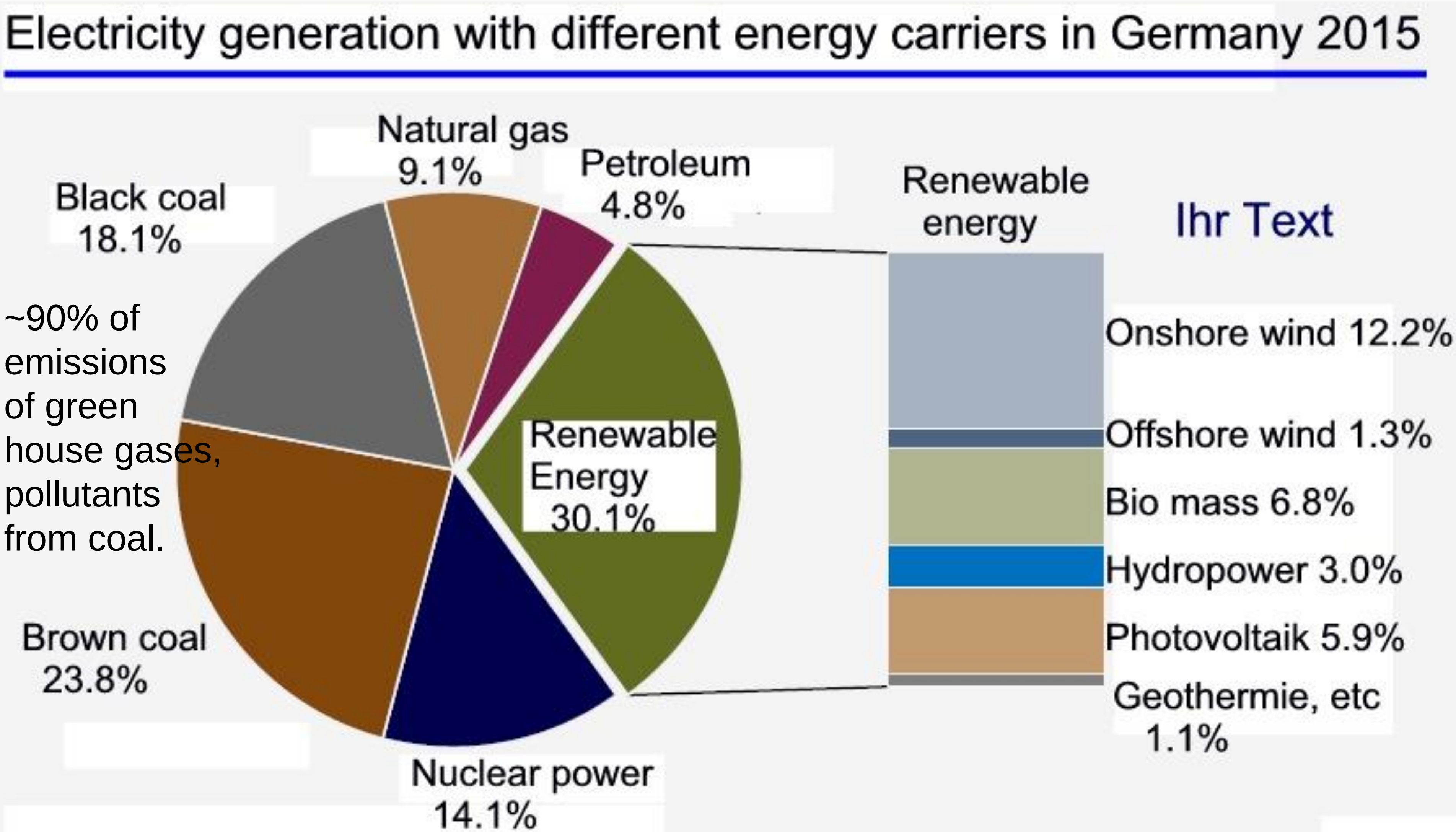
Do we have enough renewable energies?
Yes → Example solar is radiation:

The radiation power of the sun to the earth's surface exceeds the global primary energy consumption by a factor of about:
- 5400 on the earth's surface,
- 1700 on the continents.

(in Joule per Watt).



Source: Bundesverband der Energie- und Wasserwirtschaft e.V.

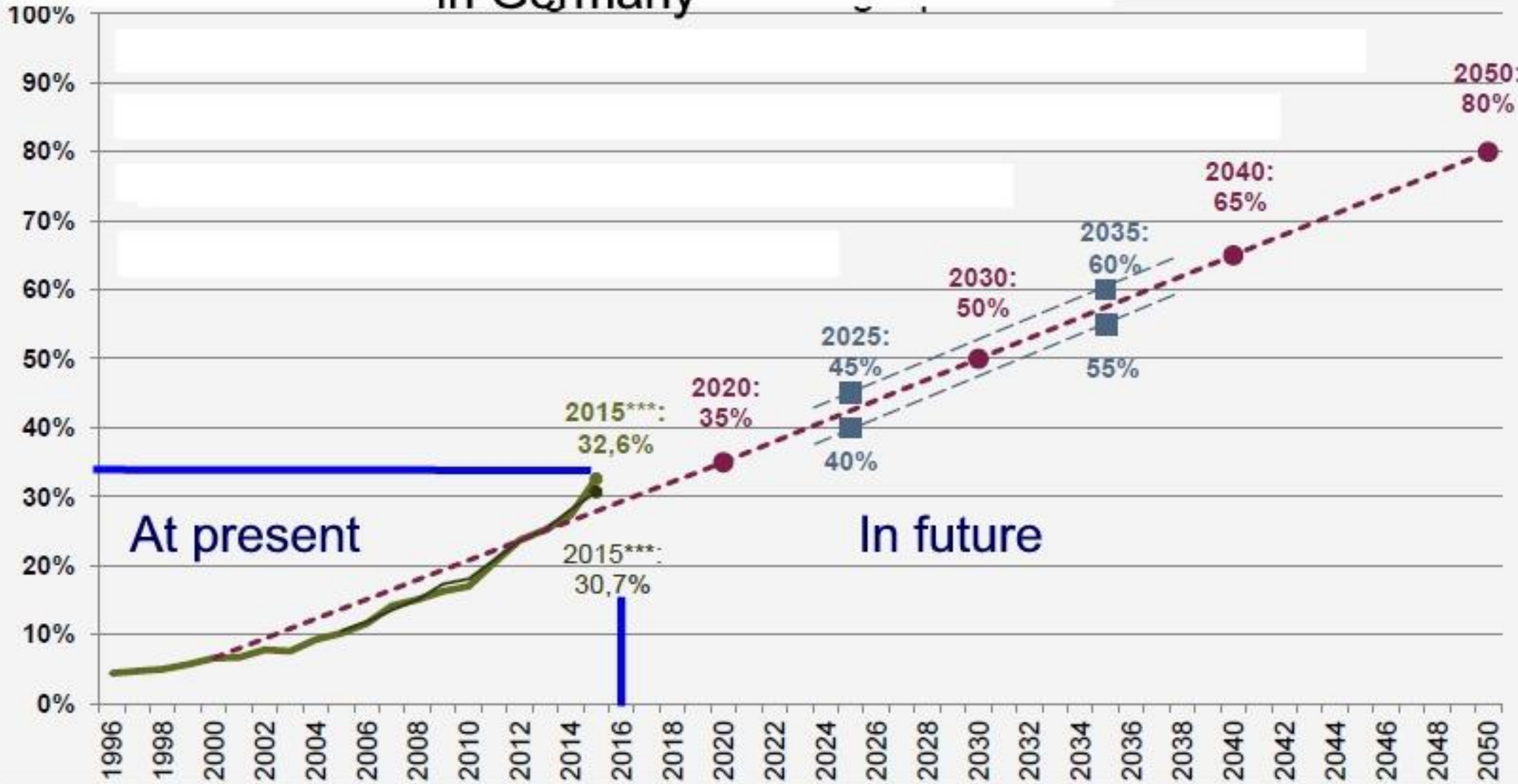


~90% of emissions of green house gases, pollutants from coal.

Ban on the construction of new nuclear power plants.
Shutdown of existing nuclear power plants to 2022nd.

Around 1.5 million photovoltaik plants in Germany!

