Photovoltaics

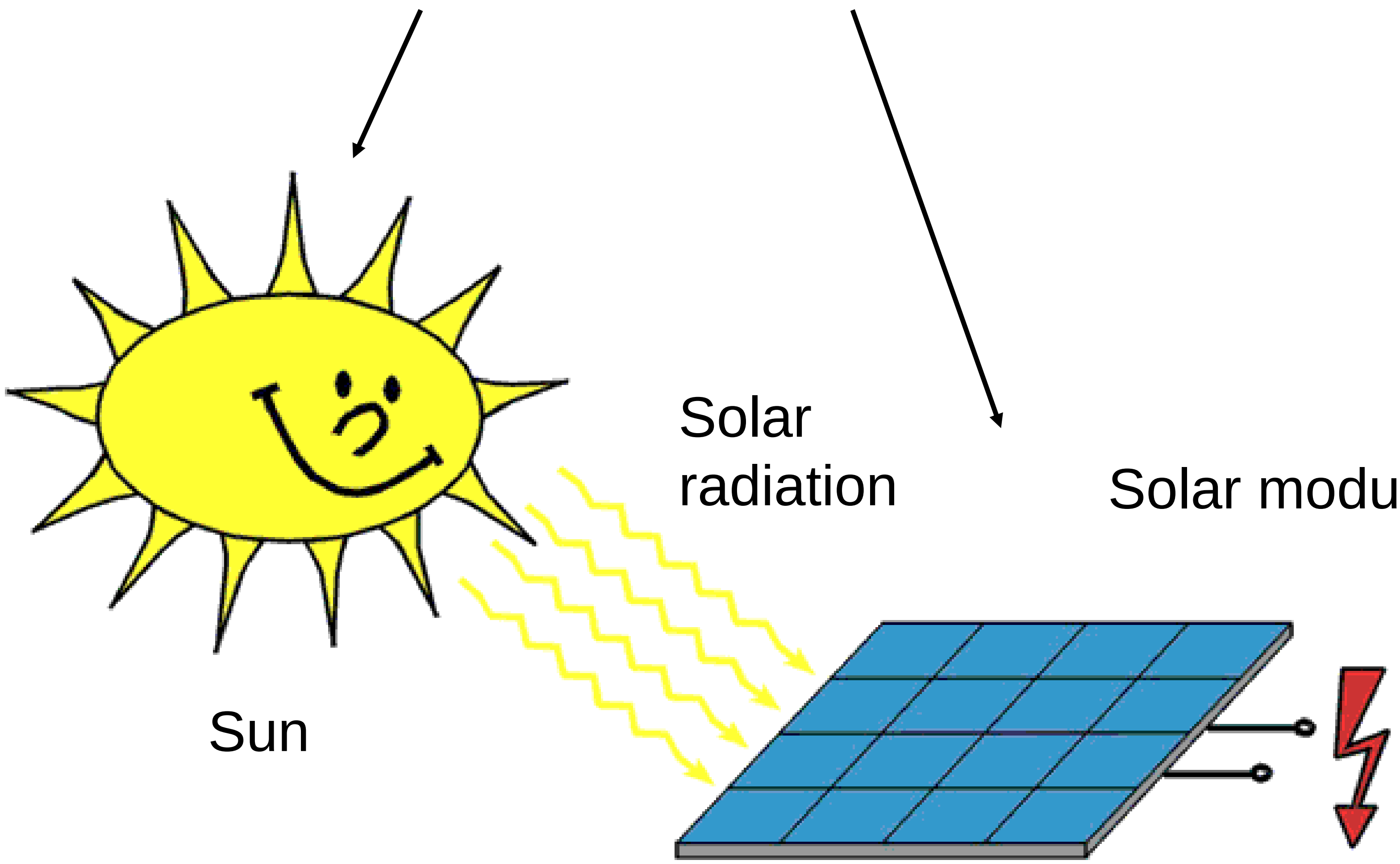
Photovoltaics (PV) literally means "light-electricity"

- 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"

DIMES
Delft Institute of Microsystems and Nanoelectronics

TU Delft
Delft University of Technology

Photo - voltaics



A. Poruba, Solartec

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

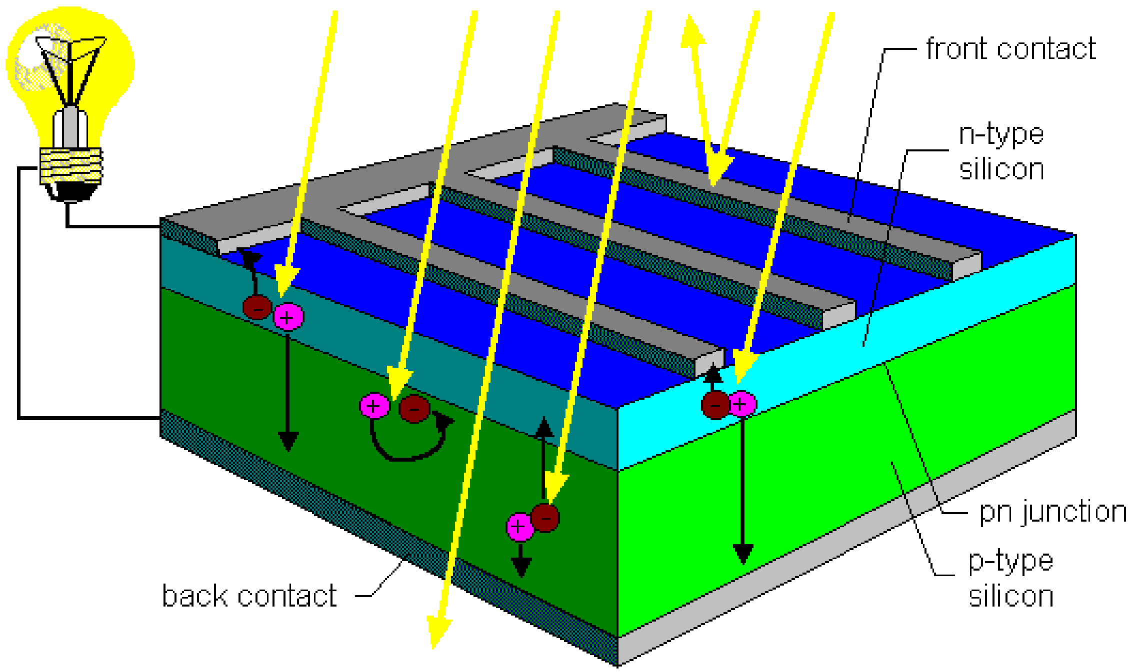
Limitations:

- 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

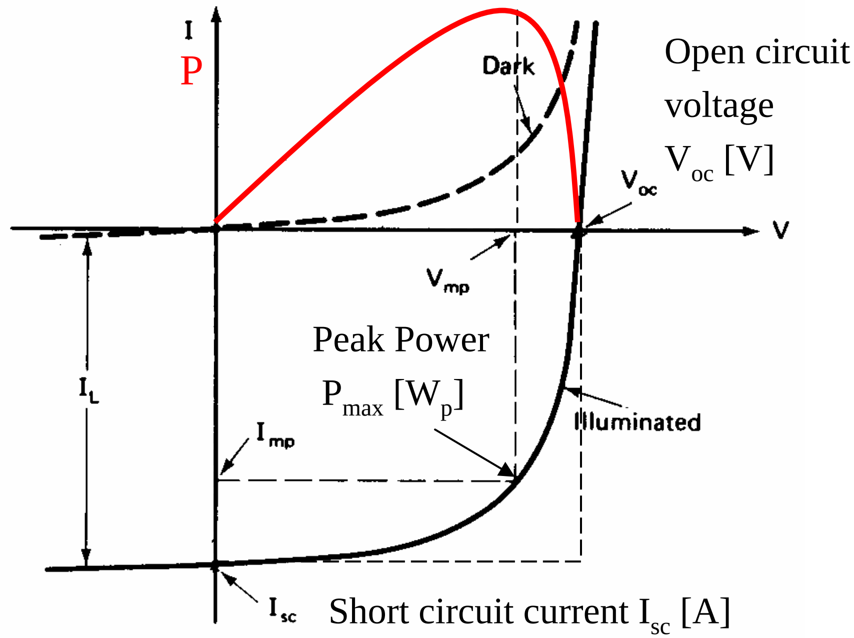
I-V measurement

Standard test conditions:

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

External parameters:

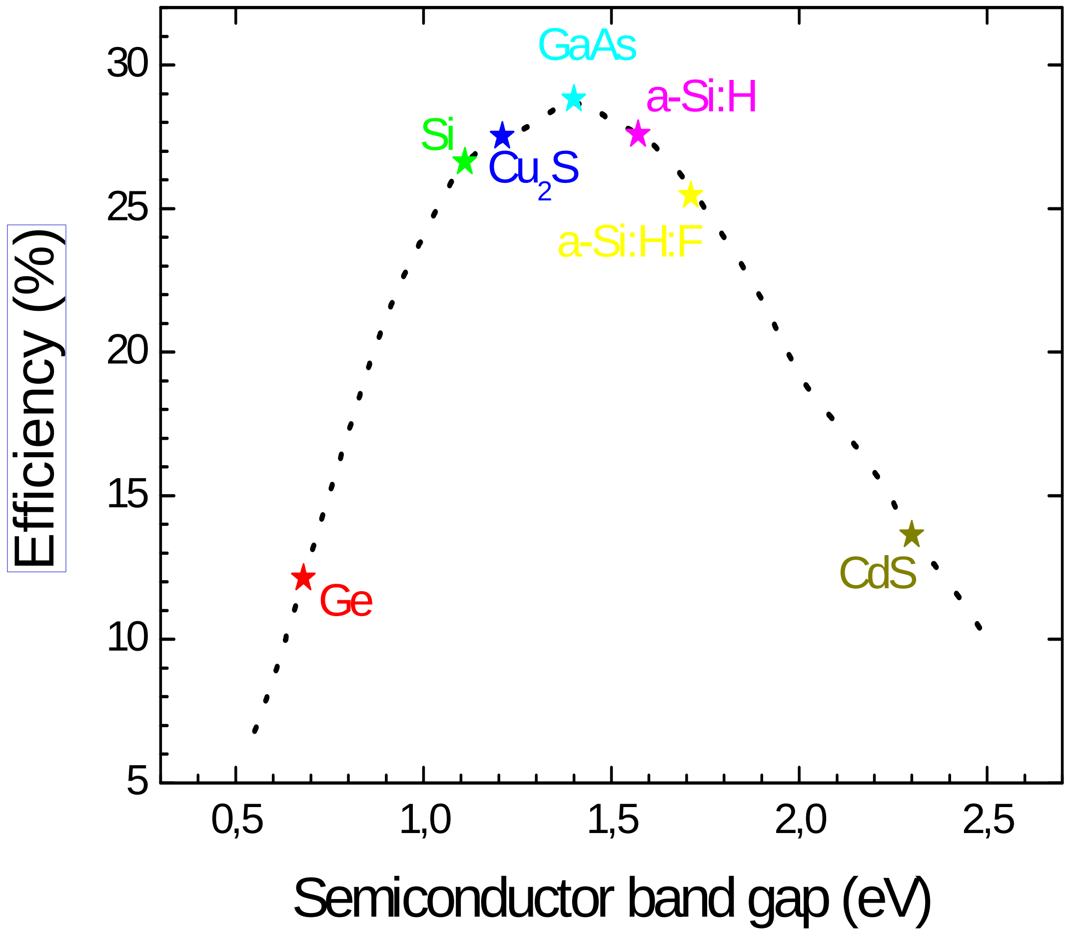
- **Short circuit current I_{sc} [A]**
- **Open circuit voltage V_{oc} [V]**
- **Fill factor ff**
- **Maximum (peak) power P_{max} [W_p]**
- **Efficiency η**



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

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

Theoretical efficiency as a function of semiconductor band gap

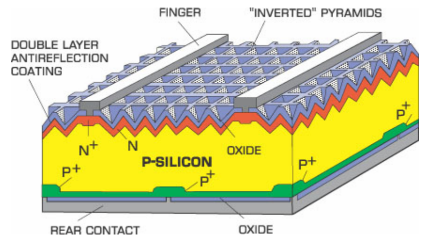


Main energy losses:

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

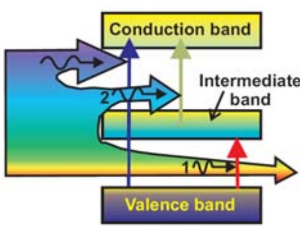
Three generations of solar cells

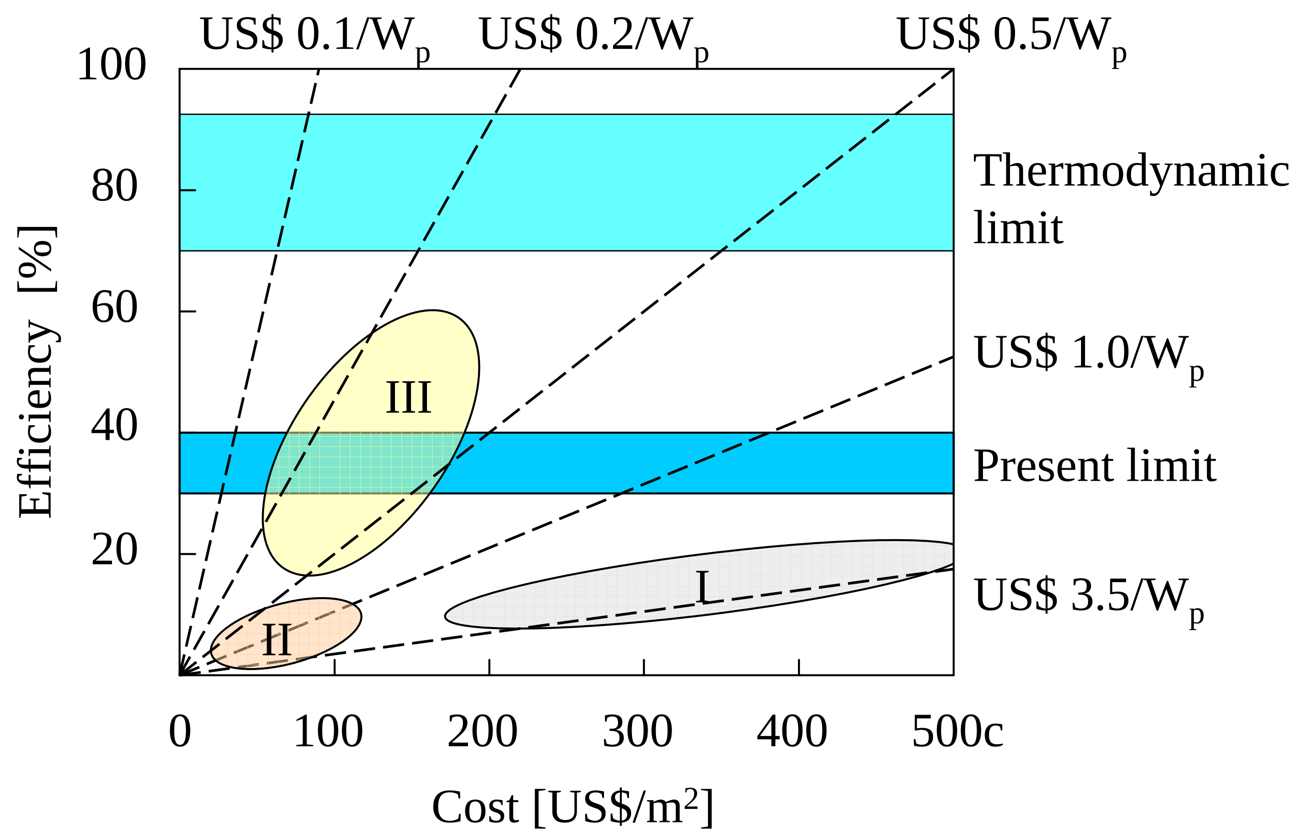
I. Wafer based Si



II. Thin films

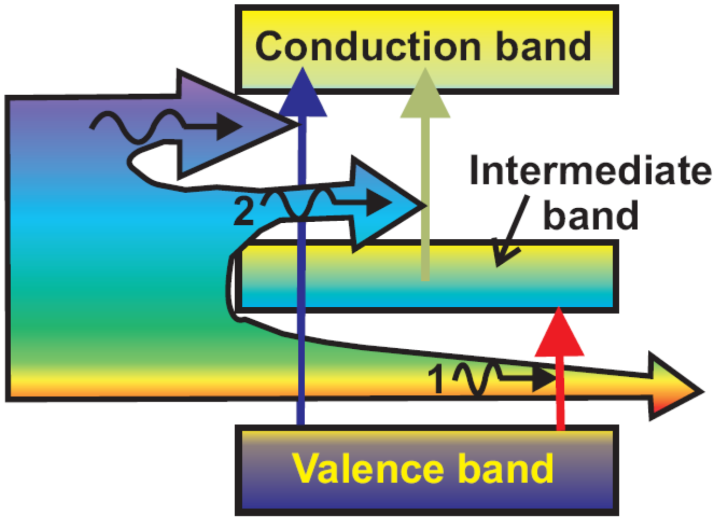
III. Cheap and efficient

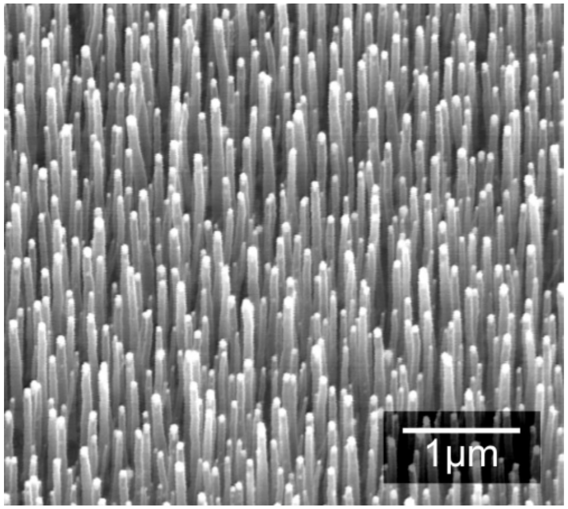


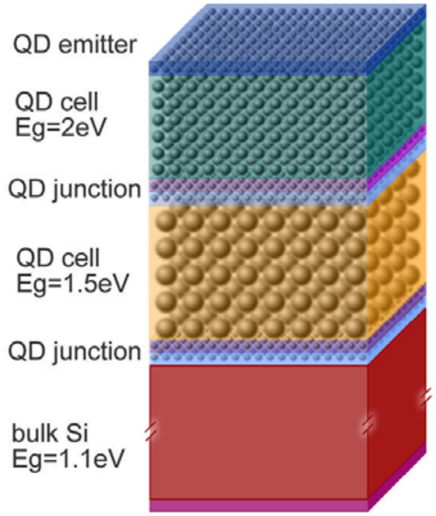


Concepts for 3rd generation cells

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







Solar cell technologies

Technology Efficiency [%]	c-Si	HIT Heterojunction with Intrinsic Thin Layer	TF Si (stabilised)	CIS	CdTe	DSSC Polymer
Record cell	24.7 Mono 19.8 Multi 16.6 transfer	22.3	9.3 Single 12.4 Tandem 13.4 Triple	18.9	17.0	11 unstable
Record module	22.7 Mono 15.3 Multi	?	10.4 Triple	13.4	10.7	4.7
Commercial module	12-17	16-17	5-9	9-11	10	not available
Cost reduction	Limited	Limited	++	++	++	++?

