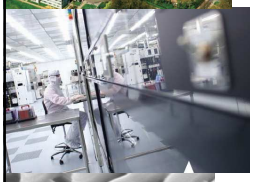
Crystalline Silicon Solar Cells - A Glance from Europe

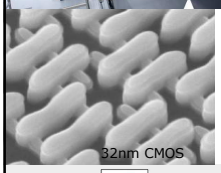
Joachim John

Outline

- Introduction to IMEC
- Motivation Photovoltaic Solar Energy
- European Solar Energy Strategic Research Agenda
- IMEC Solar Energy
- Summary and Outlook

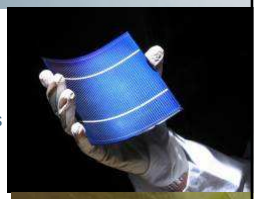
Introduction to IMEC





Statistics:

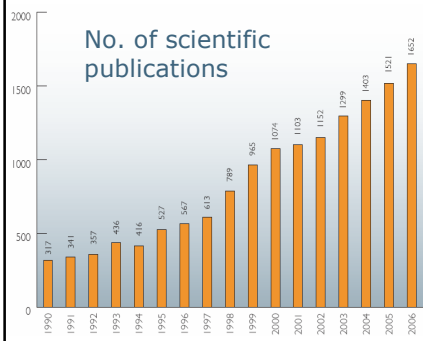
- Independent Belgian R&D institute
- Total Revenue (2006): 227 M€
- Personnel (2006): 1500
  - 330 visiting scientists and industrial residents
  - 220 PhD Students
- 35% non-Belgian, 51 nationalities
- Average age = 35 years
- 1652 scientific papers, 139 invited, 97 patents filed

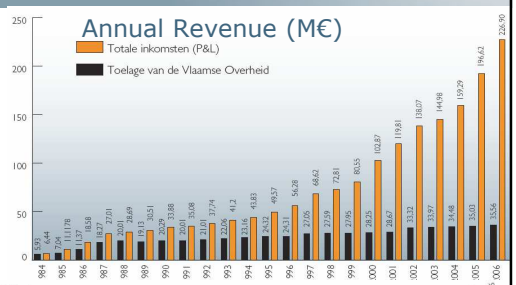


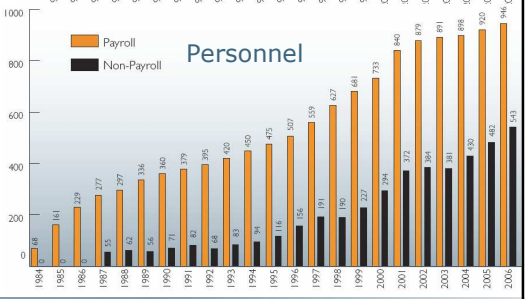
Infrastructure:

- 24,400m² offices and laboratories
- 5,200m² cleanroom I (200mm)
  - 1,750m² class 1
  - Basic process: 90nm CMOS
- 3,200m² cleanroom II (300mm)
  - Basic process: 32nm CMOS
  - Pilot Lines
    - 300mm and 200mm silicon pilot line
    - solar cell pilot line
    - multi-chip-module pilot line
  - Laboratories
    - Bio, Organic, RF, DSP
    - Material and Components Analysis

Introduction to IMEC







Introduction to IMEC

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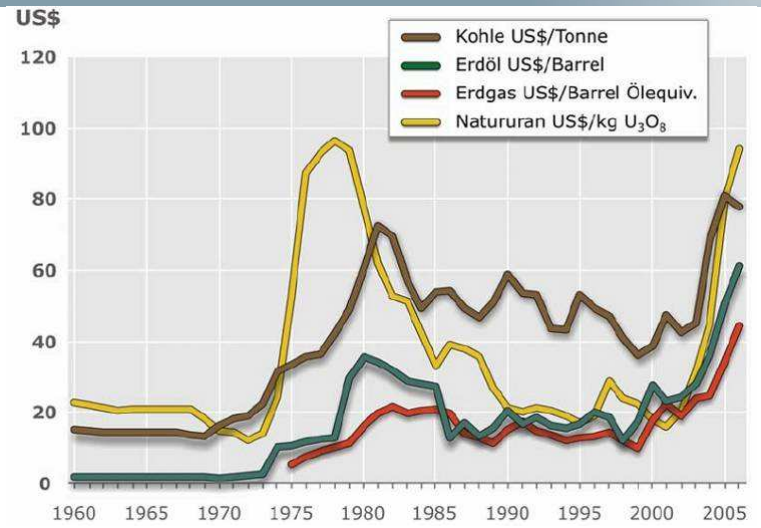
Motivation Photovoltaic's