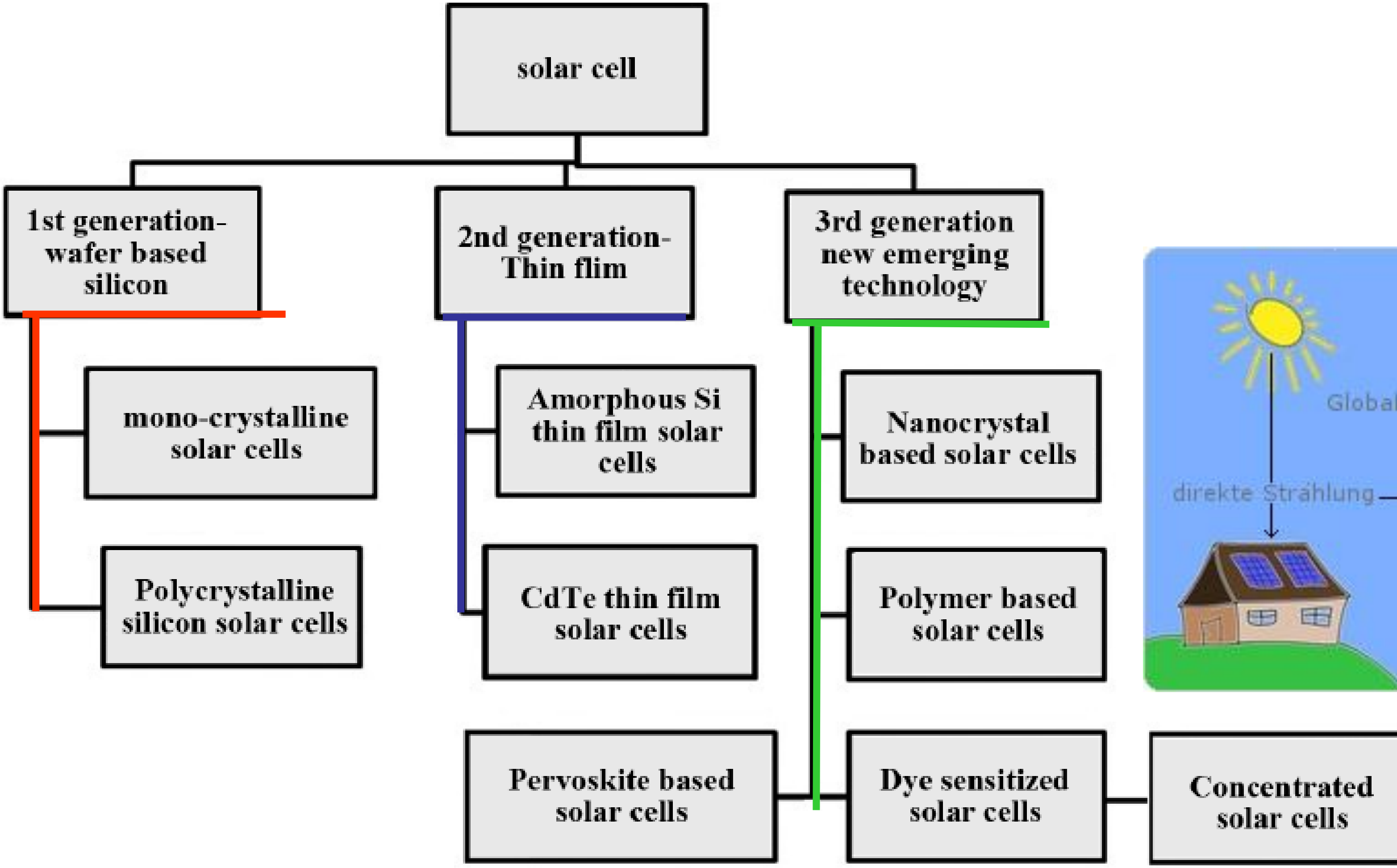
Percentage of renewable energies at electricity generation in Germany

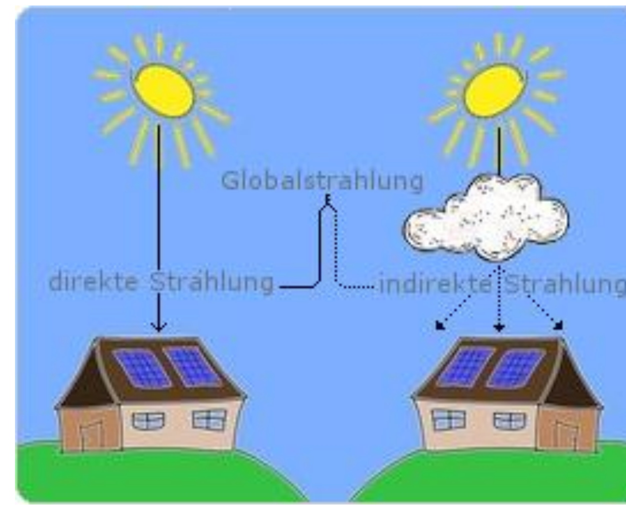


The energy system for electricity generation in future will be a mixed system based on different natural energy sources

Source: Bundesverband der Energie- und Wasserwirtschaft

Various types of photovoltaic cell technology and current trends of development





Advantage of photovoltaic cells:

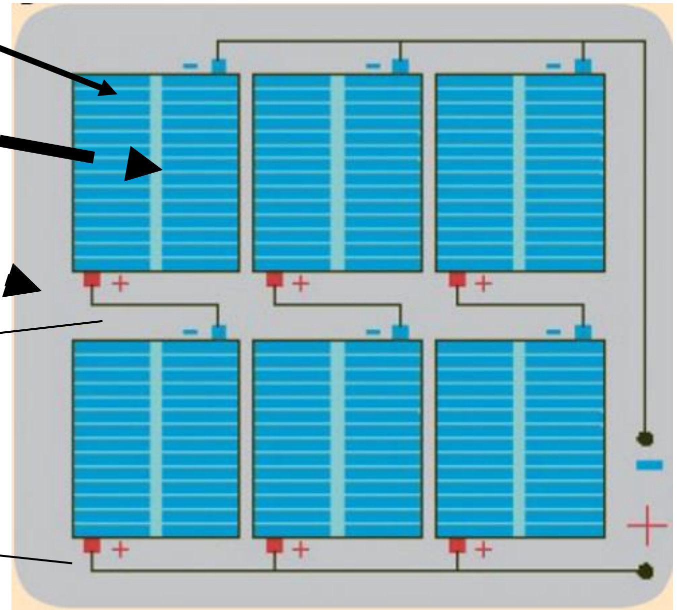
- Direct conversion of solar radiation to electrical energy.
- No mechanically moving parts, only voltage source inverter necessary.
- Direct local use on e.g. buildings.

Disadvantage: Day/night rhythm.

2. Inorganic photovoltaic solar cells mainly based on silicon

Single solar solar cell
connected to
Solar modul
connected to
Solar panel

Connection:
- Series connection increases photovoltage
- Parallel connection increases photocurrent