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)

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TU Delft Delft University of Technology

PV system

Solar cell

- semiconductor device

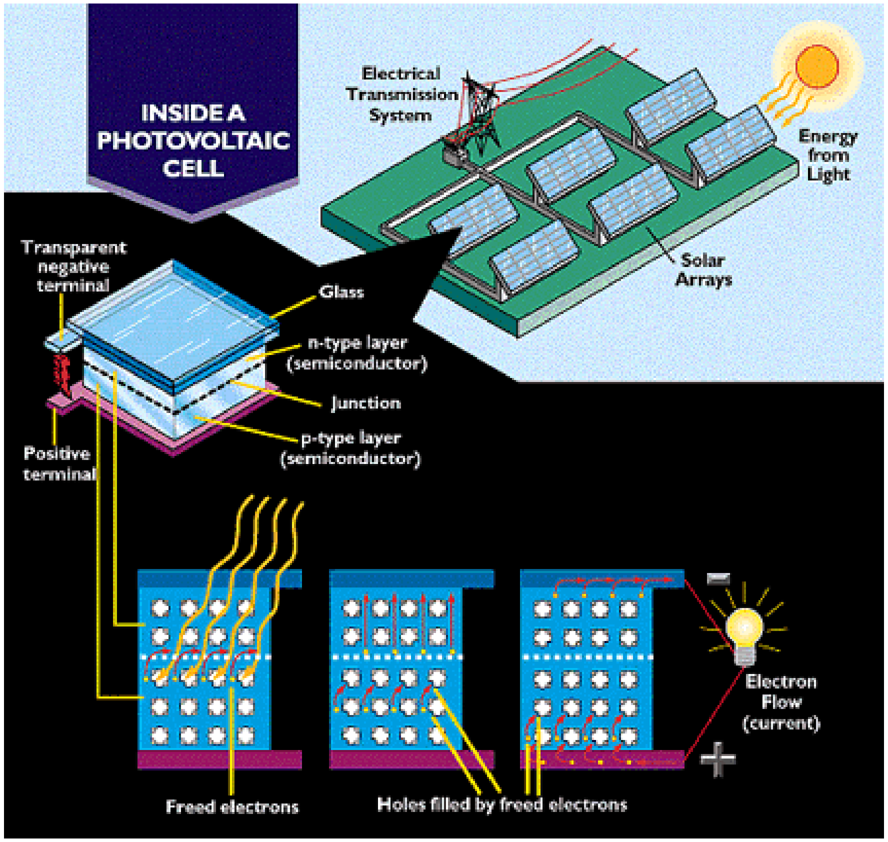
Solar panel (PV module)

- different than collector

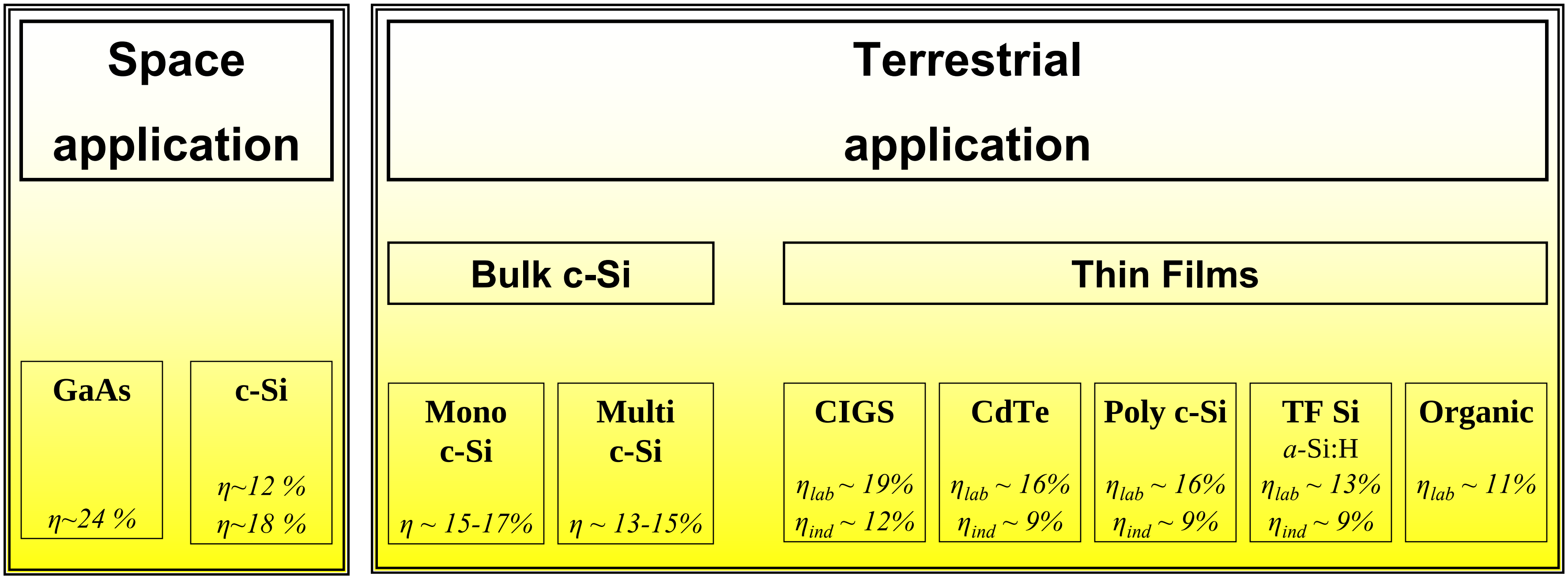
Solar array

Solar system:

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



Solar cell applications



GaAs (Gallium Arsenide)