R. E. Smalley, Rice University

Energy Generation

- Resources (what/how much)
  - Conventional (coal, oil, gas, nuclear)
  - Renewable (solar, wind, water, geo, bio)
- Cost (commercial)
  - €/W (investment, amortization, materials, personal)
- Environment (real costs)
  - Coal, oil and gas: Social cost of coal (SCC)
  - Nuclear: (external costs)
    - storage of Plutonium waste (unsolved),
    - worst case scenario insurance (not existing),
    - decontamination of the nuclear power plant (not calculated)

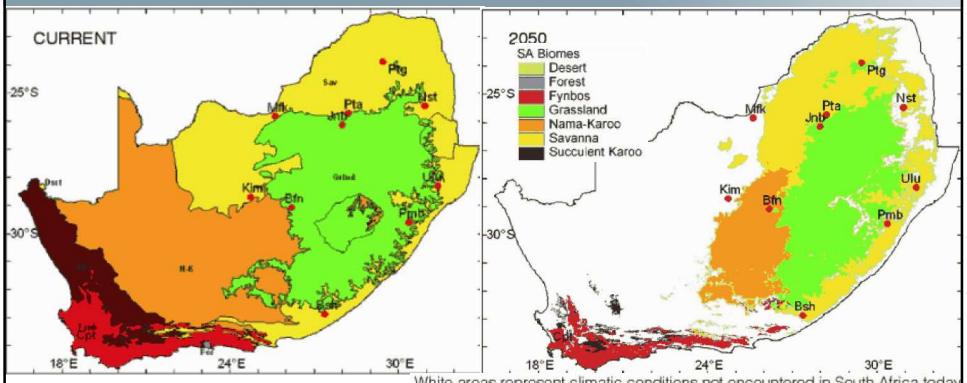
Energy Generation



Prices of coal, oil and gas increased from 2000-2005 factor 2-3, uranium factor 4.5

Source: Ministry for Environment, Germany (2007)

Impact on South Africa's Biomes



White areas represent climatic conditions not encountered in South Africa today

Biome	Current area	Area remaining in 2050	% remaining in 2050
Forest	721 154	-	0%
Fynbos	7 720 960	2 915 069	38%
Grassland	33 340 446	14 320 700	43%
Nama Karoo	29 768 902	8 211 192	28%
Savanna	42 525 186	30 608 402	72%
Succulent Karoo	8 257 625	1 557 116	19%
Thicket	4 156 647	-	0%
TOTAL	126 490 920	57 612 479	46%