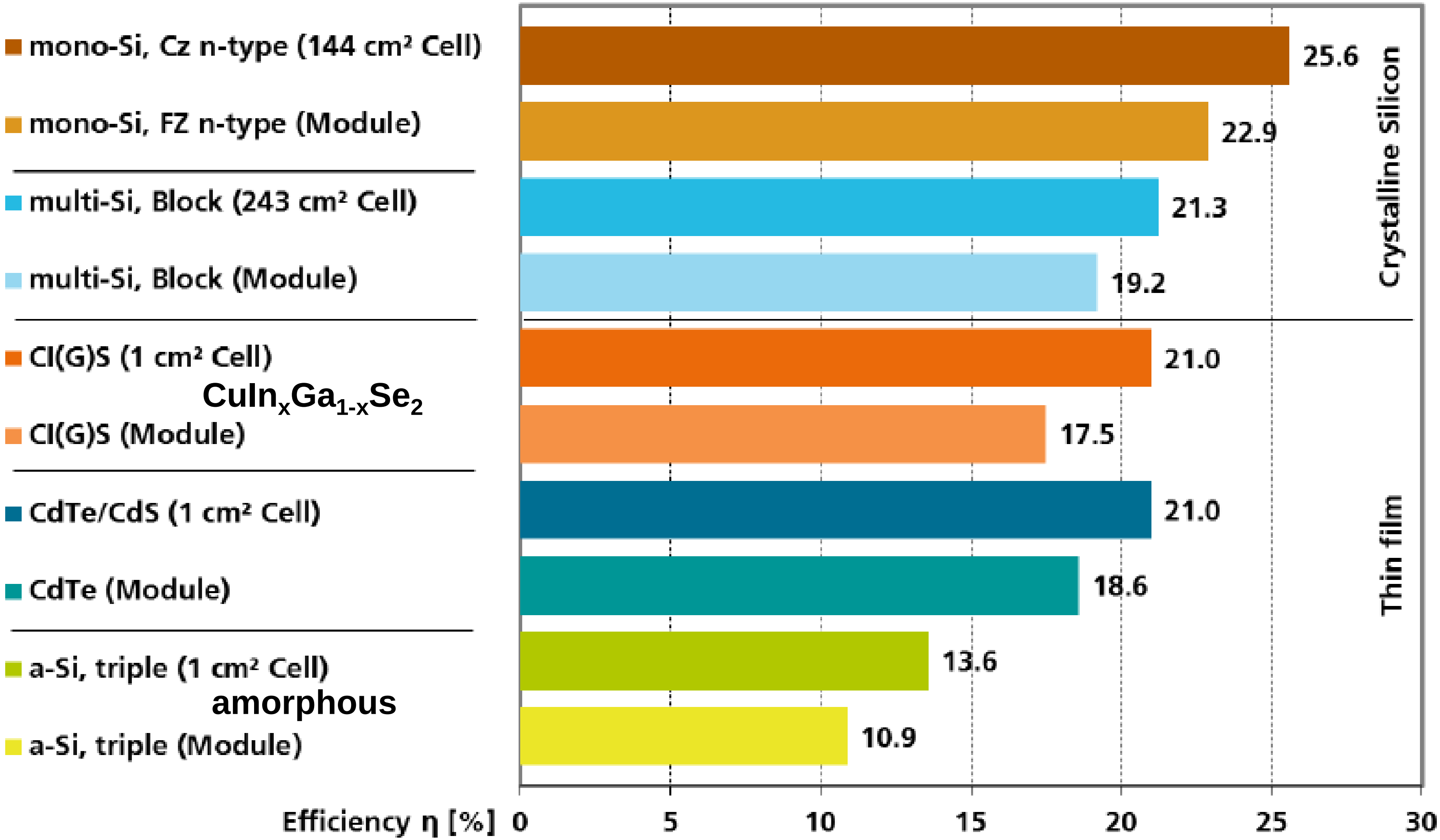
Characteristic data characterize at a single cell at a light radiation of 100 mW cm^{-2}:

Open circuit voltage V_{OC}: maximum voltage without consumer (0.7-1.0 V).
Short circuit current I_{SC} : maximum current under load by a consumer (20-30 mA cm^{-2}).

With these data and the incident light intensity of 100 mW cm^{-2} the efficiency η is calculated in percent %.

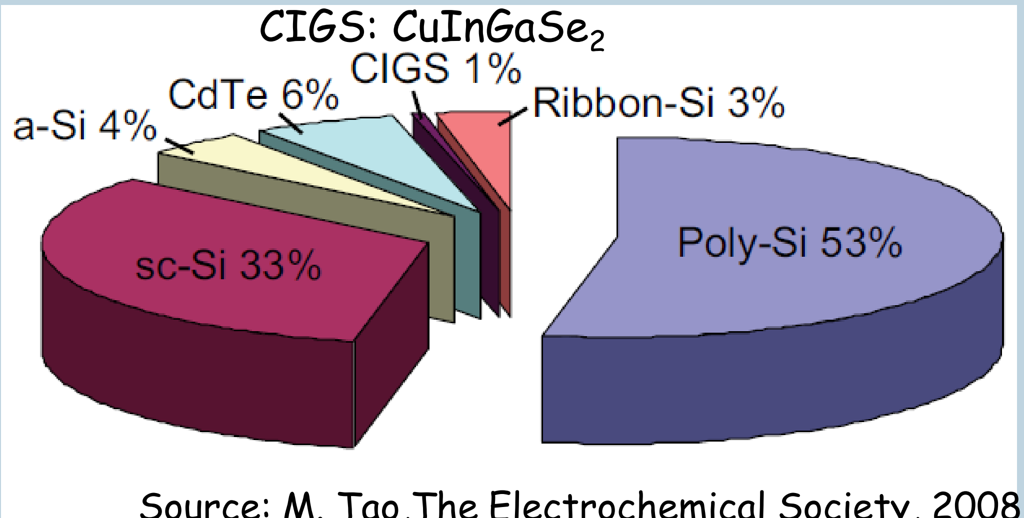
$$\text{efficiency } \eta = \frac{\text{electrical energy output}}{\text{light energy input}} \%$$

Efficiencies of inorganic photovoltaic solar cells:
Best lab cells vs. best modules (modules <u>commercially ~20% less</u>)



Source: Fraunhofer Institute of Solar Systems, Freiburg, 2016

Market share of inorganic photovoltaic (PV) solar cells

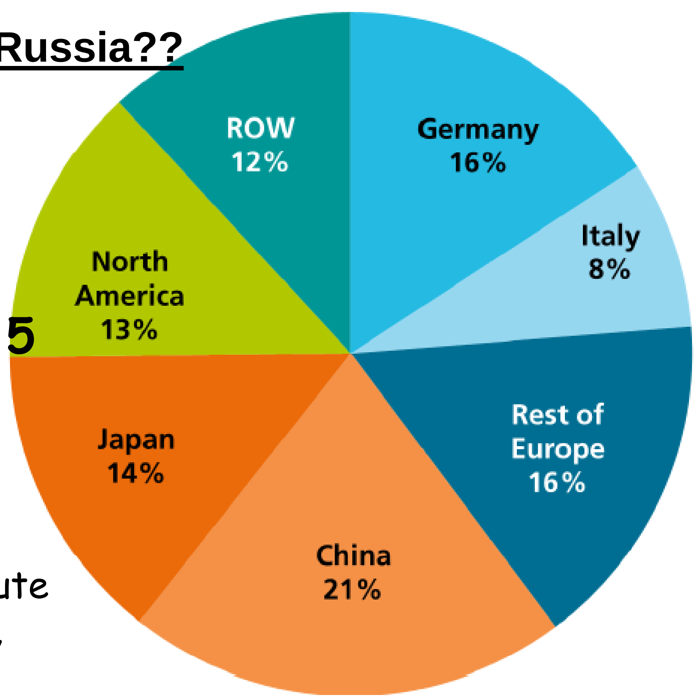


Source: M. Tao,The Electrochemical Society, 2008

2015 71% **photovoltaic module production** in China.
No photovoltaic module producer in Russia?

(see https:// en.wikipwedia.org → list of photovoltaics companies)

Russia??



