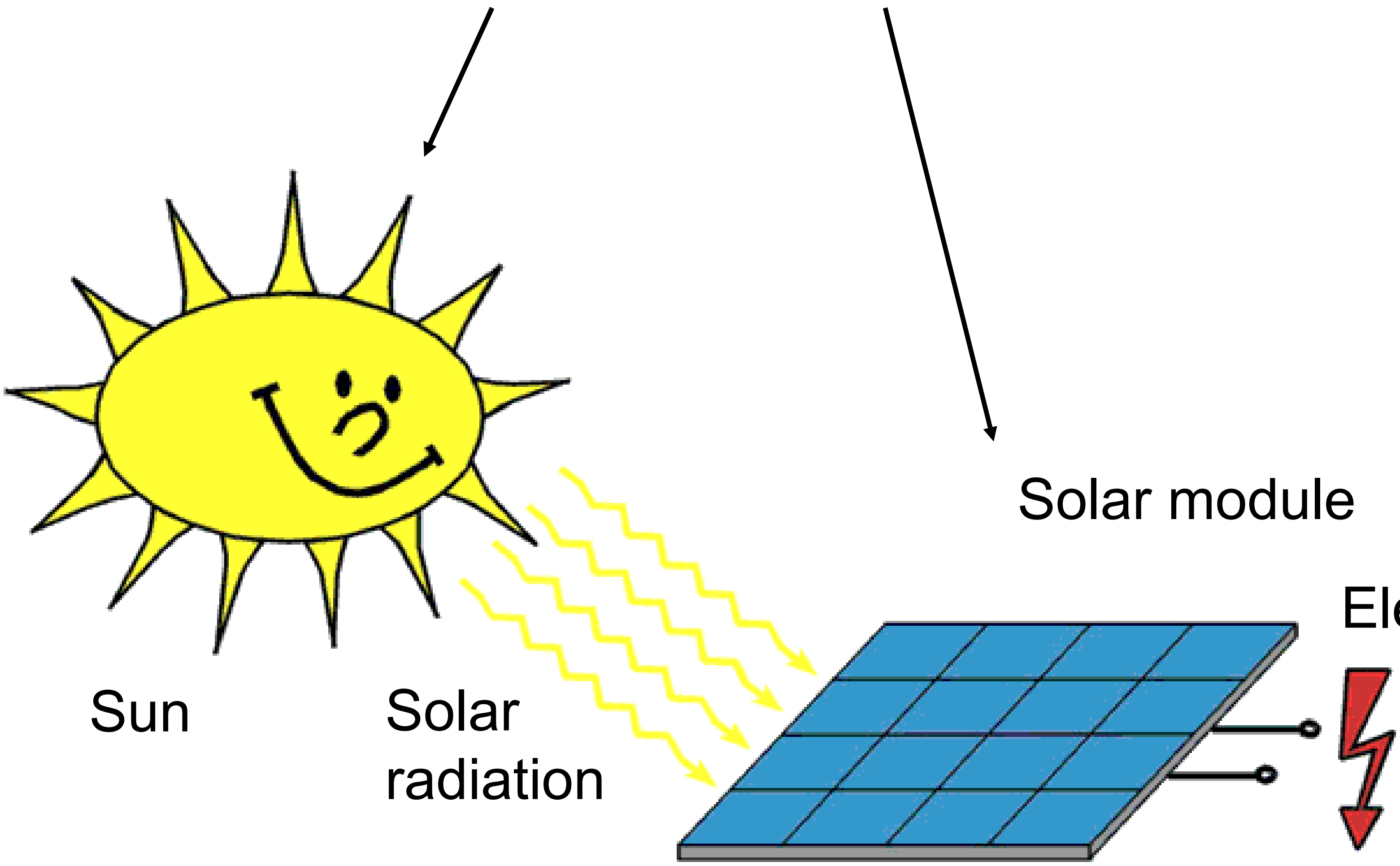
Photo - voltaics



A. Poruba, Solartec

Photovoltaics

Photovoltaics (PV) literally means "light-electricity"

- direct conversion of light into electricity based on the photovoltaic effect
- advanced semiconductor device: **solar cells**
  (**do not confuse with solar collectors**)
- the main energy source for the "post-fossil-era"



Photovoltaic solar energy

Advantages:

- environmentally friendly
- no noise, no moving parts
- no emissions
- no use of fuels and water
- minimal maintenance requirements
- long lifetime, up to 30 years
- electricity is generated wherever there is light, solar or artificial
- PV operates even in cloudy weather conditions
- modular "custom-made" energy can be sized for any application from watch to a multi-megawatt power plant

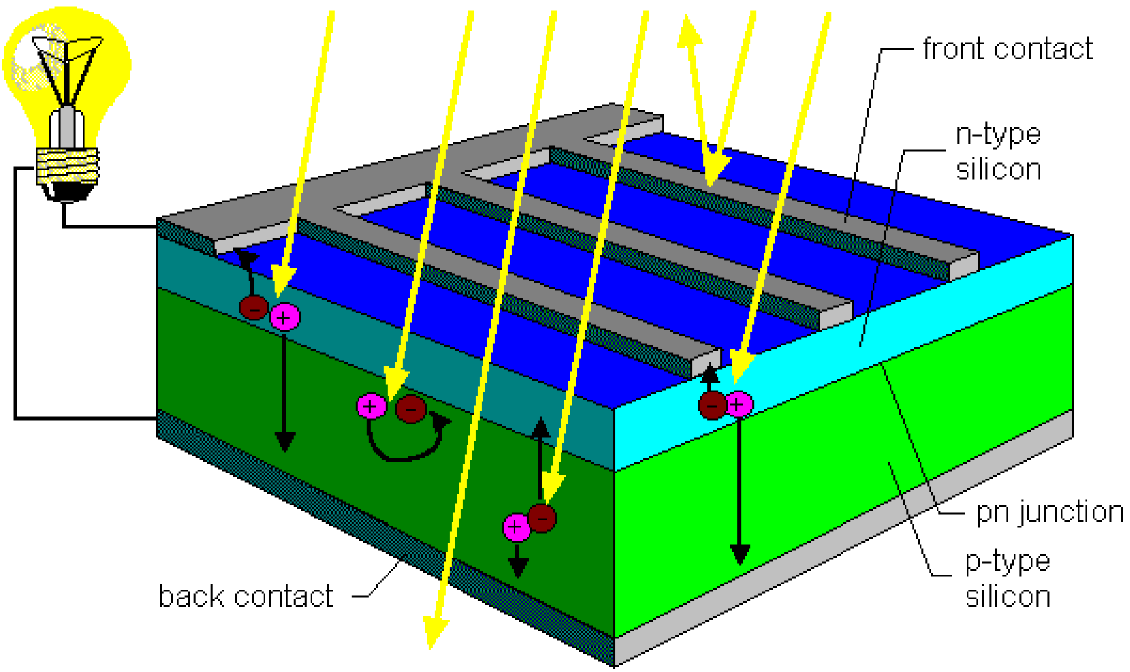
Limitations:

- PV cannot operate without light
- high initial costs that overshadow the low maintenance costs and lack of fuel costs
- large area needed for large scale applications
- PV generates direct current special DC appliances or an inverter are needed
- in off-grid applications energy storage is needed

Solar cell operation

Solar cell operation is based on the photovoltaic effect:

The generation of a voltage difference at the junction of two different materials in response to visible or other radiation.



Solar cell external parameters

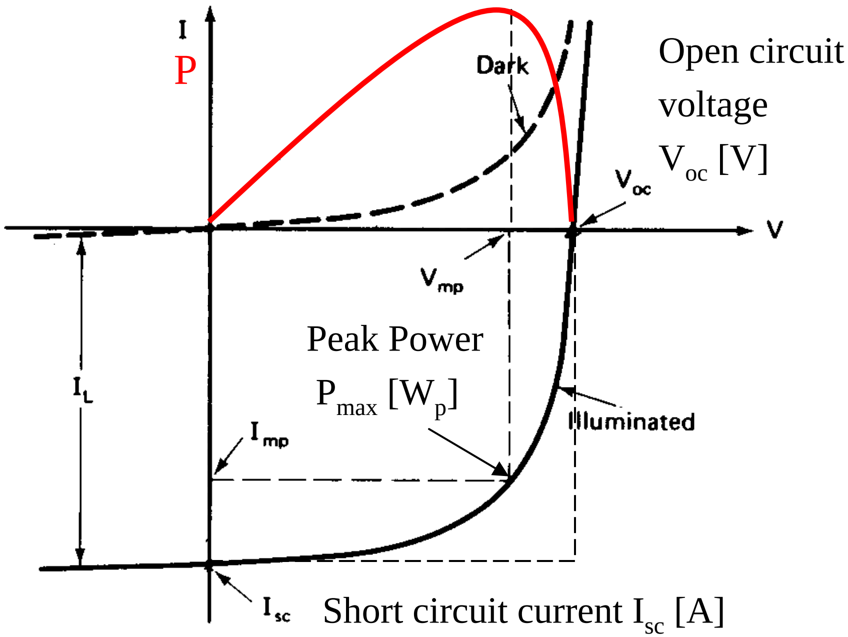
I-V measurement

Standard test conditions:

- AM1.5 spectrum
- irradiance 1000 W/m^2
- temperature 25°C

External parameters:

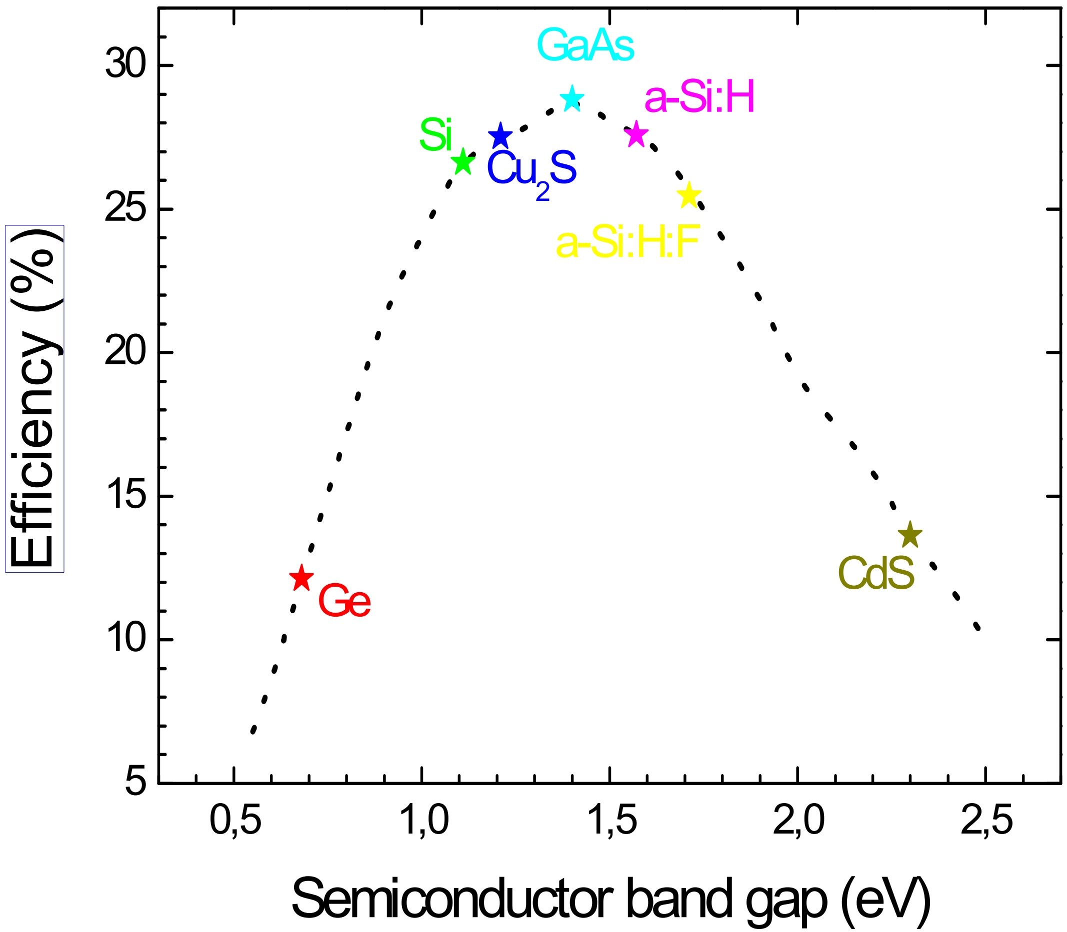
- **Short circuit current I_{sc} [A]**
- **Open circuit voltage V_{oc} [V]**
- **Fill factor ff**
- **Maximum (peak) power P_{max} [W_p]**
- **Efficiency η**



$$P_{max} = V_{mp} I_{mp} = ff\ V_{oc}\ I_{sc}$$

$$\eta = P_{max} / P_I = ff\ V_{oc}\ I_{sc} / P_I$$

Theoretical efficiency as a function of semiconductor band gap

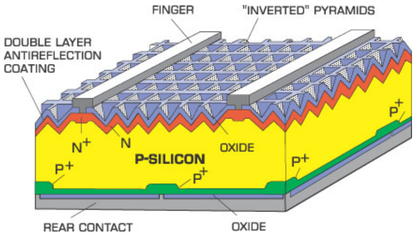


Main energy losses:

- Non-absorption of low-energy photons
- Thermalization of excess photon energy
- Voltage factor
- Fill Factor
- Collection efficiency

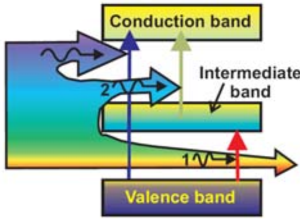
Three generations of solar cells

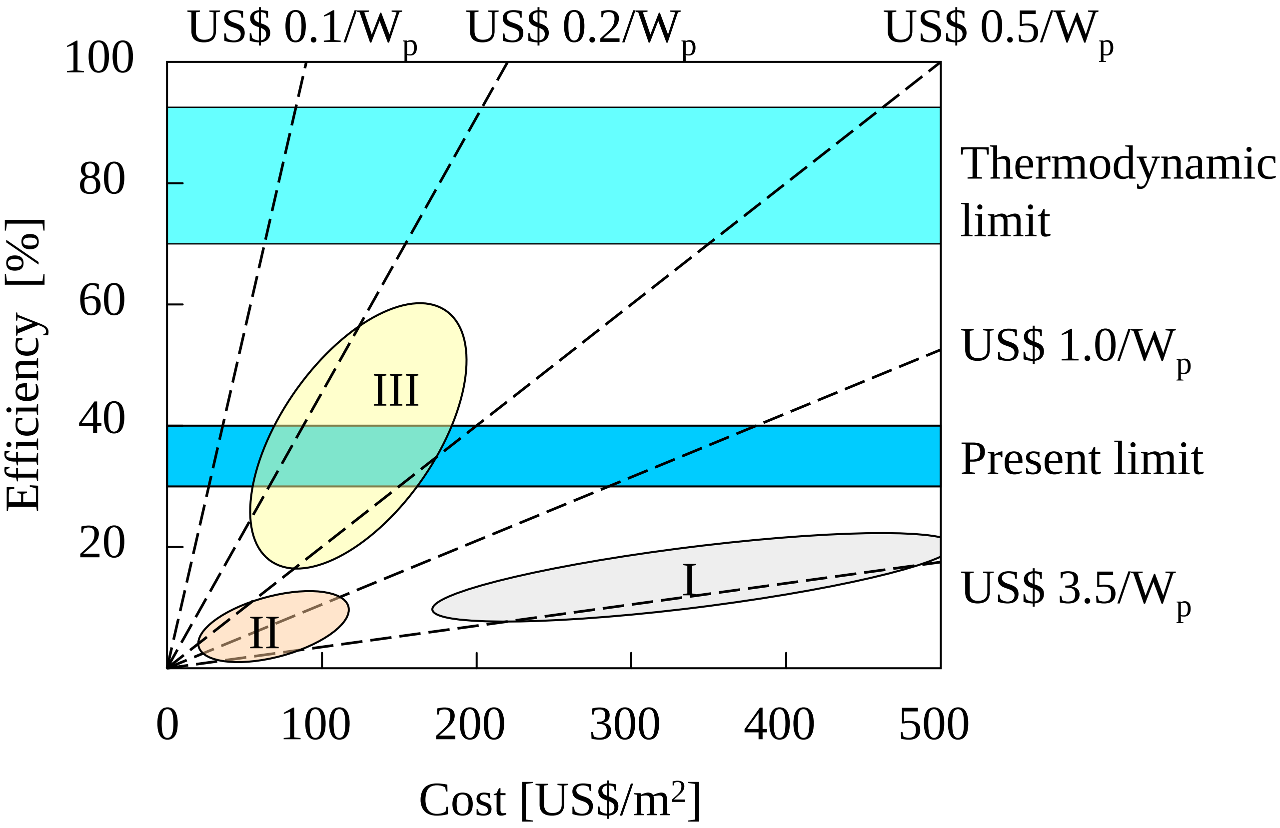
I. Wafer based Si



II. Thin films

III. Cheap and efficient





DIMES Delft Institute of Microsystems and Nanoelectronics

TU Delft Delft University of Technology

Bulk materials for solar cells

Bulk Crystalline Silicon

Thin-film materials for solar cells

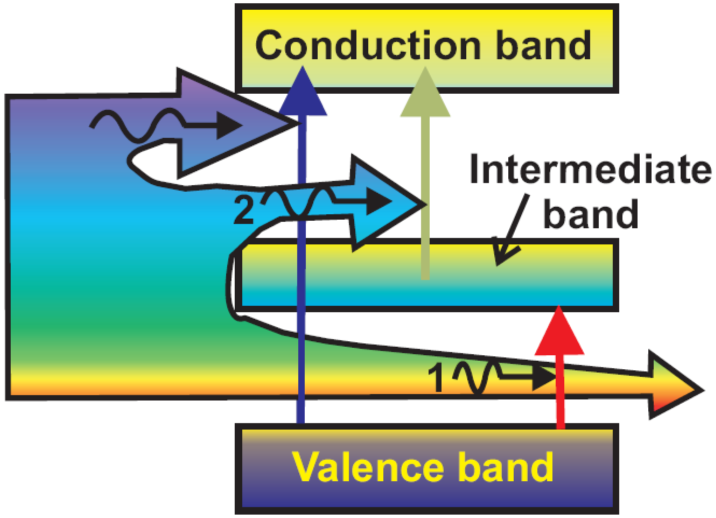
Thin-film Silicon

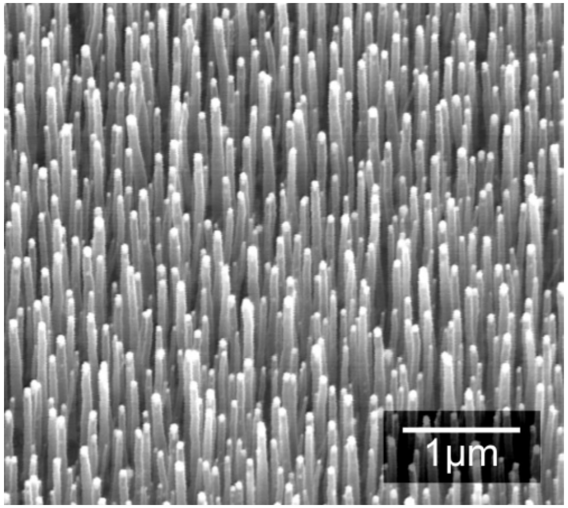
Hydrogenated amorphous silicon (a-Si:H)