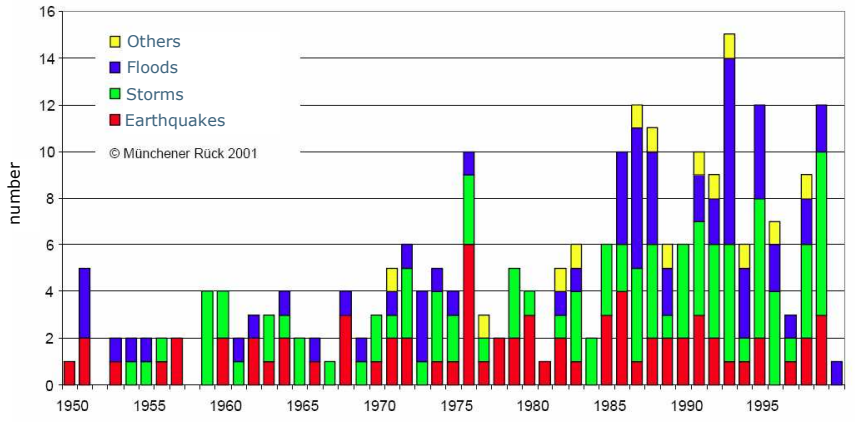
$\Delta T=2.5°C$

Source: J. TURPIE et al,2002
Economic Impacts of Climate Change in South Africa

Consequential Costs

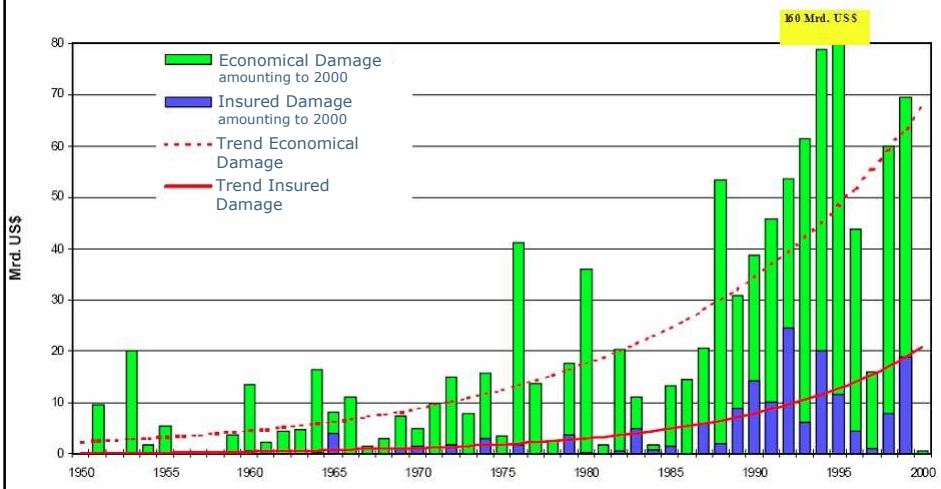
Caused by :
- Climate change
- Air pollution
- Water pollution
- Ground pollution

Increase of natural disasters 1950-2000



Consequential Costs

Increase and trend of economical damage of natural disasters 1950-2000



Source: Münchner Rück Insurance (2001)

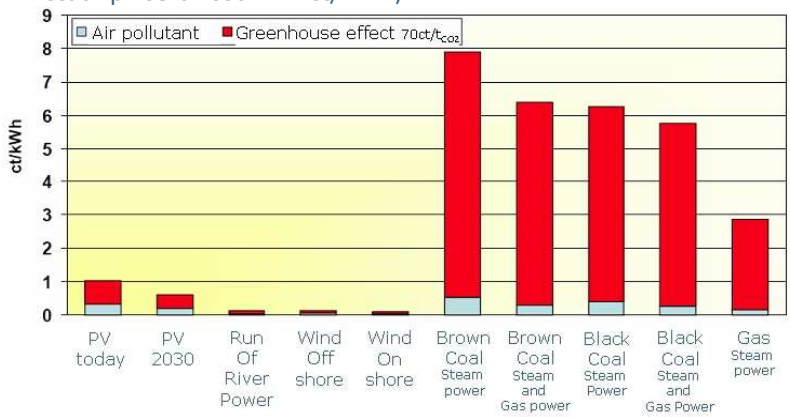
Consequential Costs

In SA: 316Mt CO_2, 8,2 Tonnen CO_2 per person = Italy or France

Social cost of coal (SCC)

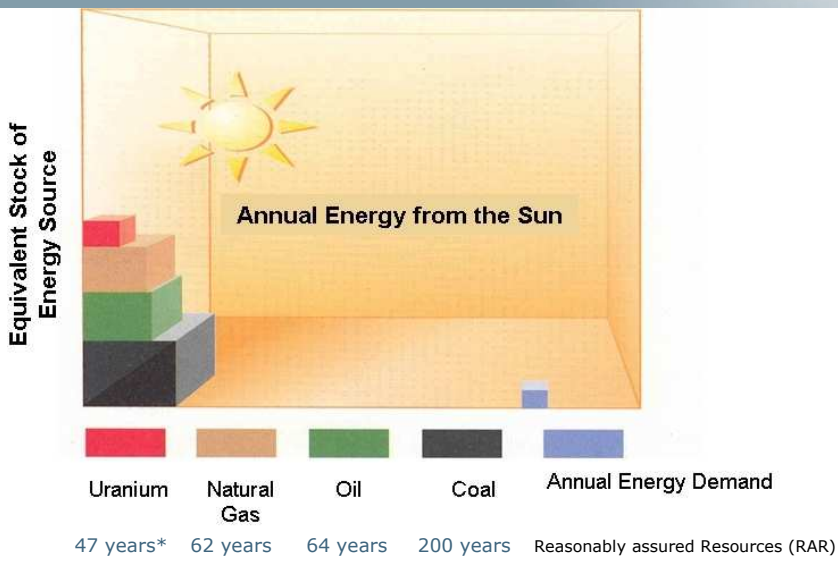
0.15 €/t_{CO2} up to 3 €/t_{CO2} *, (UK Department for Environment, Food and Rural Affairs - Defra)