Global PV plant installation by region, 2015

Source: Fraunhofer Institute of Solar Systems, Freiburg, 2016

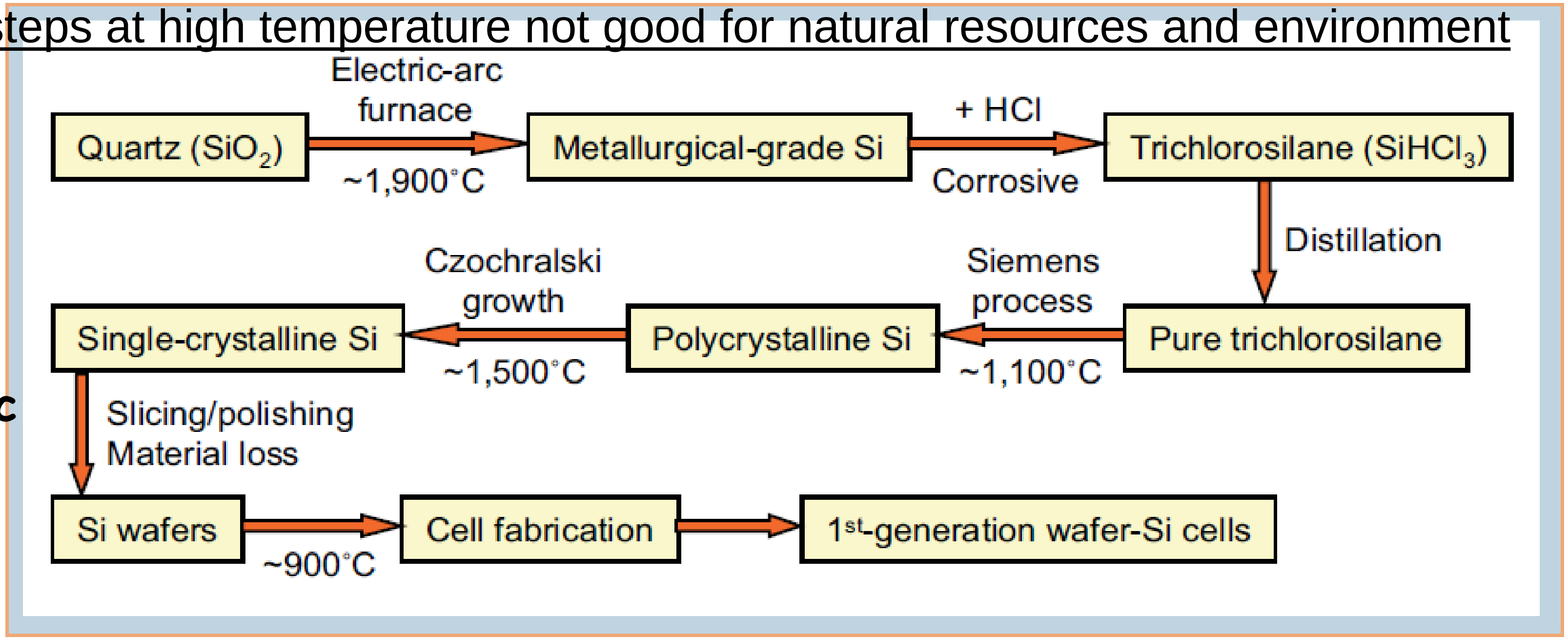
Energy payback time
(time of a device to generate as much energy as was needed to fabricate the device, depends on the kind of cell):

- In Germany 1.2 till 3.2 years
- In Sicily 0.7 till 2 years

Electricity costs in Germany:
14 till 17 Cents/kWh
(Household price ~27 Cents/kWh)

7 process steps at high temperature not good for natural resources and environment

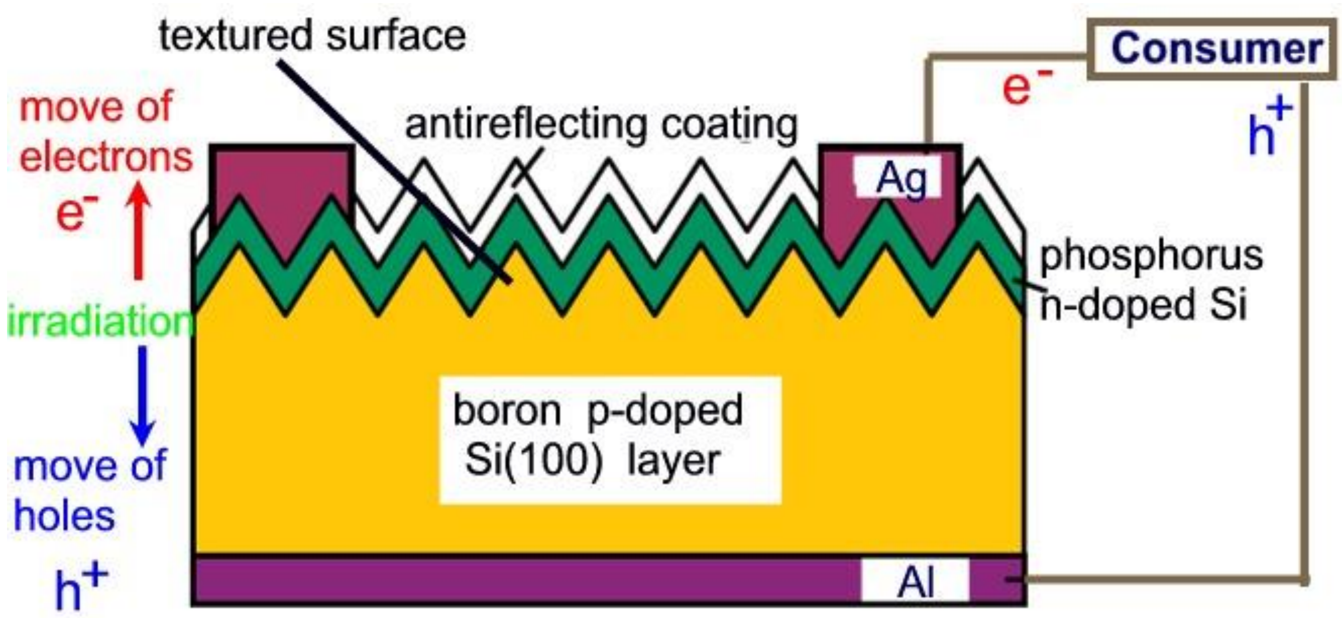
Industrial process quartz to single-crystal Si photovoltaic cell



Construction of inorganic photovoltaic cells

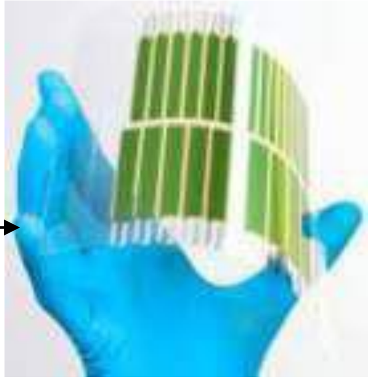
Cross section of a single-crystal Si photovoltaic cell.

Result: Under solar radiation move of electrons and holes in different directions. Generation of direct current (DC).

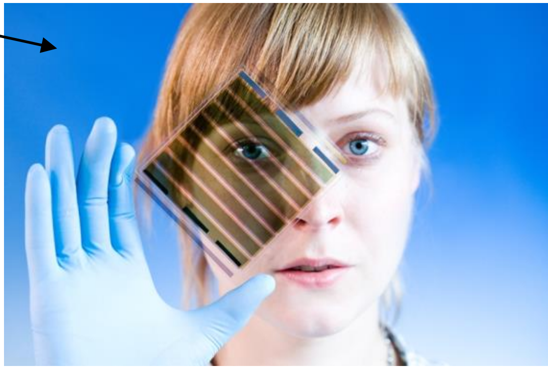


3. Organic and related photovoltaic solar cells

- **3.1 Solid state organic photovoltaic cells**
- **3.2 Dye sensitized solar cells (DSSC)**
- **3.3 Perovskite solar cells**



Advantages:
- Thin: 250-500 nm. Light. Flexible cells possible.
- Organic materials only ~1g per sqm.
- Transparency 40-50% possible.
- Pay back time of energy: ~6 month
- No loss of efficiency at low light intensity
- Continuous roll-to-roll printing process for production possible.



Problems:
- Maximum efficiencies of small lab cells 12 till 21%.
- But efficiencies of modules 4 till 8% must be improved.
- Cells must be encapsulated against oxygen and water!

Main problem:
- Degradation must be reduced and stability must be improved to more than 20 years!