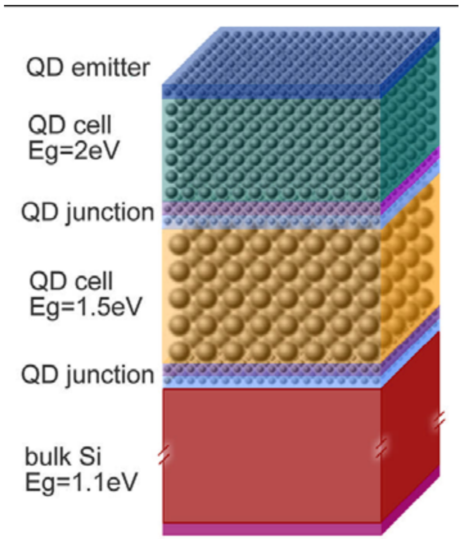
Hydrogenated microcrystalline silicon (μc-Si:H)

Concepts for future cells

- Up- and down conversion
- Intermediate band
- Hot carriers
- Superlattices
- Quantum dots
- Nanotubes

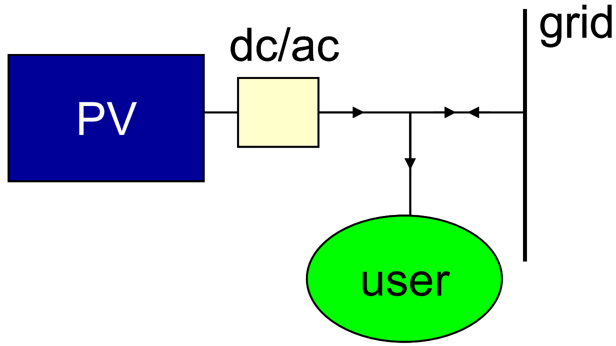




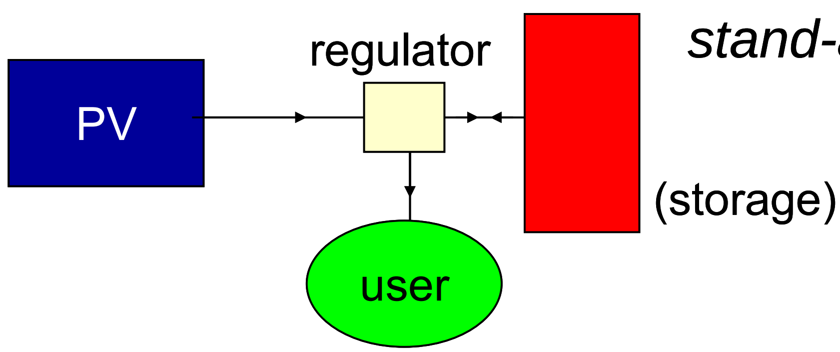


PV system

Two main types:



grid-connected system



stand-alone system

PV system

Solar cell

- semiconductor device

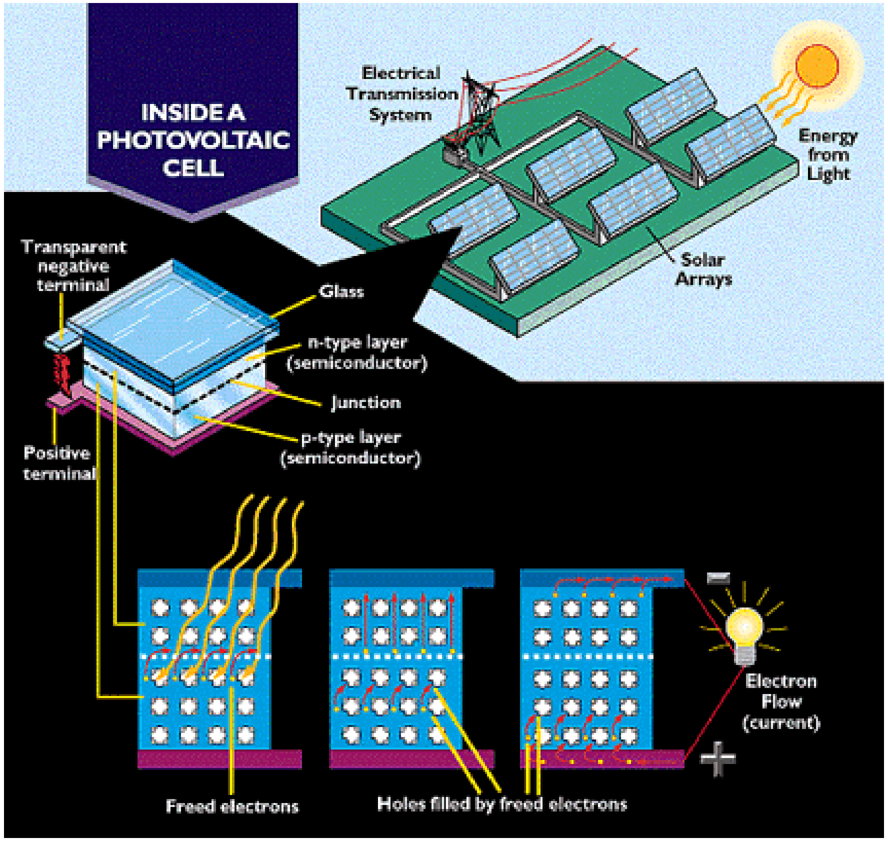
Solar panel (PV module)

- different than collector

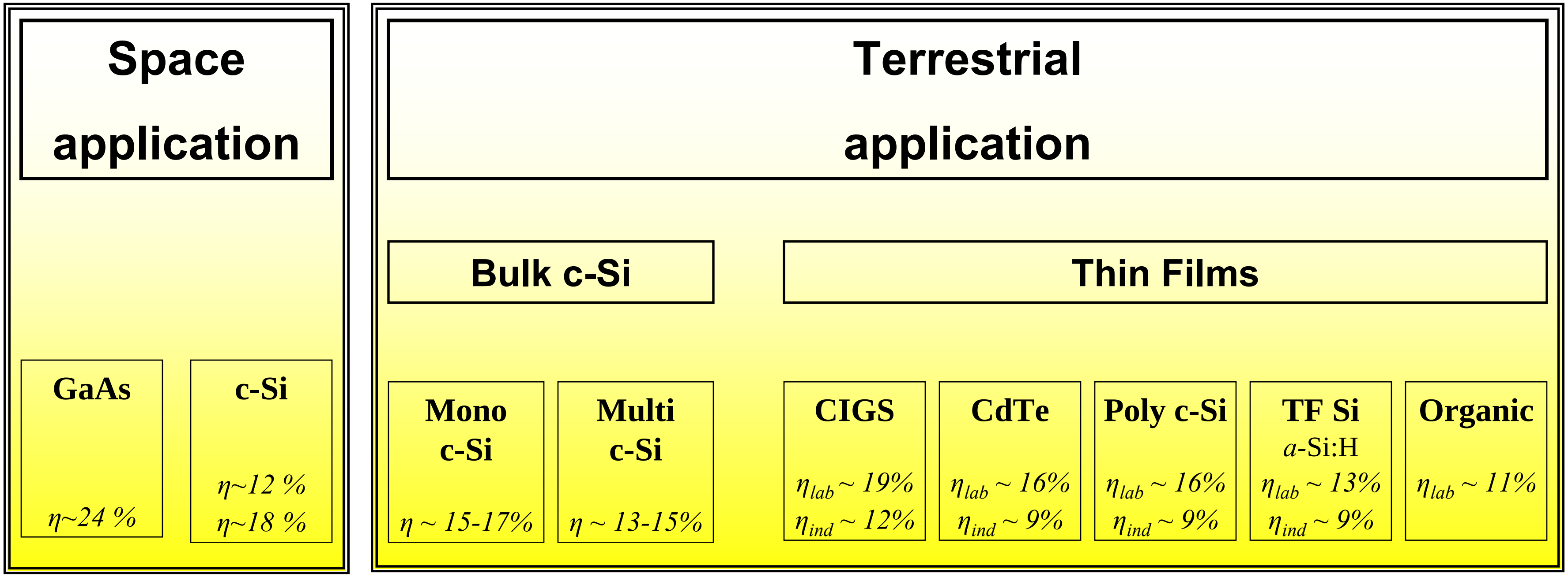
Solar array

Solar system:

- solar panel
- battery
- inverters
- electrical components
- appliance



Solar cell applications



GaAs (Gallium Arsenide)