Actual price of coal = 7ct/kWh,



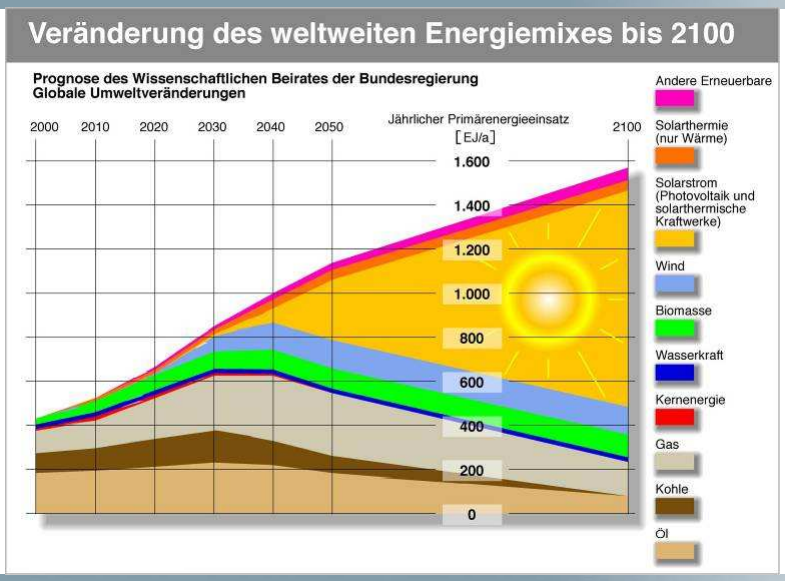
*Downing et al. (2005)

Stock of Energy Source



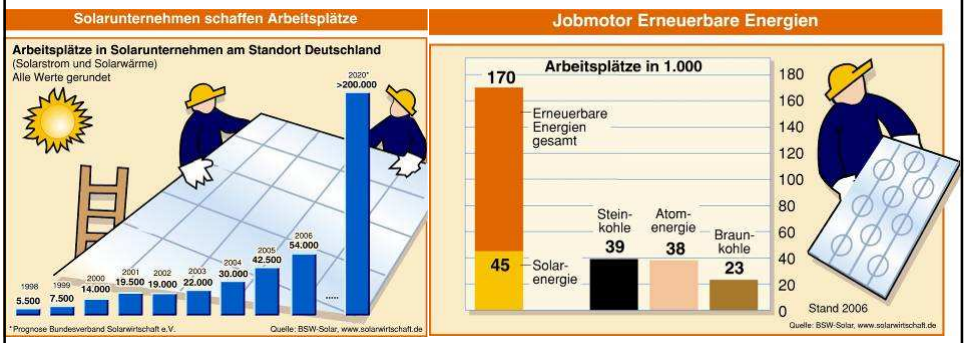
* Red Book (NEA/OECD)

Change of the worldwide energy generation



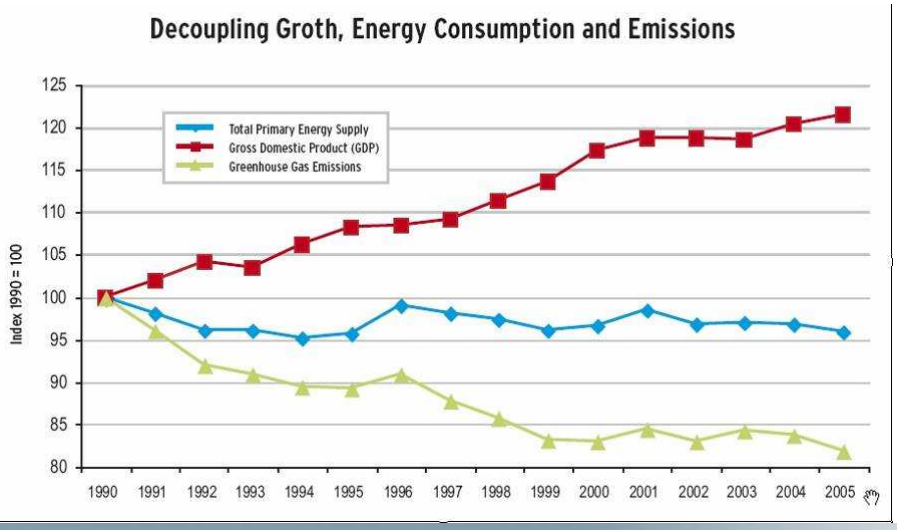
Source: scientific advice council of the federal government (germany)