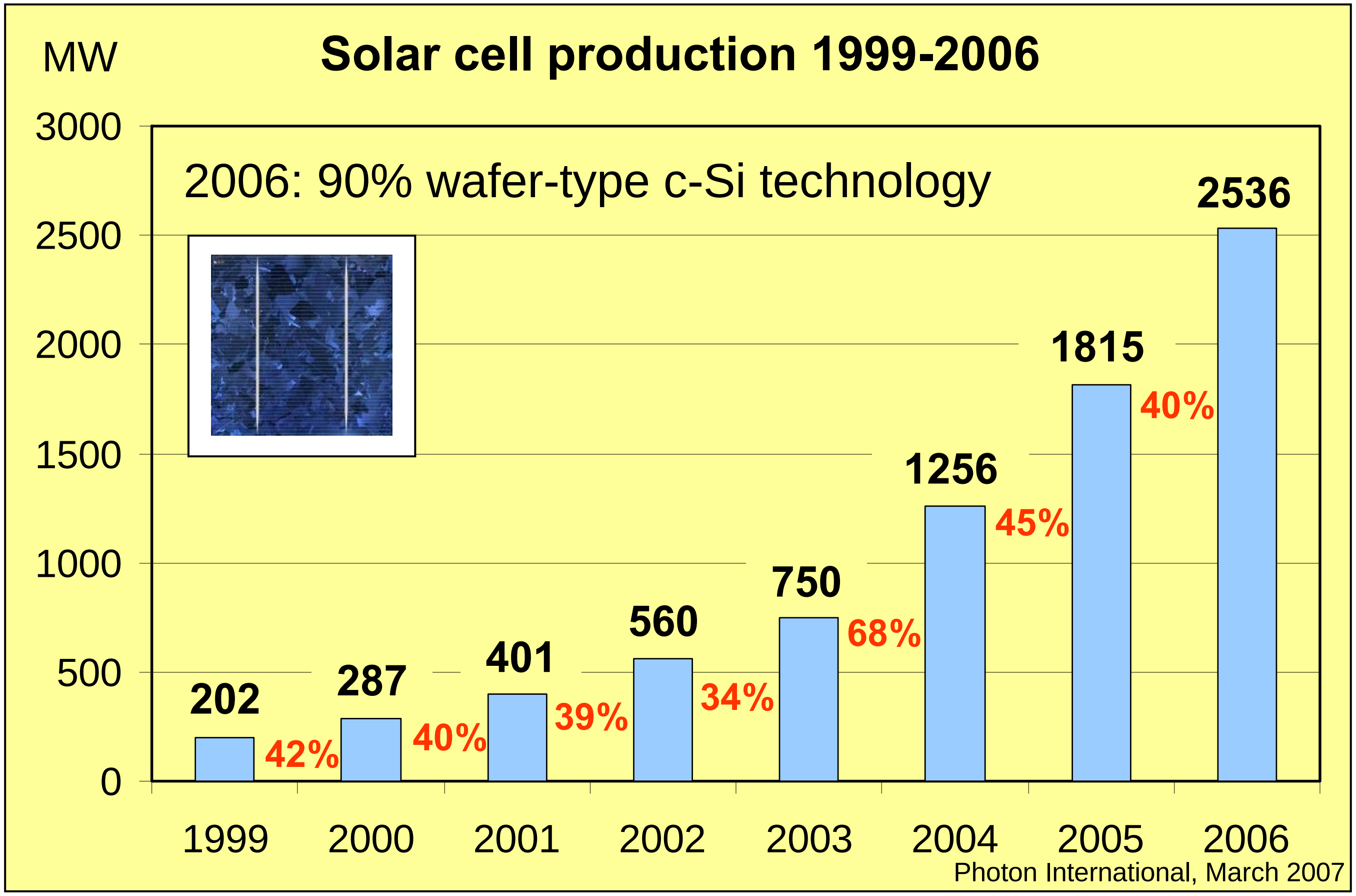
CIGS (Copper Indium Gallium Diselenide)

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 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 module market

Market sector [MWp]	**1993**	**1996**	**1999**	**2001**	**2003**
Consumer products	**18**	**22**	**35**	**45**	**65**
US off-grid residential	**5**	**8**	**13**	**19**	**30**
World off-grid rural	**8**	**15**	**31**	**45**	**70**
Communications/signal	**18**	**23**	**35**	**46**	**70**
PV/diesel commercial	**10**	**12**	**25**	**36**	**50**
Grid connected	**2**	**7**	**60**	**199**	**365**
Central power	**2**	**2**	**2**	**5**	**8**
Total	**63**	**89**	**201**	**395**	**658**
Average price (US$/$W_p$)	**4.25**	**4.00**	**3.50**	**3.50**	**3.00**

P.D. Maycock, Renewable Energy World, Vol. 7, No. 4, 2004

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:

Reducing module costs

↓ raw materials & labor, investments

↑ efficiency, lifetime

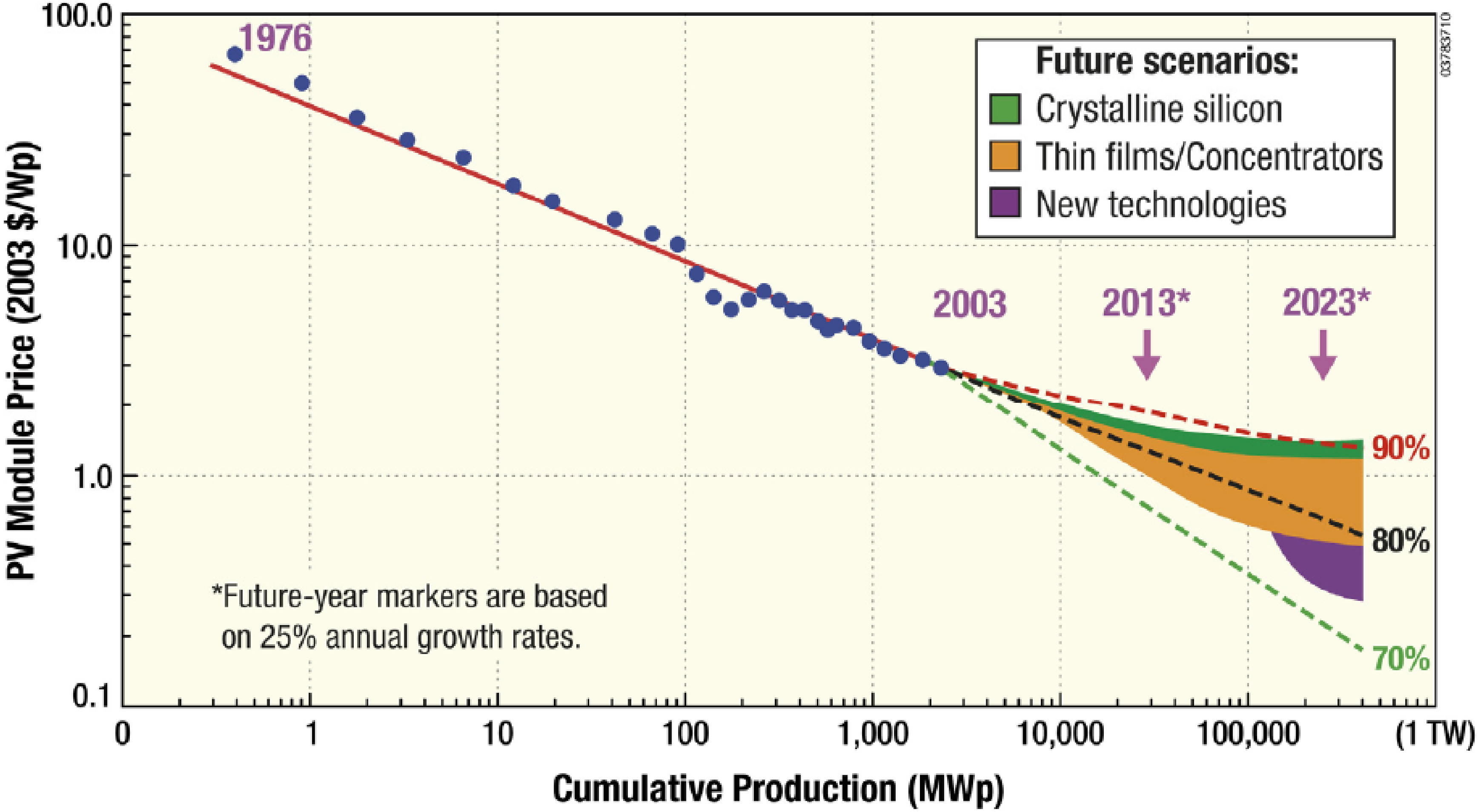
Optimizing systems integration

↓ area and power related costs

Note: overall optimum ≠ highest efficiency

Learning curve

The *combined* effect of technology development and manufacturing experience



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

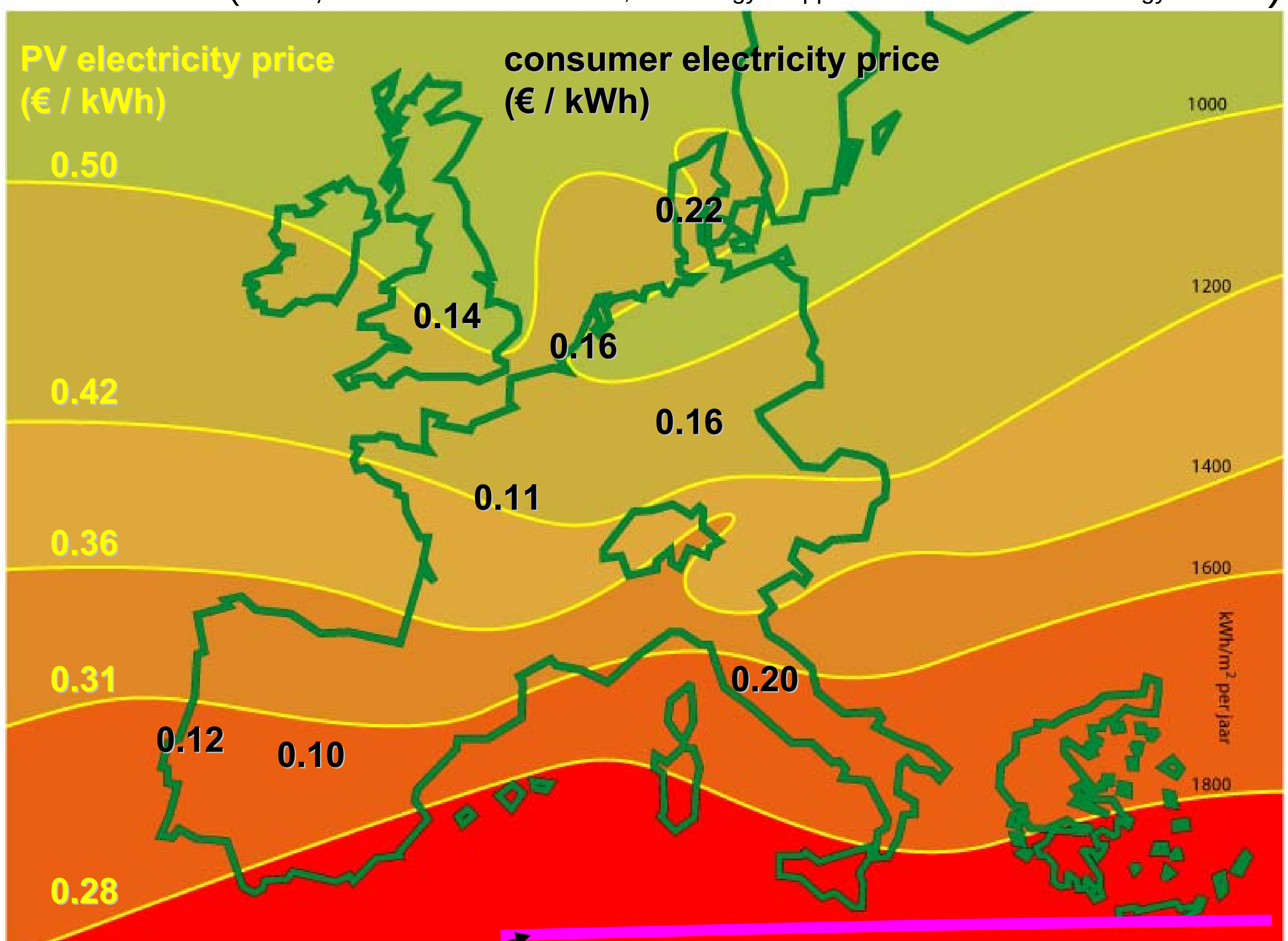
PV electricity price

Wim Sinke (ECN, Leader of WG 3 : Science, technology & applications of EU PV Technology Platform)

2005

PV electricity prices*) compared with typical **consumer electricity prices**

*) depreciation 25 yrs, real interest rate 4%, O&M cost 1%/yr, PR 0.75 (example)