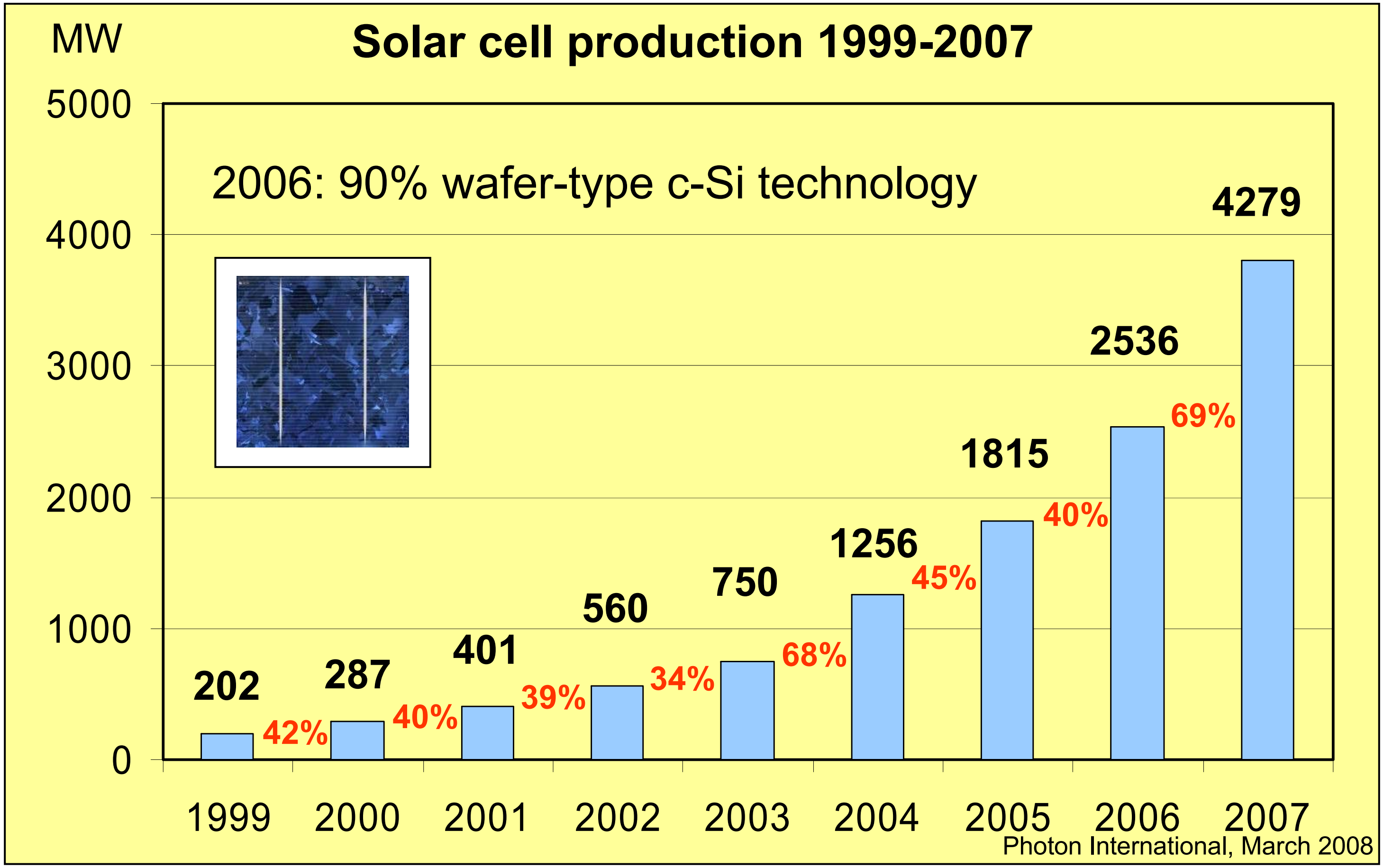
CIGS (Copper Indium Gallium Diselenide)

CdTe (Cadmium Telluride)

***a*-Si:H** (Hydrogenated amorphous silicon)

PV industry

PV industry: the fastest growing industry in the world



Market

Jobs

Predictions

Estimation market:

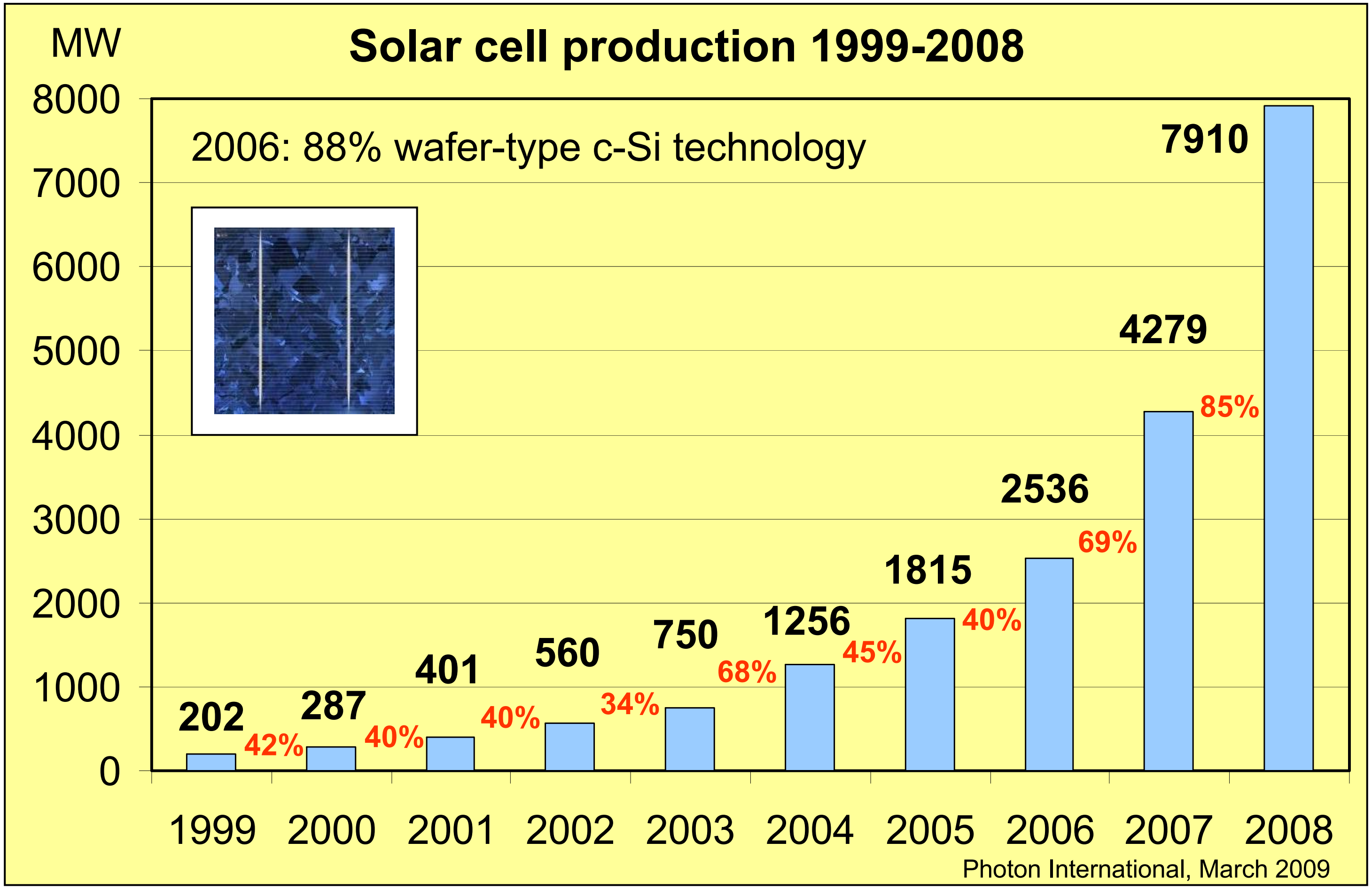
2005

~ 9 000x10⁶ €

~ 70 000 jobs

PV industry

PV industry: the fastest growing industry in the world



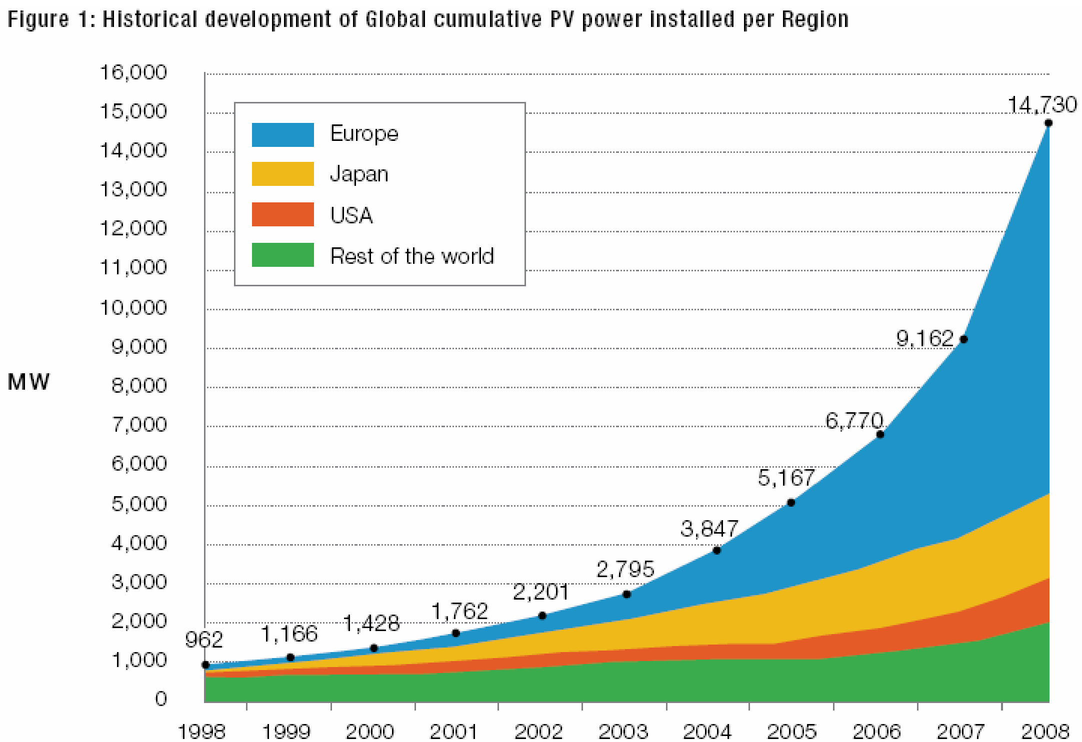
Estimation market:

2008

~ 23 x 10^9 €

~ 120 000 jobs

PV market



- The solar PV market has been booming.
- End of 2008 the Global cumulative capacity was approaching 15 GW
- Europe is leading the way with more than 9 GW representing over 65%
- Japan (2.1 GW, 15%) and the US (1.2 GW, 8%)