Renewable energy as a job motor



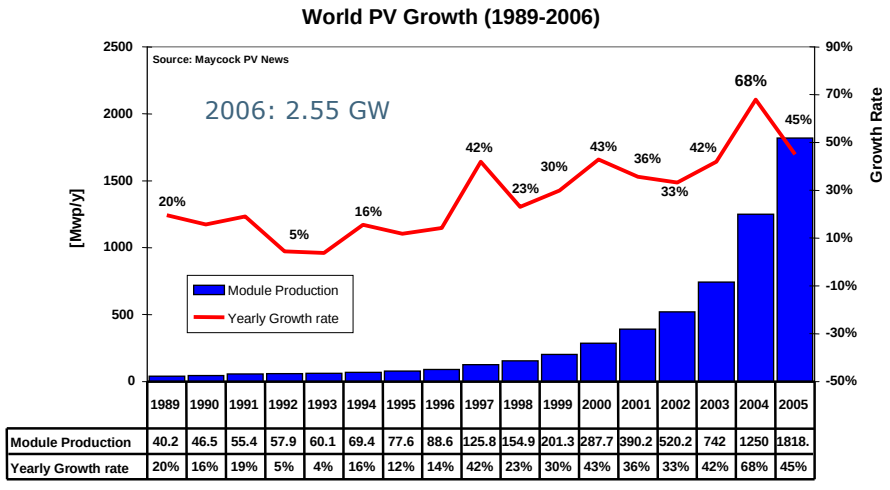
- 30.000 new jobs between 2000 and 2006 in Germany
- More jobs as in conventional energy industry together

Economy growth with less green house gas emission



imec Source: Federal Ministry of Economics and Technology, Germany 2006

PV-market



	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Module Production	40.2	46.5	55.4	57.9	60.1	69.4	77.6	88.6	125.8	154.9	201.3	287.7	390.2	520.2	742	1250	1818.
Yearly Growth rate	20%	16%	19%	5%	4%	16%	12%	14%	42%	23%	30%	43%	36%	33%	42%	68%	45%

imec

Present PV-technologies: terrestrial application

Cell Technology	Type of junction	Lab efficiency [%]	Industrial efficiency [%]	Market share [%]
Bulk crystalline Si solar cells 	p-n homojunction	24.7	13 – 17	92
a-Si:H  (a-Si:H; a-SiGe:H, µc-S	p-i-n homojunction multijunction	13	6-7 single junction 9-10 multijunction	5
$CuIn(Ga)Se_2(S_2)$ =CIS 	p-n heterojunction with CdS	18.8	9 - 13	} 3
CdTe 	p-n heterojunction with CdS	17	9 - 12	

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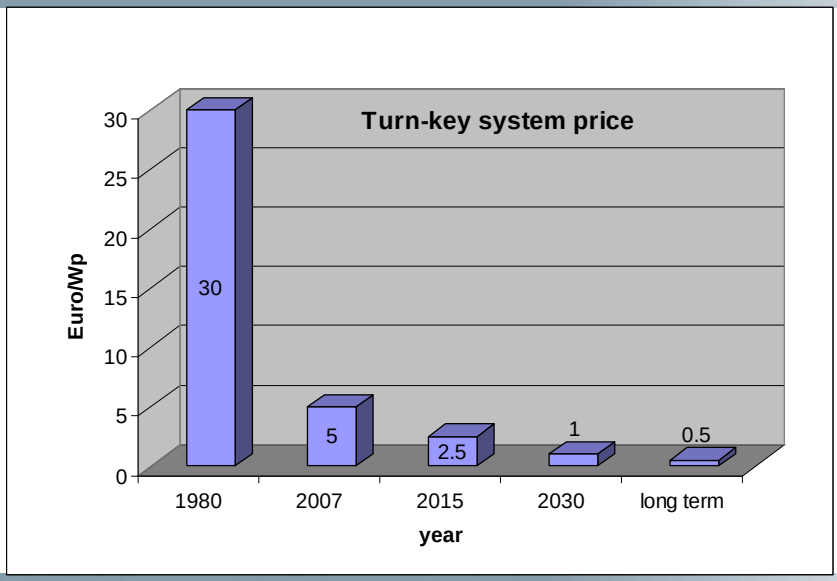
A Strategic Research Agenda for PV Solar Energy Technology