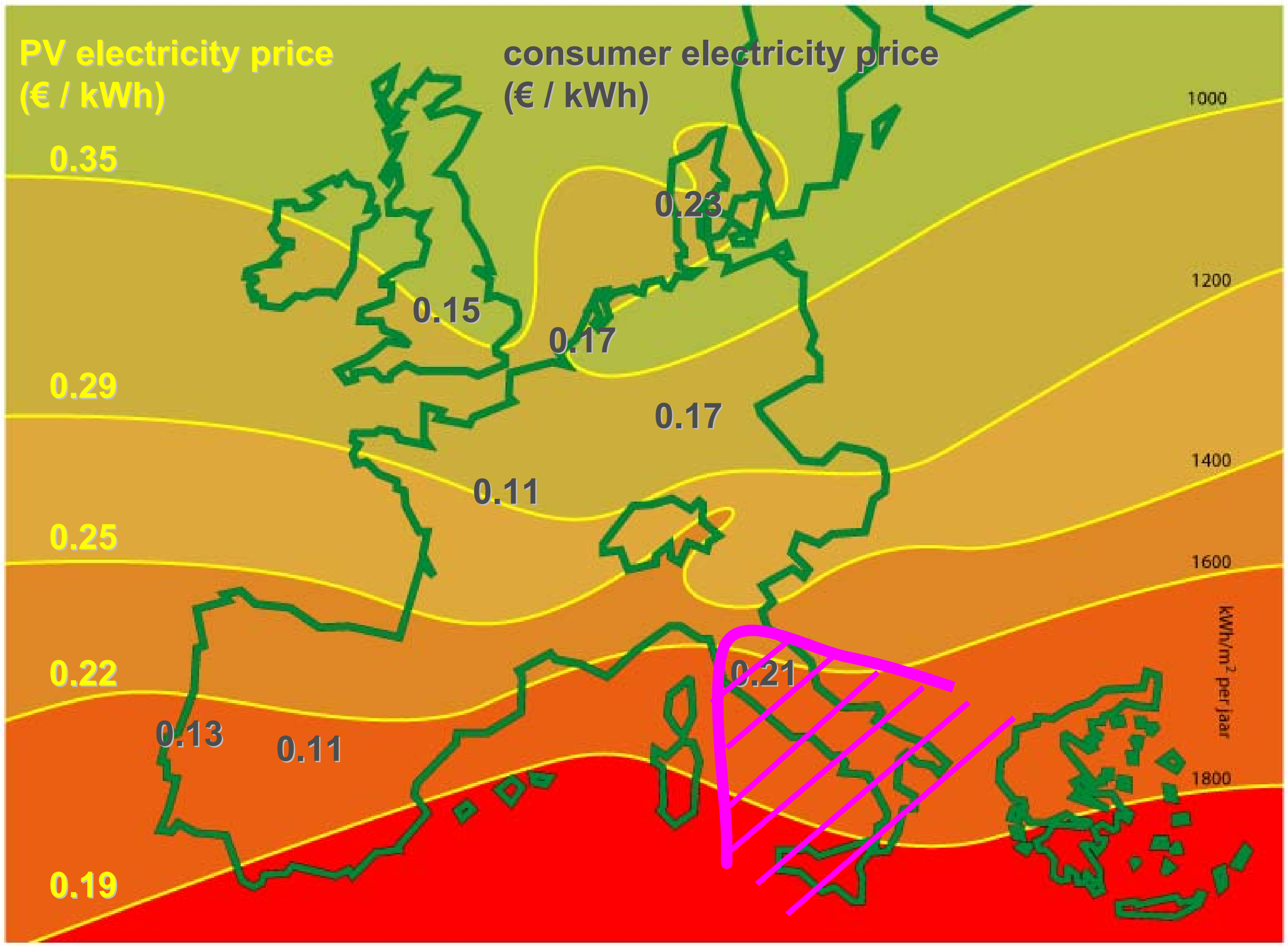


"grid parity"

PV electricity price

2010

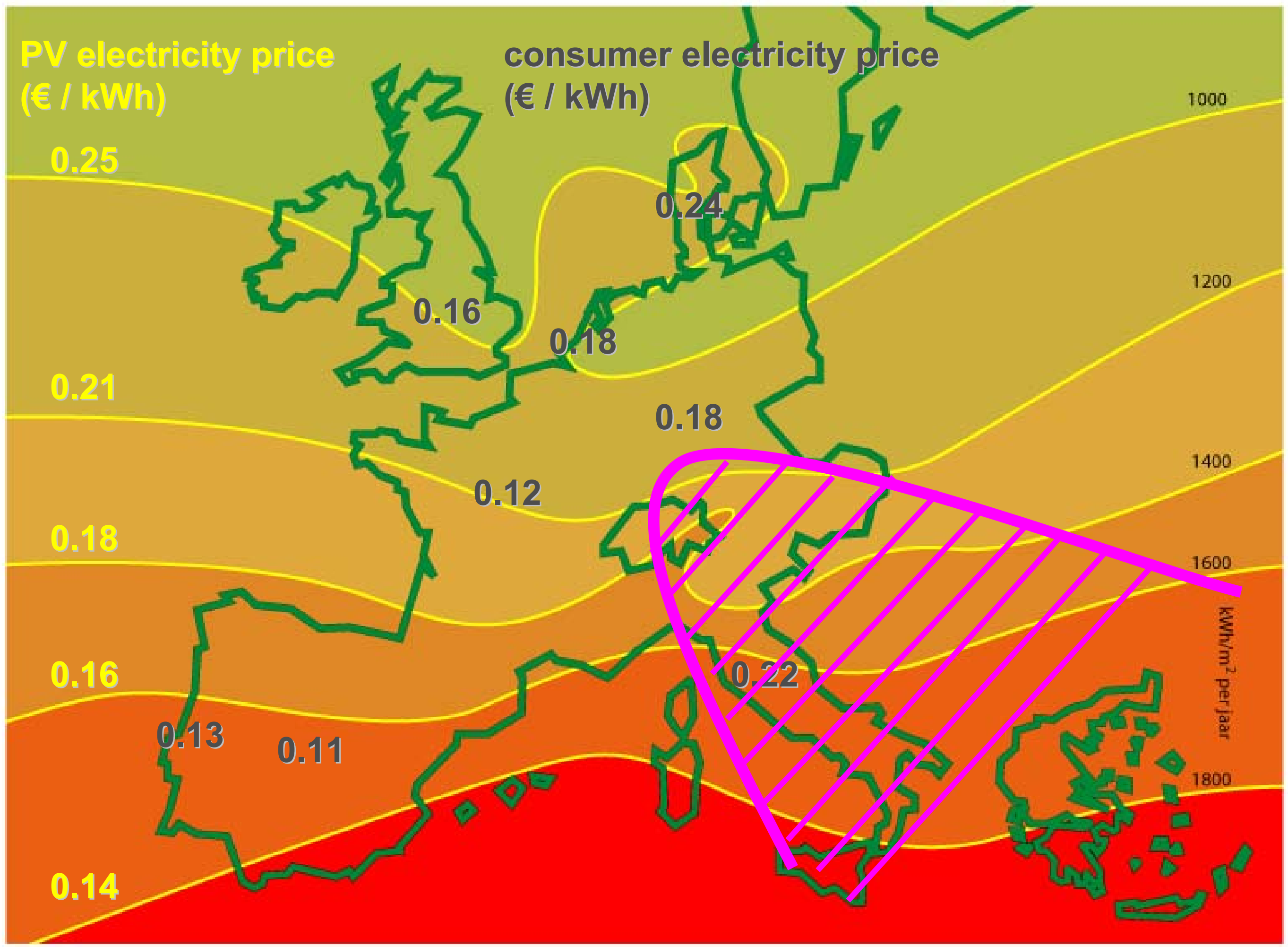
PV electricity prices compared with expected **consumer electricity prices** **(+ 1%/yr)**