Source: EPIA

PV applications

1. Off-grid (stand alone) residential power systems

(solar home systems for individual household)

2. Grid connected PV systems

(roofs and outer walls of buildings, noise barriers along the motorways)

3. Off-grid industrial power systems

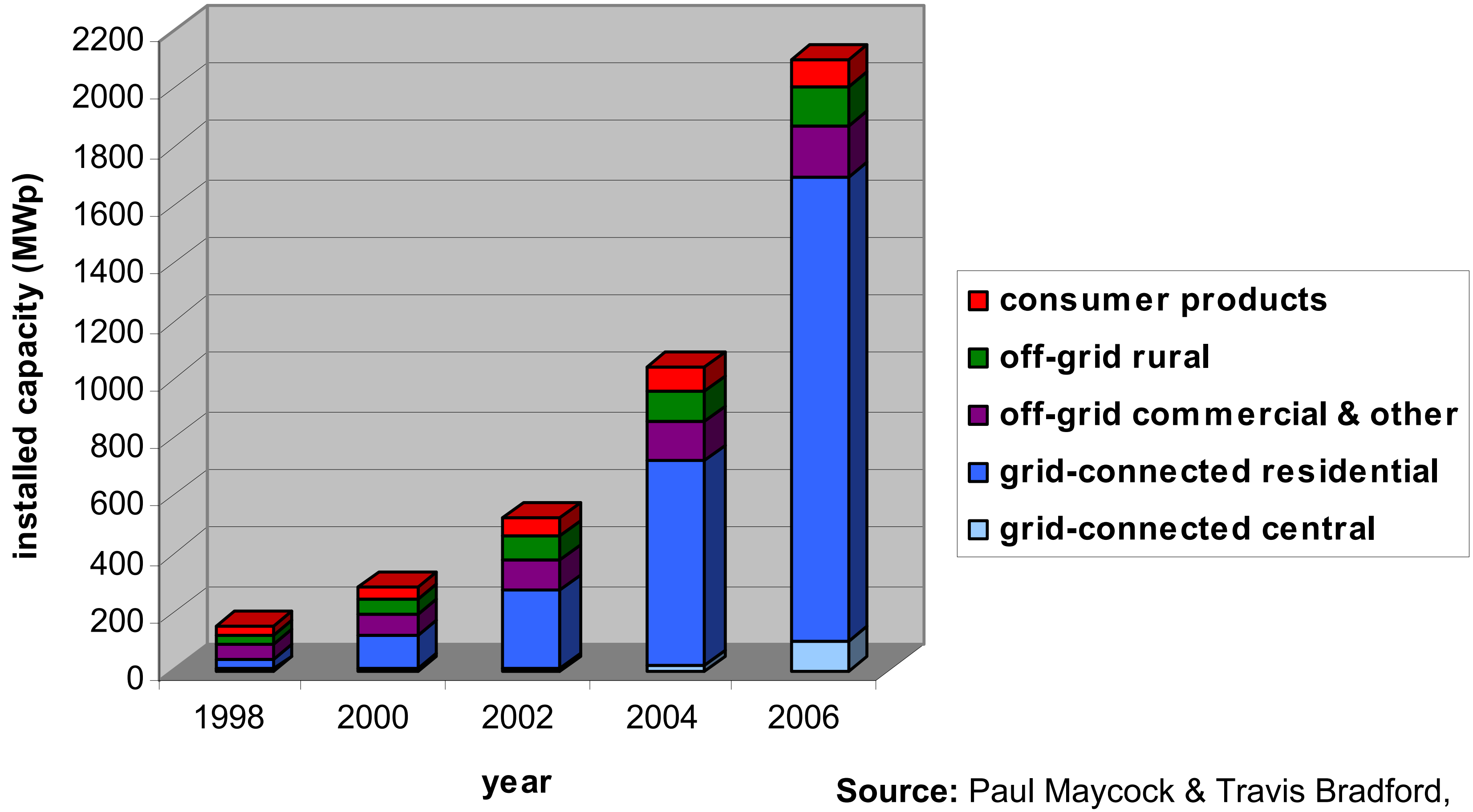
(water management, lighting, and telecommunication)

4. Consumer products

(watches, calculators, and lanterns)

5. Space applications

PV applications



Source: Paul Maycock & Travis Bradford, Renewable Energy World (July/Aug 2007)

Primary challenge for PV

Cost reduction of factor 5

to become competitive with conventional electricity

Today PV module price: 3.5-5.0 €/W_p **(W_p = Watt peak)**

Integral approach:

<u>Reducing module costs</u>

↓ raw materials & labor, investments

↑ efficiency, lifetime

<u>Optimizing systems integration</u>

↓ area and power related costs

Note: overall optimum ≠ highest efficiency

Cost reduction of PV systems

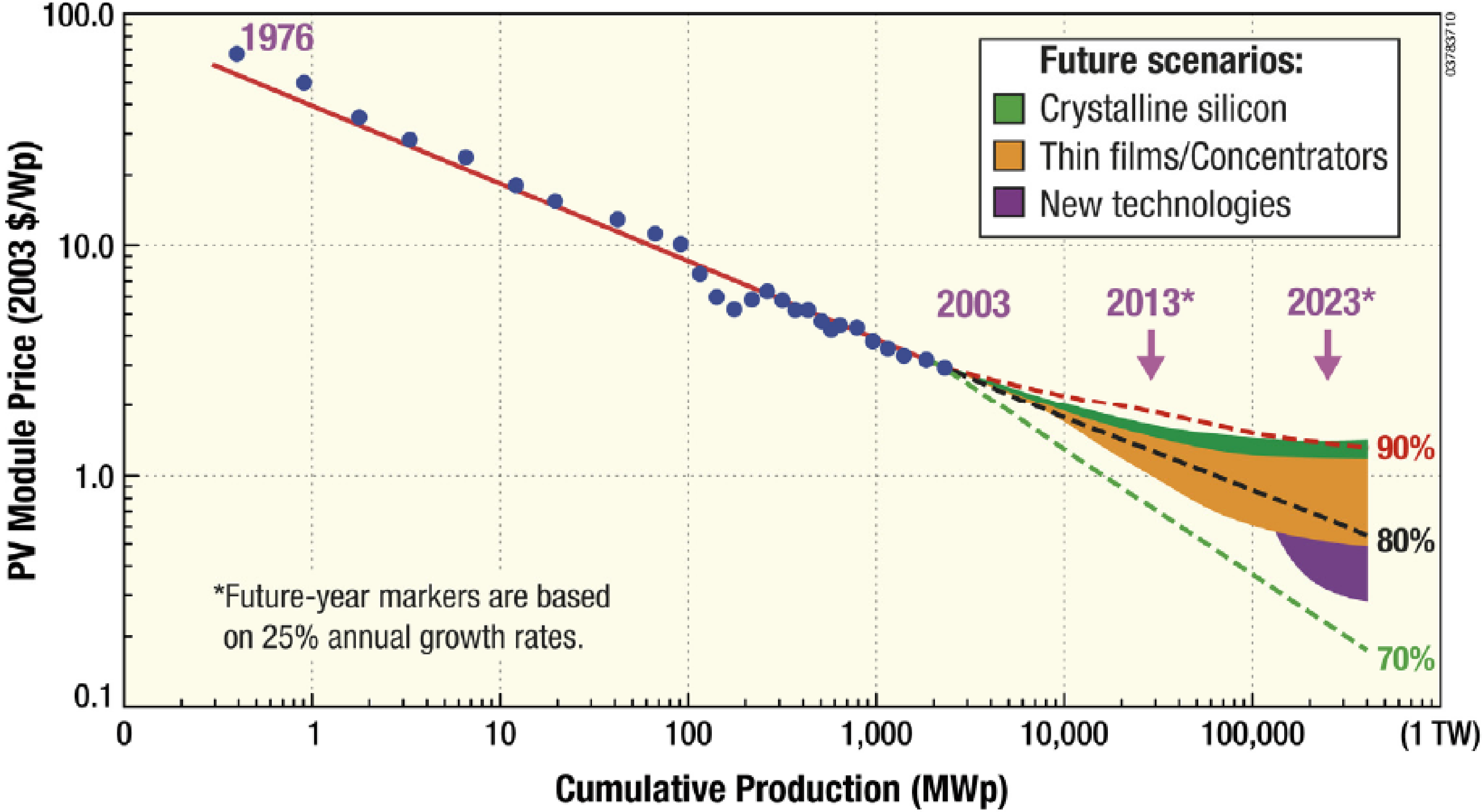
Requirements:

- low cost solar energy material
- high efficiency and good stability
- low manufacturing cost with good yield
- environmental safety and short energy pay back time