Some companies started production:
- Niche applications
- Façades of buildings as demonstrators and pilot objects

3.1 Solid state organic photovoltaic cells

Combination of a solid organic donor (p-conductor) with an organic acceptor (n-conductor)

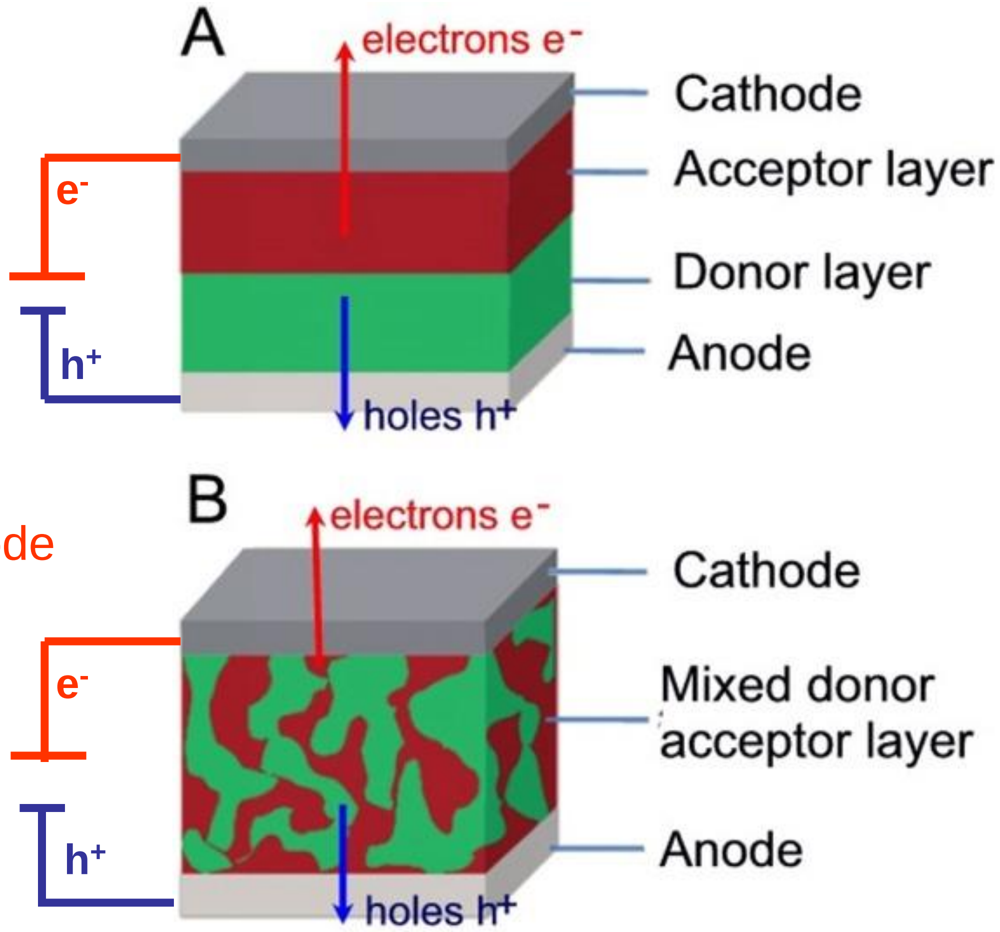
Stack structure with solid organic semiconductors

A: Planar heterojunction cell (PHJ) prepared by vapour deposition

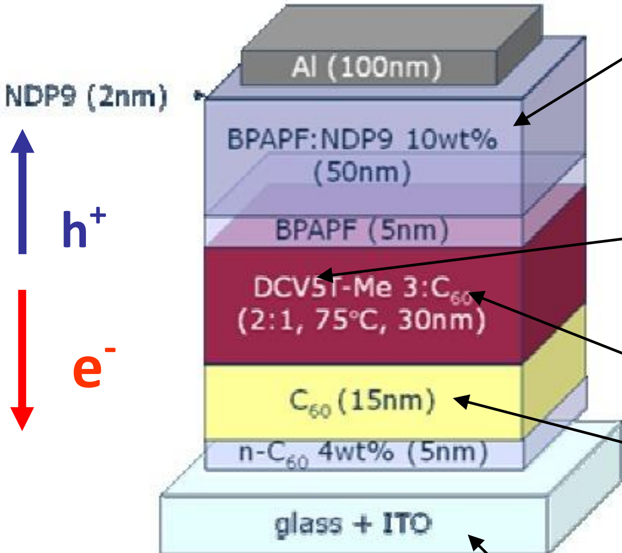
B: Bulk heterojunction cell prepared by coating/printing from solution

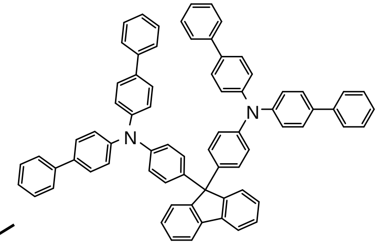
Under irradiation with visible, solar light:

- Absorption of light.
- Formation of an excited electron/hole pair (exciton).
- Diffusion of electron to the cathode
- Diffusion of holes to the anode.



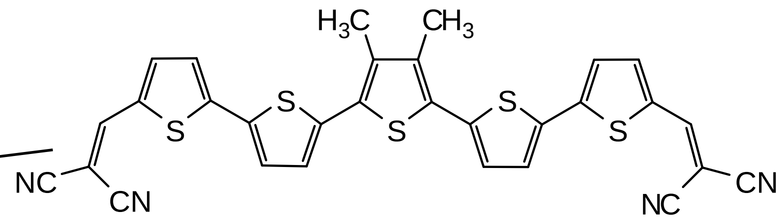
Example of a bulk heterojunction (BHJ) cell





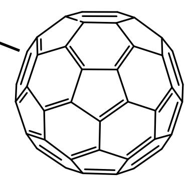
BPAPF

hole transporter (doped with NDP9)



DCV5Z-Me3

Thiophenes:
- donor



C_{60} (auch C_{70})

Fullerene:
- acceptor
 and
- electron transporter

ITO: indium tin oxide conducting glass

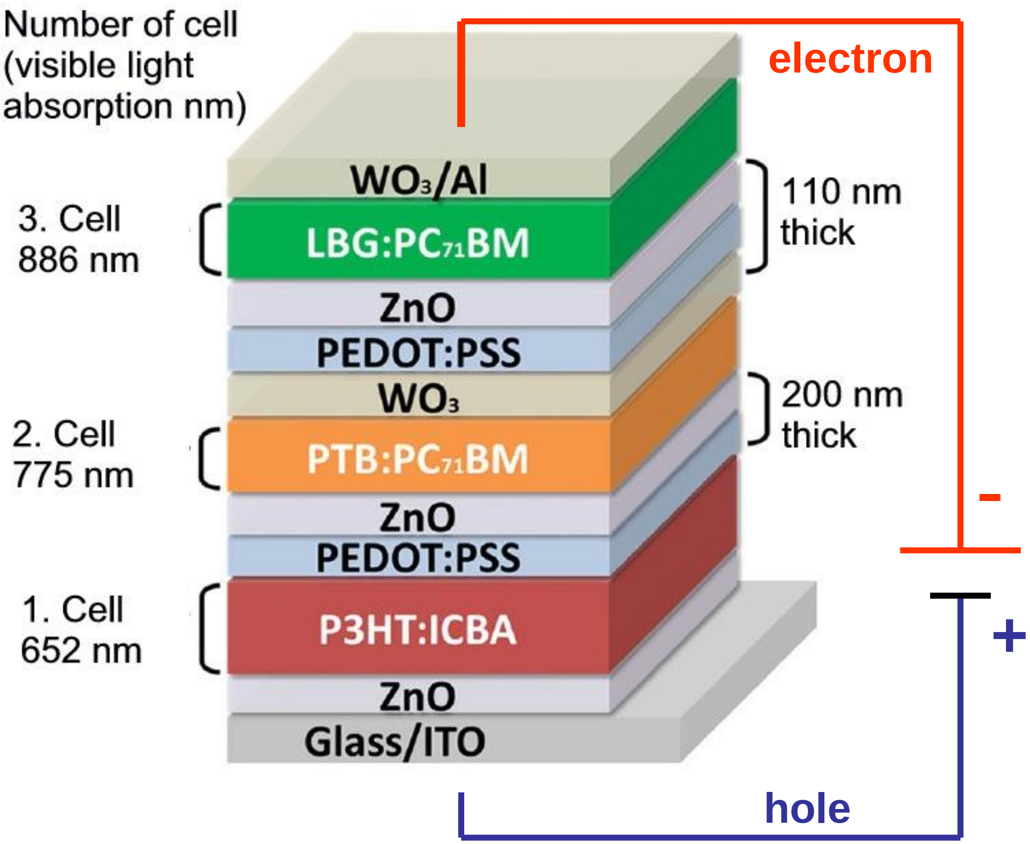
V_{OC}: 0,95 V

I_{SC}: 1.5 mA cm^2

***η*: 6.9%**

Source: Fitzner, Leo, et al., *J. Am. Chem. Soc*. **2012**, *134*, 11064

Photovoltaic properties of single, double, triple BHJ cells

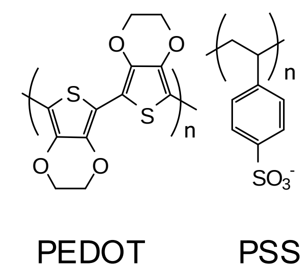


Tandem: Series conection increasing photovoltage

Cell components

- LGB, PTB, P3HT: different polymer thiophene derivatives as donors (p-conductors) absorbing at different wavelength
- PCBM, ICBA: different fullerene derivatives as acceptors
- WO_3 as electron conductor
- PEDOT:PSS and ZnO as hole conductor
- ITO: indium tin oxide conducting glass

Active cell area 0.2 cm^2



Solar cell	V_{OC} in V (series connection)	I_{SC} in mA cm^2		Efficiency in %
Single cell	0.70 -0.84	9.93 –17.4		5.8-7.8
Double cell	1.42-1.53	8.81-11.30		9.6-10-7
Triple cell	2.26-2.28	7.30-7.63		11.0-11.6

Source: Yang et al., Adv. Mater. 2014, 26, 5670

Information about Heliatek company in Dresden, Germany

1. **Triple tandem cell** (size 2 cm^2): efficiency 13.2% (world record).