PV electricity price

2015

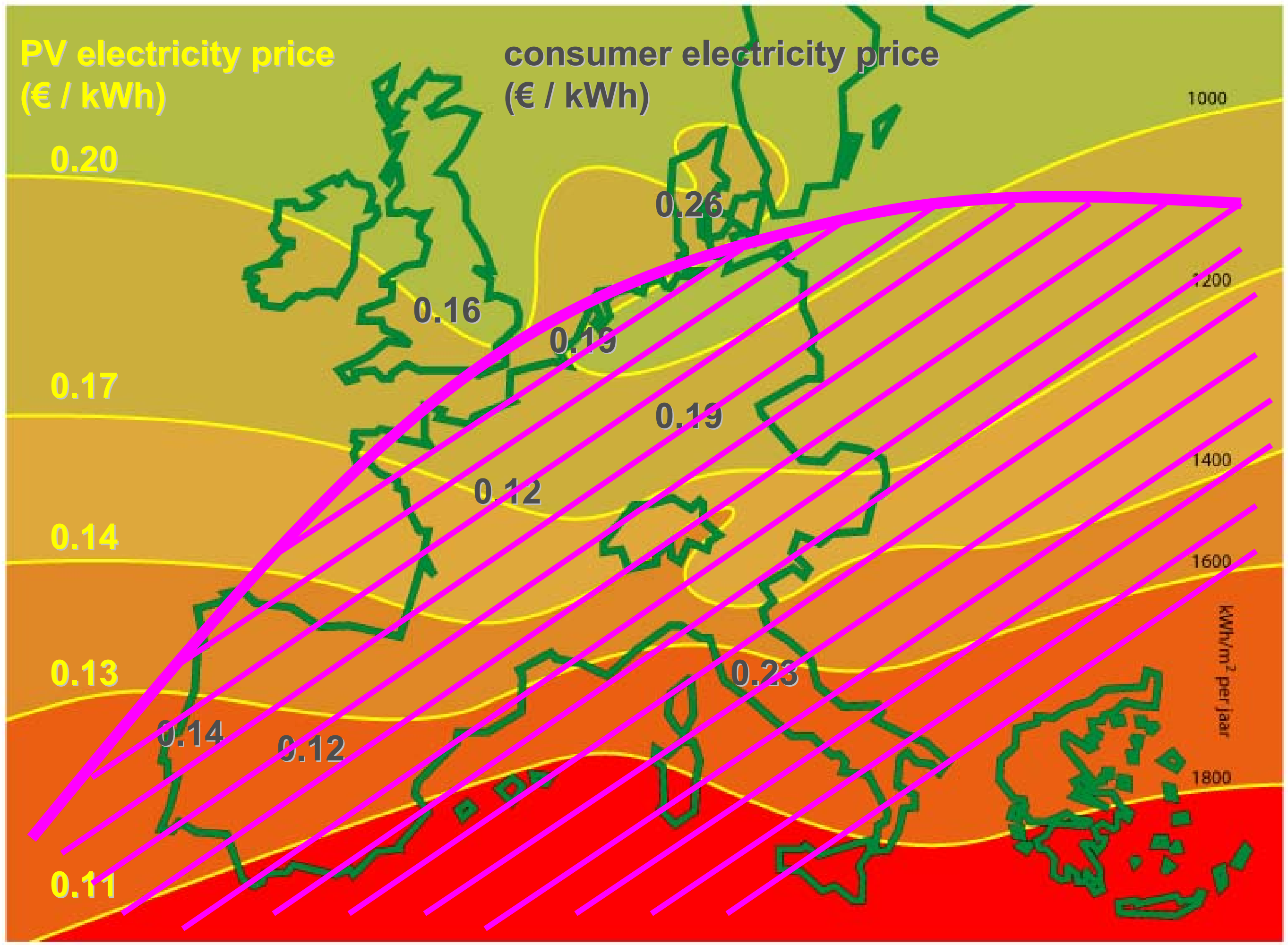
PV electricity prices compared with expected **consumer electricity prices (+ 1%/yr)**



PV electricity price

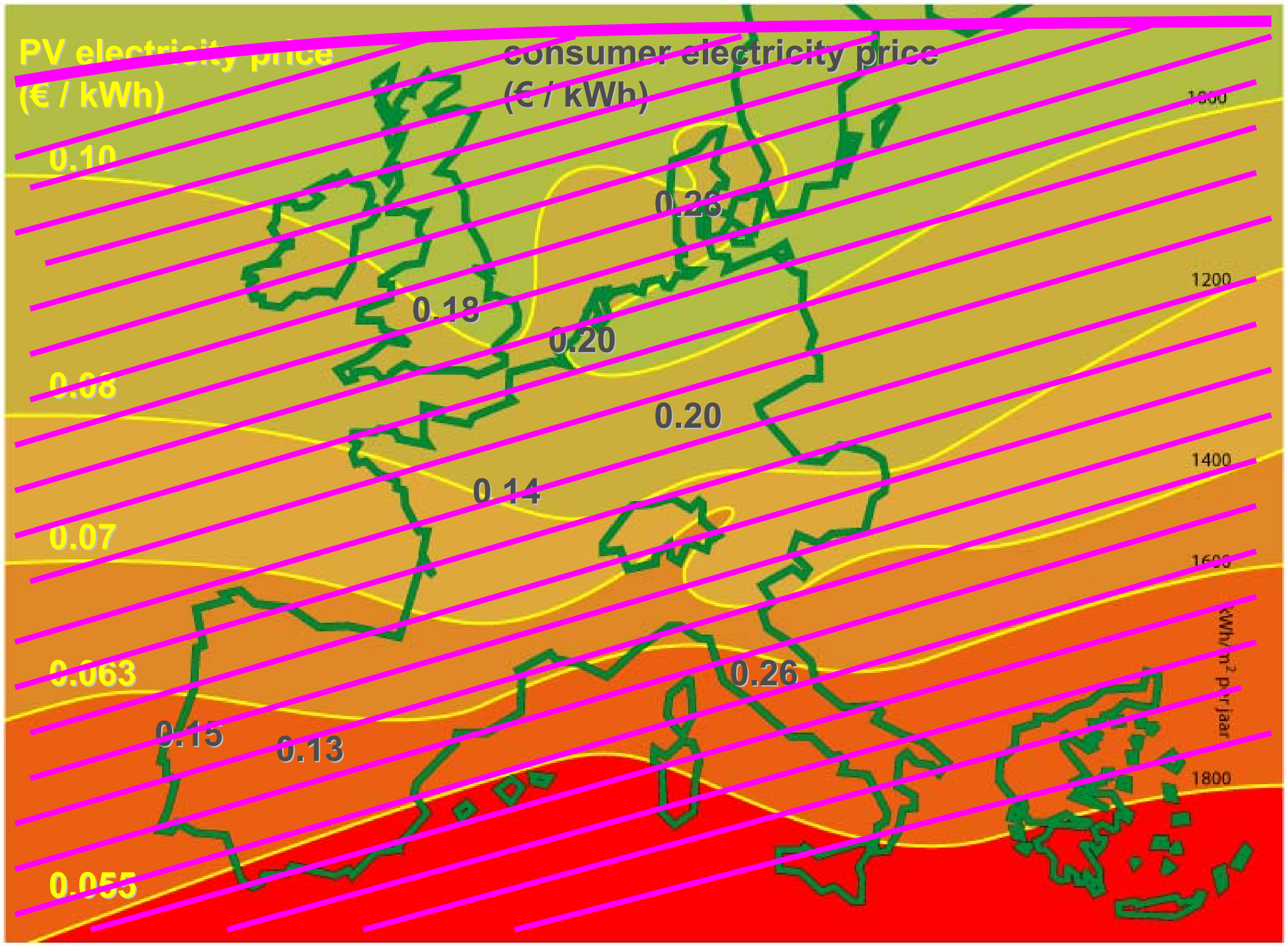
2020

PV electricity prices compared with expected **consumer electricity prices (+ 1%/yr)**



PV electricity price

2030



PV electricity prices compared with expected **consumer electricity prices (+ 1%/yr)**