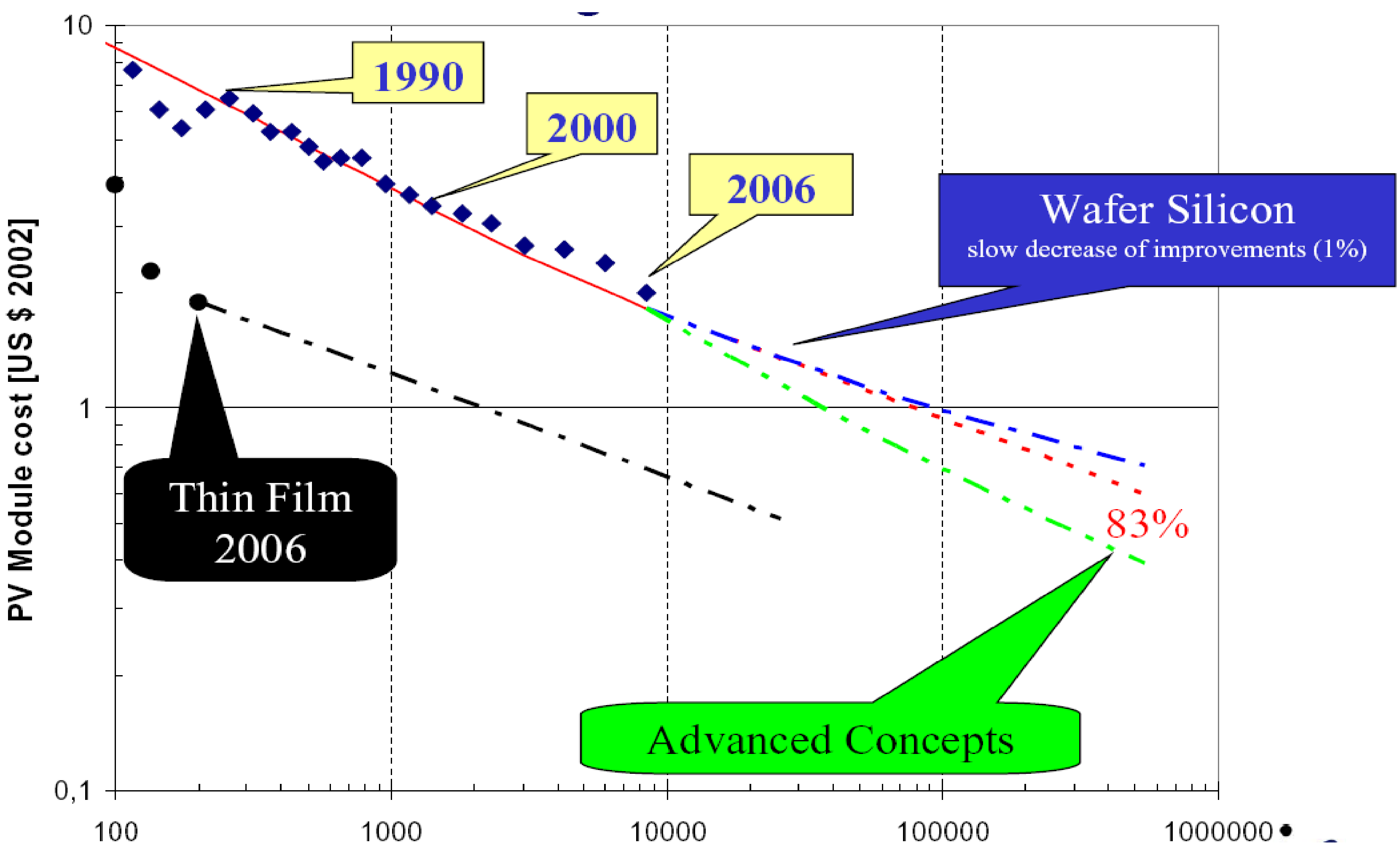
Energy pay back time: the time required for an energy conversion system or device to produce as much energy as is consumed for its production

Learning curve

The *combined* effect of technology development and manufacturing experience

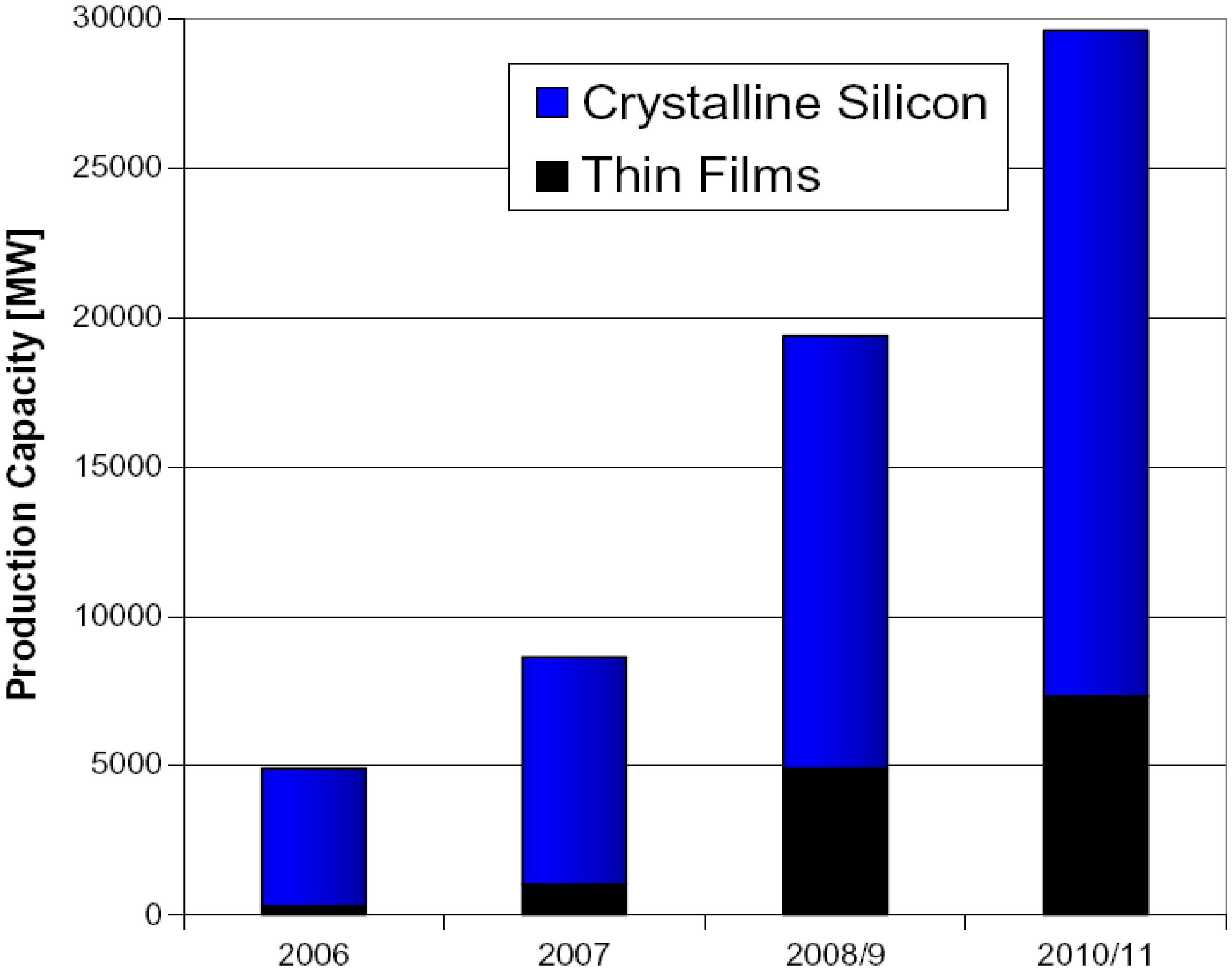


Learning curve scenarios



Arnulf Jäger-Waldau, JSPS workshop 2007

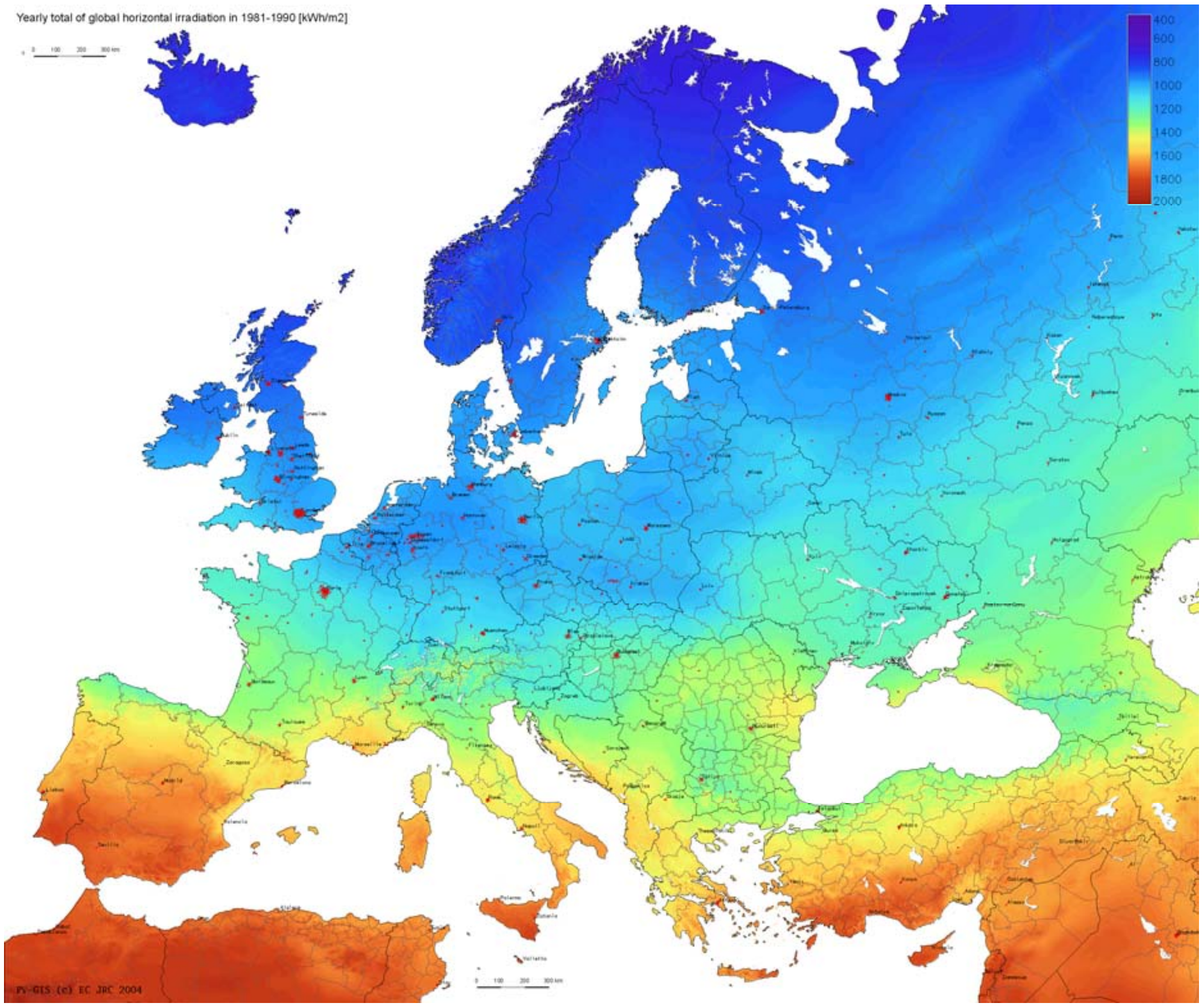
Announced capacity increases



Arnulf Jäger-Waldau, JSPS workshop 2007

Grid parity in Europe

2007 (lines to guide the eye)