2. **Entrance of Heliatek building in Dresden covered with organic solar cells.**

Large façade installation in Dresden. Efficiency ~8%. Life time: Some years expected.
Energy output 20% higher than a conventional Si plant.
Photovoltaic module production capacity 2017 roughly 15.000 sqm per year.

3. Information from Heliatek (30.8.2016)

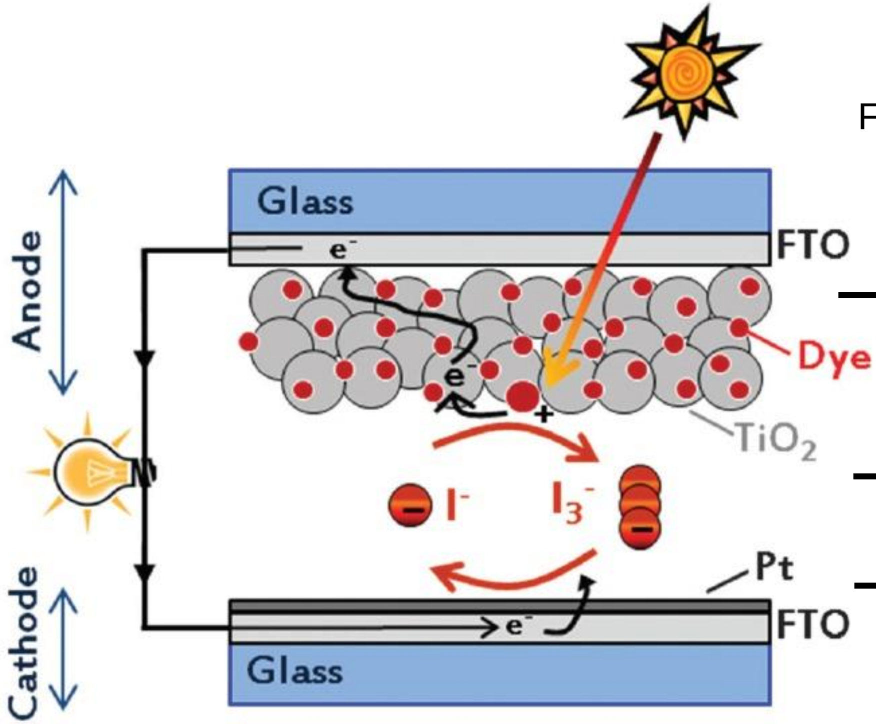
The greated plant of organic solar cells (10 kW_p) with HeliaFilm is now rigorously tested under the tropical weather conditions of Singapore (JTC's Cleantech Park I and II building).

3.2 Dye sensitized solar cells (DSSC) (Grätzel cell)

Combination of a dye (sensitizer) on TiO_2 in an liquid redox electrolyte

Scheme of the components of a DSSC cell

FTO: Fluoro doped indium tin oxide



TiO_2 with bound dye on conducting glass.

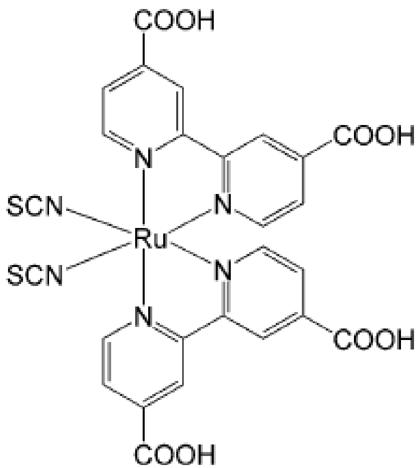
Liquid redox electolyte $I_3^-/3J^-$

Pt (or carbon) counter electrode

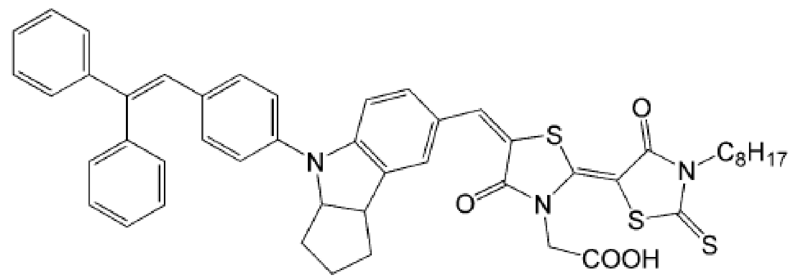
1. Absorption of a light by the dye on TiO_2 → excited state of the dye.
2. Oxidation of the dye, electron to conduction band of TiO_2.
3. Transfer of electron via the load to counter electrode.
4. Reduction of the redox electrolyte
5. Diffusion of the reduced electrolyte to the oxidized dye on TiO_2 → neutral dye.

Cells must be encapsulated!

Examples of organic dys/sensitizers in DSSC cells

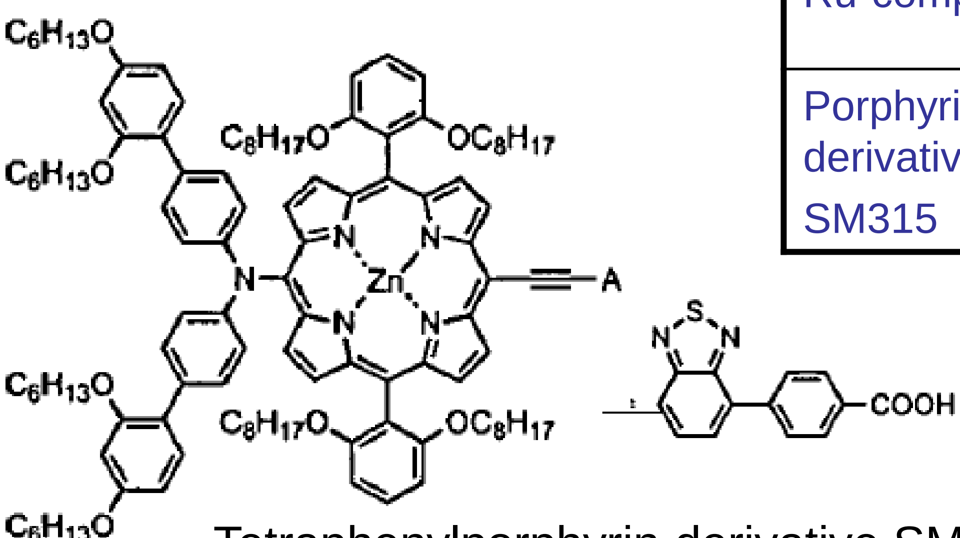


Ru complex N3/N719



Organic dye D205

Dye/ Sensitizer	V_{OC} in V	I_{SC} in mA cm^2		Efficiency in %
Organic dye D205	0.72	18.6		<9.5
Ru-complex	0.85	11.7		<11.2
Porphyrin derivative SM315	0.91	18.1		<13.0



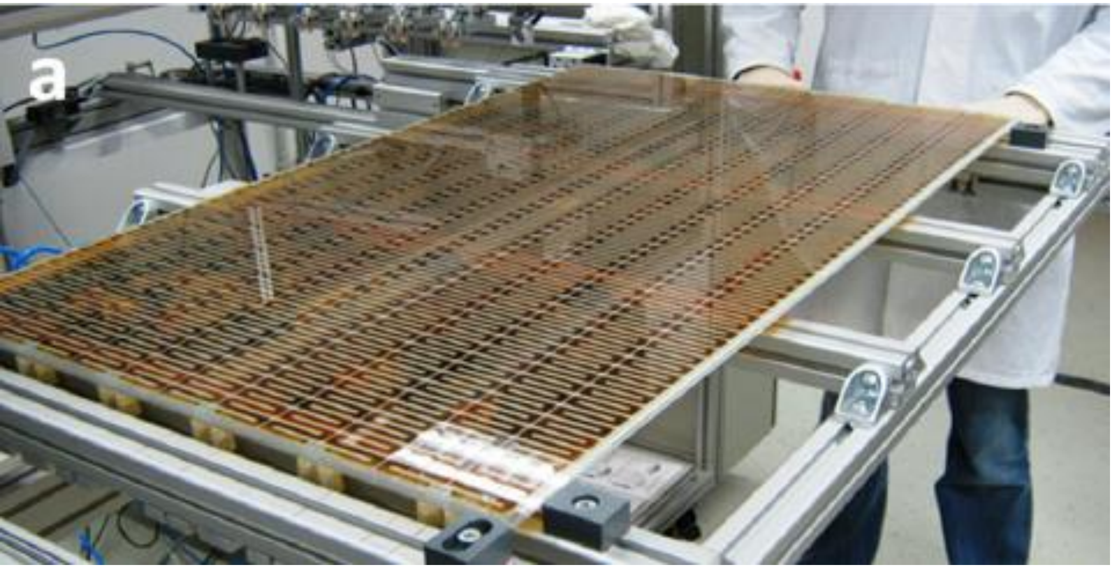
Tetraphenylporphyrin derivative SM315

Size of cells: 0.1-0.5 cm^2

Sources: Different publications of Grätzel. Nazeeruddin, Ooyama, etc.

Upe-scale fabrication of DSSC modules on conducting glass substrate by using partly printing technique

(Hinsch et al., Prog. Photovolt.: Res. Appl. 2012, 20, 698)



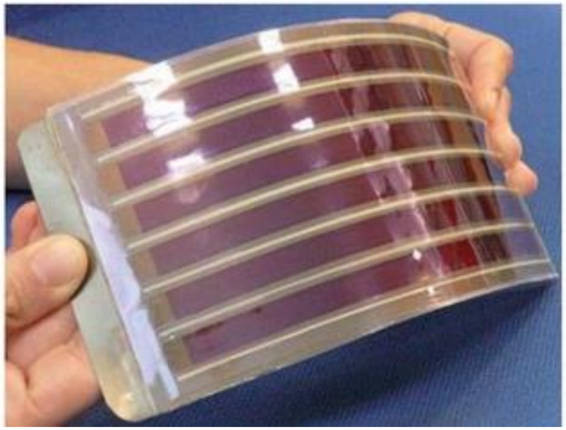
Automated pilot-type equipment for the dye and electrolyte filling as well as for the final sealing of large area DSSC modules.

Comparison of small and large devices with the Ru dye N715 (irradiation 100 mW cm^{-2})

Device	Size (cm^2)	Efficiency (%)
single cell	0.2	11.1
Module	100	6.1
Module	6000	2.3

Expected energy payback time of 5-7%: 0.5 years.

Up-scale fabrication of DSSCs on flexible polymer substrates with Ru complexes as sensitizers



Source: Brown et al.,
J. Mater. Chem. A 2014, 2, 10788

DSSCs integrated into the Façade in panels at the SwissTech Convention Center
(Company Solaronix, Aubonne, Switzerland)

Size of cells100 cm^2,
efficiency η 6.4%

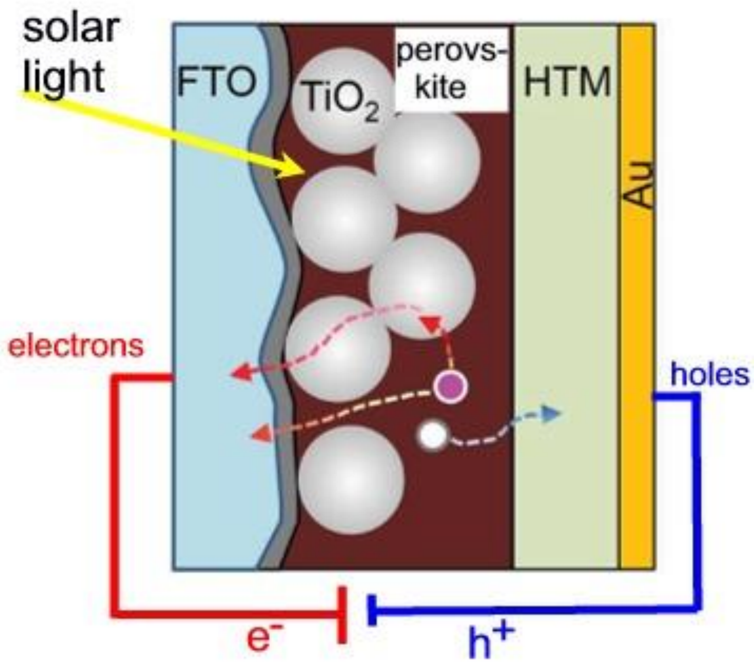
3.3 Inorganic/organic perovskite solar cells

Much interest recently in **perovskite solar cells.** Efficiency of lab cells: increase from 3.8% in 2009 to ~21% in 2016 (theoretically up to 31%).

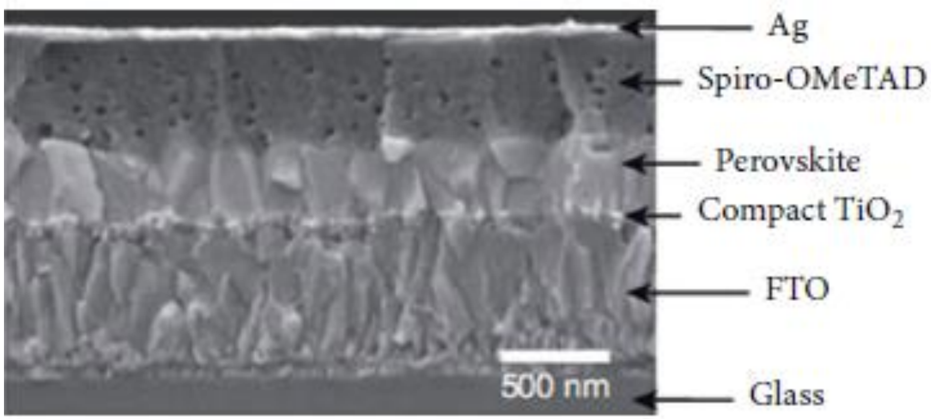
Perovskites ABX_3: minerals of a cubic crystal structure.
Active compound in perovskite solar cells absorbing in the visible region and with high mobility of charge carriers: **$CH_3NH_3^- PbJ_3^+$**

Cell configuration:
glass/FTO/ TiO_2 / $CH_3NH_3^-$ /PbI_3^+ / hole transporting material (HTL) / Au

Scheme of the components of a cell

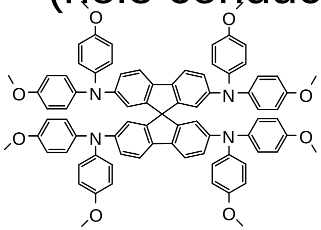


SEM through a cells

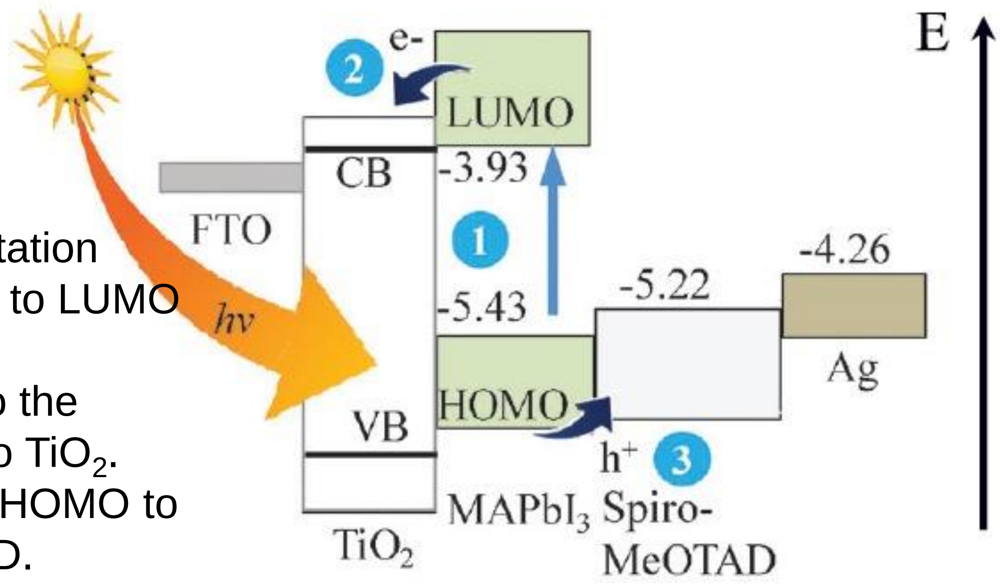


FTO: Fluoro doped indium tin oxide

Energy band diagram of a perovskite solar cell
(hole conductor: MeOTAD)