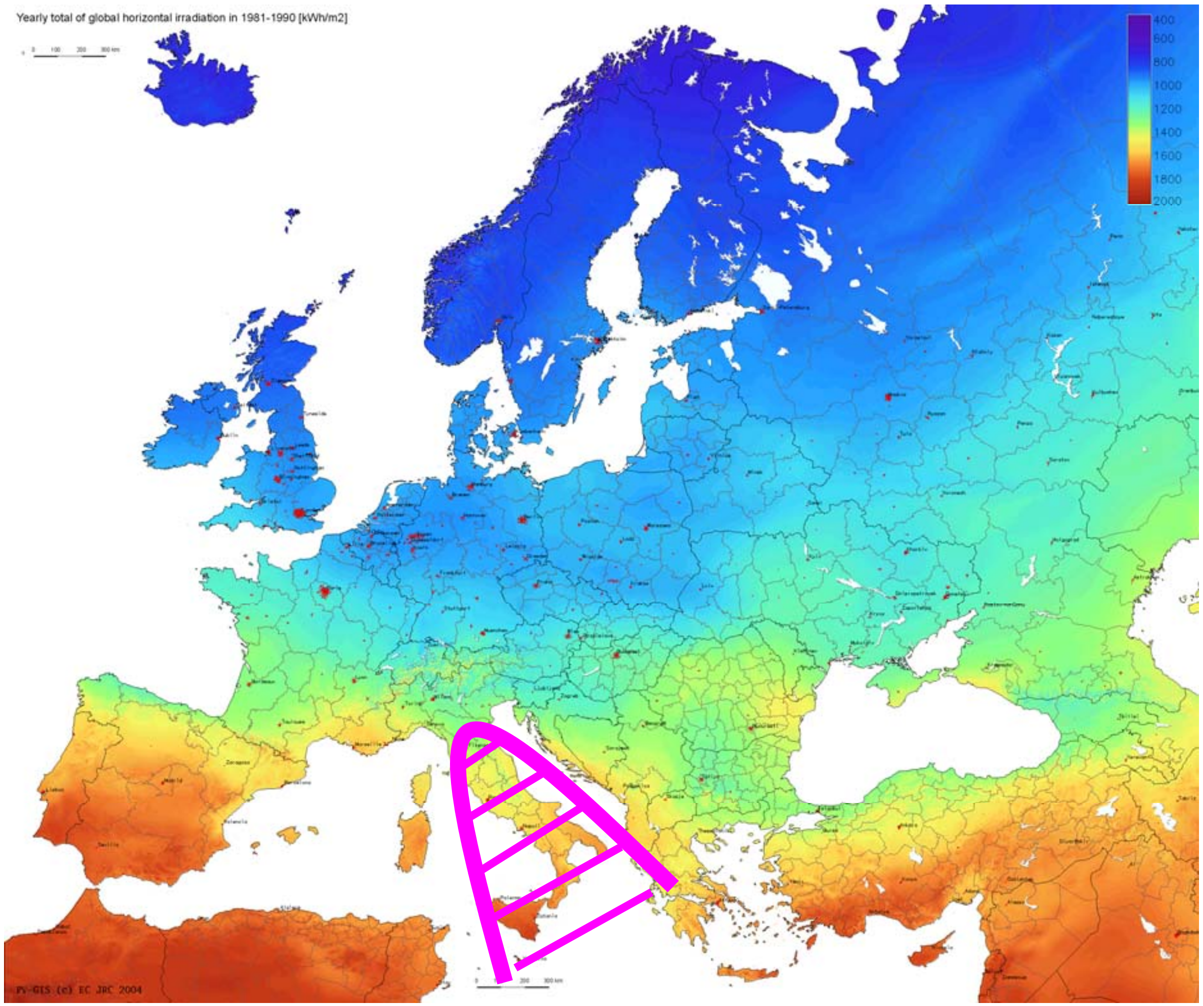
irradiation (kWh/m²·yr)	PV generation cost (€/kWh)
600	0.83
1000	0.50
1400	0.36
1800	0.28

Source: Wim Sinke

Iinsolation map: Šúri M., Huld T.A., Dunlop E.D. Ossenbrink H.A., 2007. Potential of solar electricity generation in the European Union member states and candidate countries. Solar Energy (in press), http://re.jrc.ec.europa.eu/pvgis/

Grid parity in Europe

2010 (lines to guide the eye)

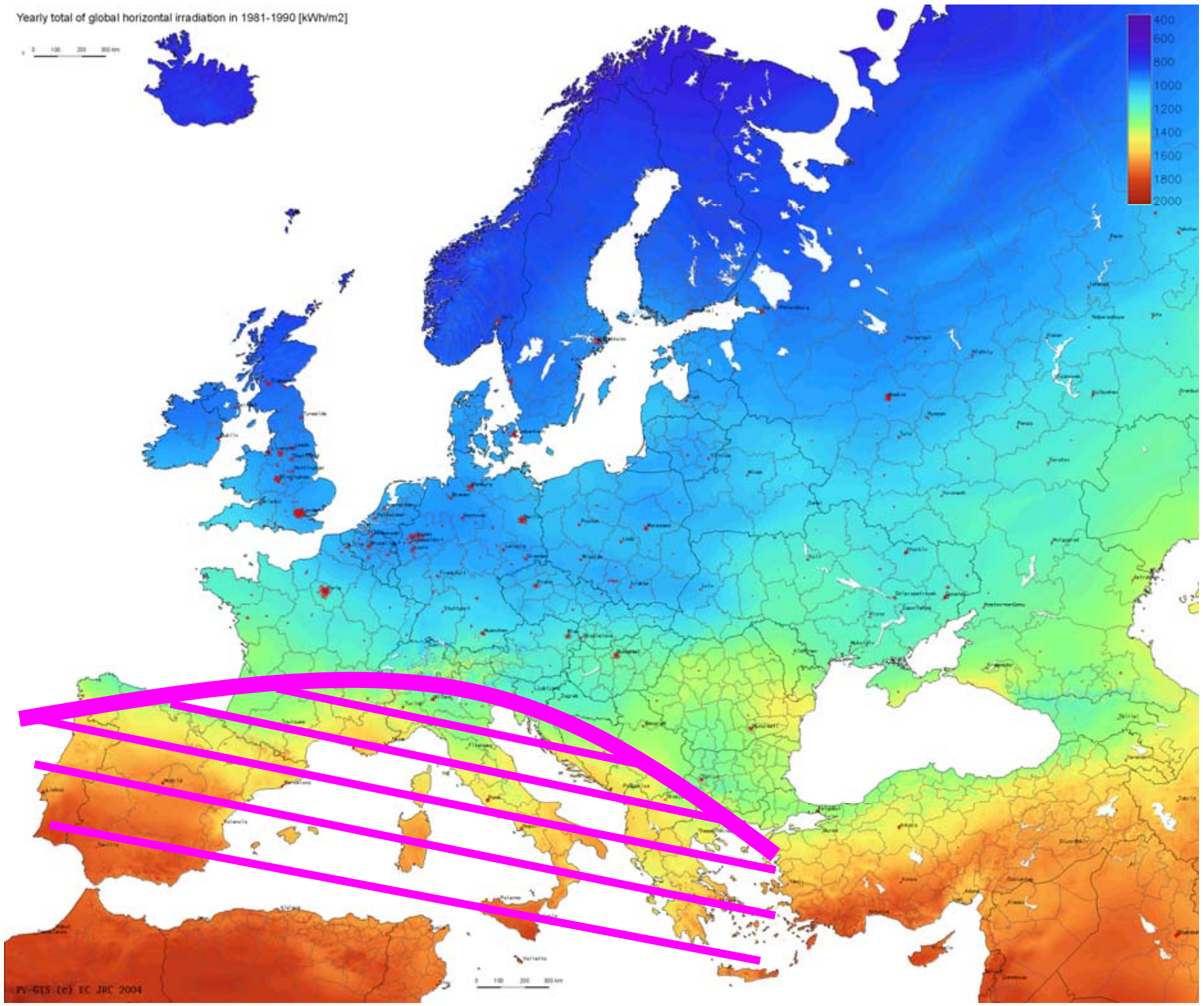


irradiation (kWh/m²·yr)	PV generation cost (€/kWh)
600	0.50
1000	0.30
1400	0.21
1800	0.17

Source: Wim Sinke

Grid parity in Europe

2015 (lines to guide the eye)

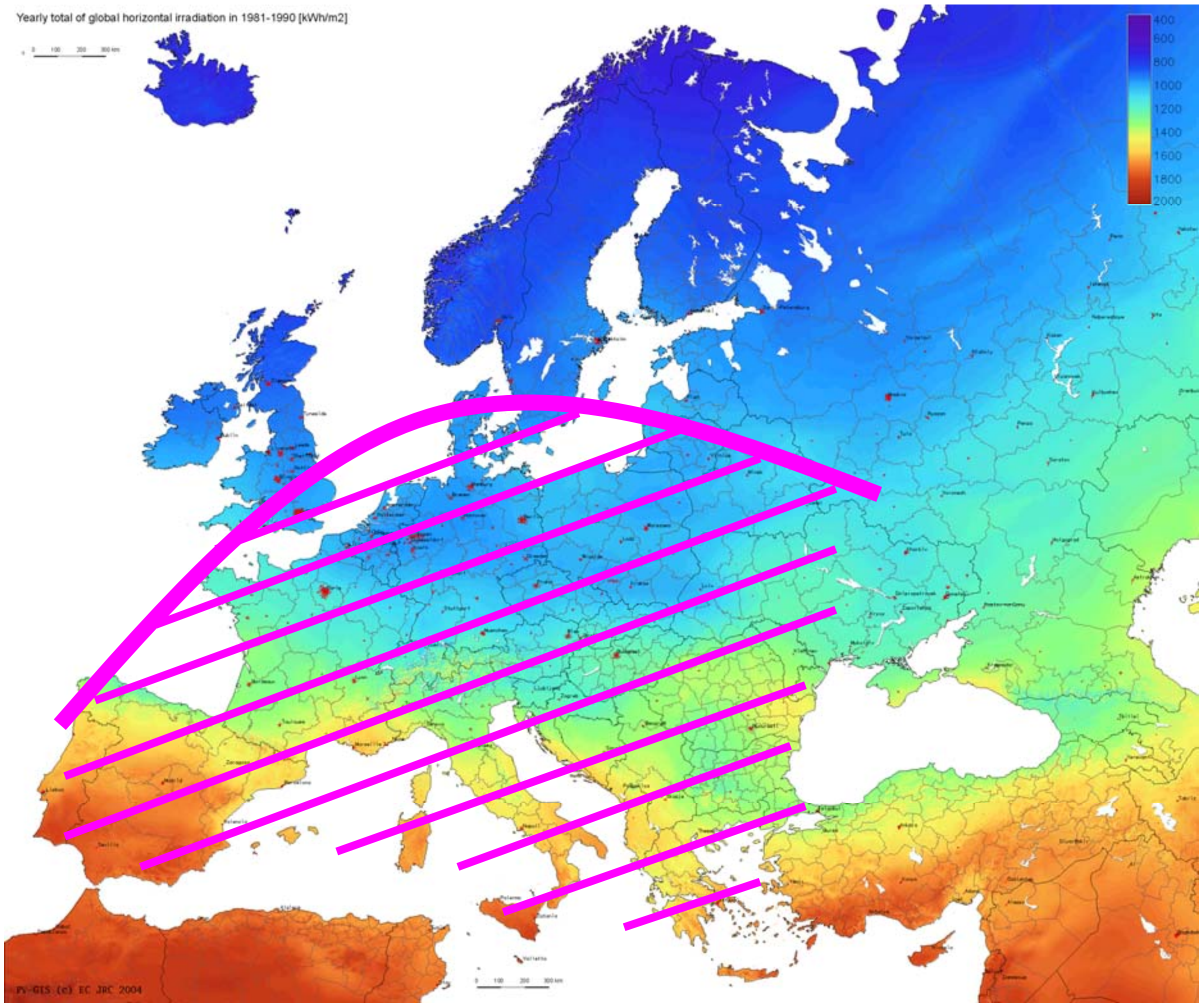


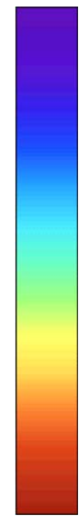
irradiation (kWh/m²·yr)	PV generation cost (€/kWh)
600	0.42
1000	0.25
1400	0.18
1800	0.14

Source: Wim Sinke

Grid parity in Europe

2020 (lines to guide the eye)



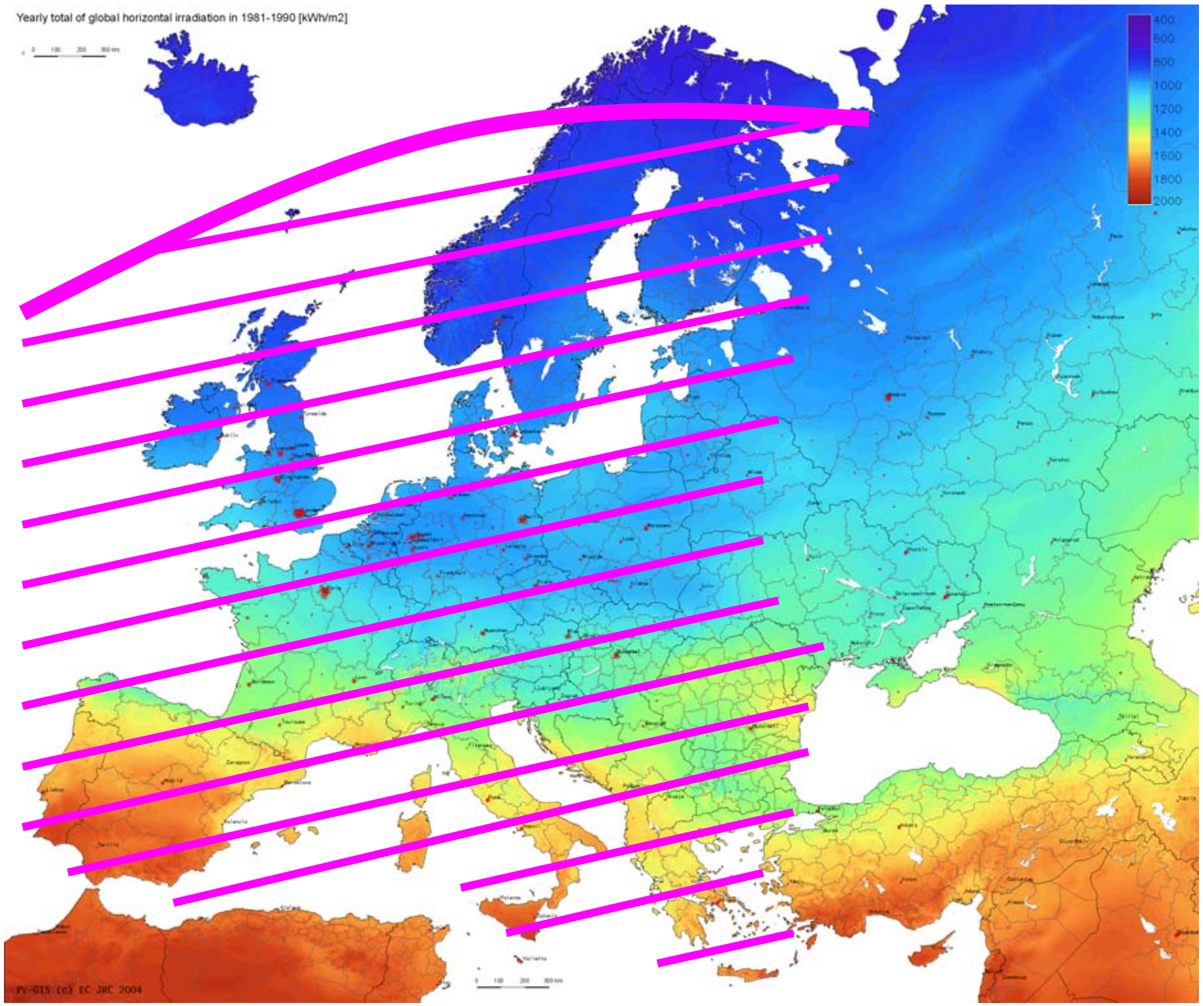


irradiation (kWh/m²·yr)	PV generation cost (€/kWh)
600	0.33
1000	0.20
1400	0.14
1800	0.11

Source: Wim Sinke

Grid parity in Europe

2030 (lines to guide the eye)



irradiation ($kWh/m^2 \cdot yr$)	PV generation cost (€/kWh)
600	0.17
1000	0.10
1400	0.07
1800	0.06

Source: Wim Sinke

WLS-PV (TW scale)

- **Turn-key system price <1 €/Wp (now >4 €/Wp)**
- **(→ generation costs <0.05~0.10 €/kWh)**
  - low-cost modules (0.5~1 €/Wp) at very high efficiency (>30%)
  - or: very low-cost modules (0.25~0.5 €/Wp) at moderate efficiency (>10%)

- **Use of non-toxic, abundantly available materials, and/or fully closed cycles**

- **Stability >20 years**
  - intrinsic (active materials) and extrinsic (passive materials)

- **But: also need transition technologies, to develop the market and to demonstrate scienific/technical and economical potential**

Source: Wim Sinke

WLS-PV (TW scale)

10^6 km^2 PV systems:

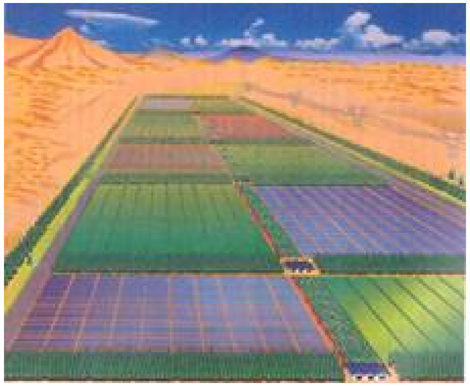
- **0.1 ~ 10 μm conversion layers: 10^5 ~ 10^7 m3 (>10^5 tons)**
- **1 ~ 10 μm conductive layers: 10^6 ~ 10^7 m^3**

(concentrators: × 1⁄100 ~ 1⁄1000 ; add optics & trackers)

- **30 μm ~ 3 mm encapsulation layers: $3{\cdot}10^7$ - $3{\cdot}10^9$ m3**

+ cabling (Cu, Al ?)

+ support structures (concrete, Fe, wood ?)



Source: Wim Sinke