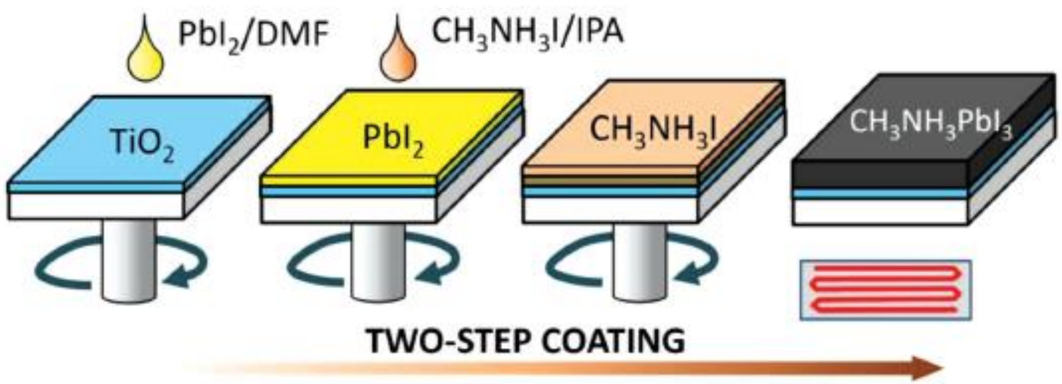


1. Under irradiation excitation of electron from HOMO to LUMO of $CH_3NH_3PbI_3$.
2. Transfer of electron to the conduction band (VB) to TiO_2.
3. Transfer of hole from HOMO to hole conductor MeOTAD.



Advantage simple preparation of a cell:

- Glass/FTO with 350 nm TiO_2; Solution of PbJ_2 spin coating on TiO_2.
- Dipping into CH_3NH_3+I^- solution; **formation $CH_3NH_3PbI_3$**.
- spiro-OMeTAD as HTM from solution spin coating.
- Evaporation Au. Encapsulation of the cell. Active cell area only ~ 0.1-0.5 cm^2.



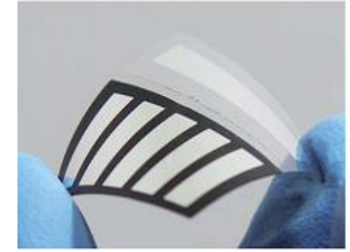
Advantage of cells:
- Relatively easy preparation
- Inexpensive materials

Flexible perovskite solar cells

Kim et al., Energy & Environ. Science 2014

Flexible cells with PCE 12.2%.

They withstand >1000 cycles of bendings.



Photovoltaic parameters of few perovskite solar cell (active area ~0.2 cm^2)

Results from different reports

V_{OC} in V	I_{SC} in mA cm^2		Efficiency in %
1.1	21.6		17.0
1.1	22.8		19.3
1.1	24.6		20.1

Main problem of such cells is stability. Recent progress.

Stability of 2 devices (active area ~0.2 cm^2) under ambient conditions as function of storage time. Efficiencies ~16% (normalized to 1.0).

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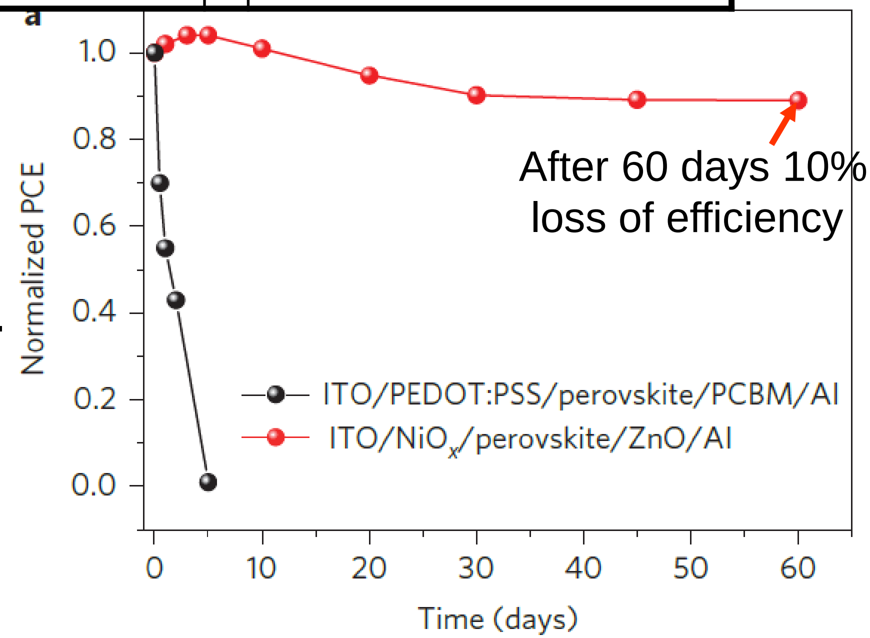


You et al., Nature Nanotechnology 2016, 11, 75.

Other problems:

- Toxicity of lead.
- Loss of efficiency in modules.

4. Summary

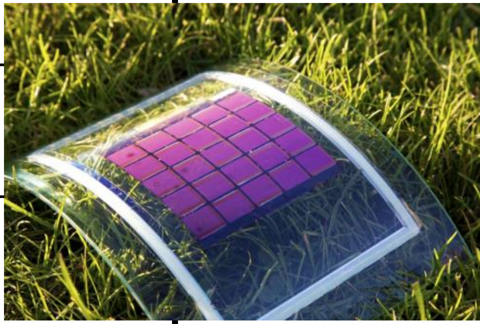
Photovoltaic solar cells

First generation realized

Second generation partly realized

Third generation not realized. Problem stability

Photovoltaic cell	Device	Efficiency /%
Single crystalline Si	Module	17- 18
Multi crystalline Si	Module	12 - 14
Amorphous Si	Module	7 - 9
CI(G)S (Cu, In, (Ga), Se	Module	10 - 12
Small molecule bulk organic solar cell (BHJ)	Lab cell	9 - 12
Polymer molecule organic solar cell (PHJ)	Lab cell	10 – 12
Dye sensitized solar cell (DSSC)	Lab cell	11- 13
Perovskite solar cell	Lab cell	12 - 21



Costs of electricity by source for new power stations, 2013

Energy carrier	Eurocent per kWh
Inorganic photovoltaic, small power plant	7,9 – 11,6
Inorganic photovoltaic, large power plant	9,8 – 14.2
Three different organic photovoltaic cells, small power plant (not realized, expected)	11.0 ??, later less than 10
Wind offshore	11.9 – 19.4
Wind onshore	4,4 – 10,7
Natural gas	7,5 – 9,8
Black coal	6,3 – 8,0
Brown coal	3,8 – 5,3
Nuclear power plant	7,0 – 12,5

Source: google → Fraunhofer ISE Stromgestehungskosten Erneuerbare Energien)

Important:
In future different energy carriers will be used for generation of electrical energy.
Renewable energy sources including solar radiation will also play an important role.

Direct production of electrical energy from solar radiation: Commercial inorganic photovoltaic solar cells and more in detail development of organic solar cells

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2. **Inorganic photovoltaic solar cells**
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3.1 Solid state organic photovoltaic solar cells

3.2 Dye sensitized solar cells

3.3 Inorganic/organic perovskite solar cells

4. **Summary**

University Bremen

One of several photovoltaic plants on the roofs of university buildings.