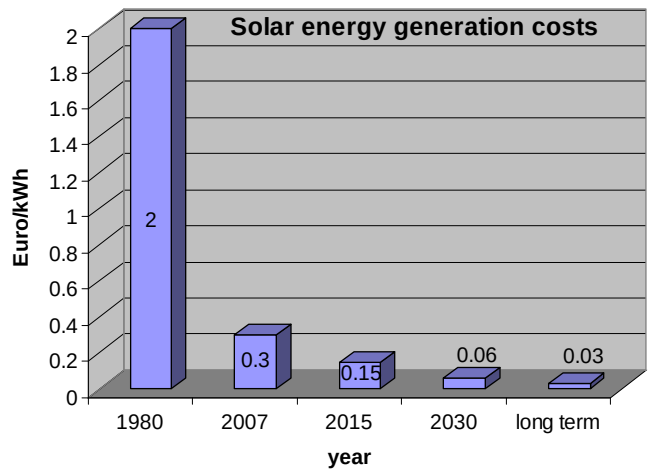
imec Source: Photovoltaic Technology Platform, 2007

European Research Agenda



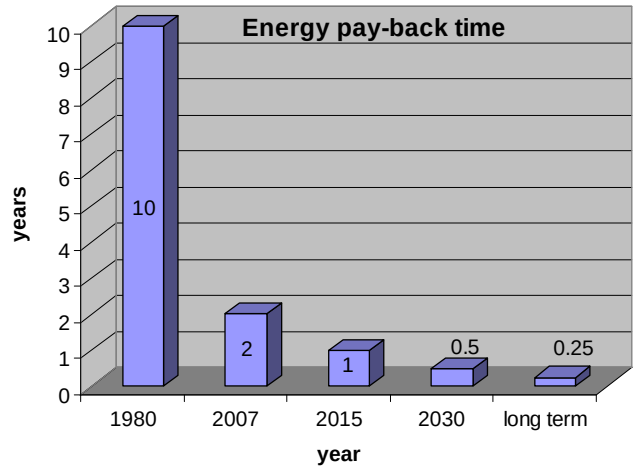
imec Source: European Technology Platform 2007

European Research Agenda



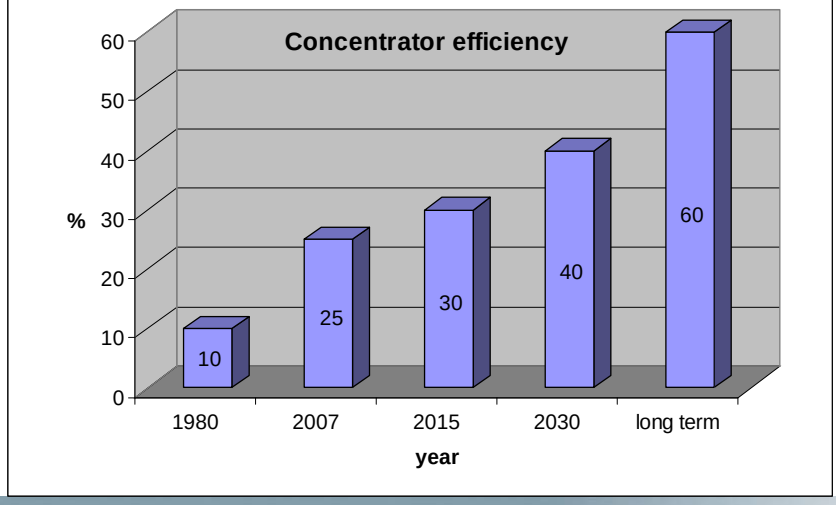
imec Source: European Technology Platform 2007 Joachim John | 23

European Research Agenda



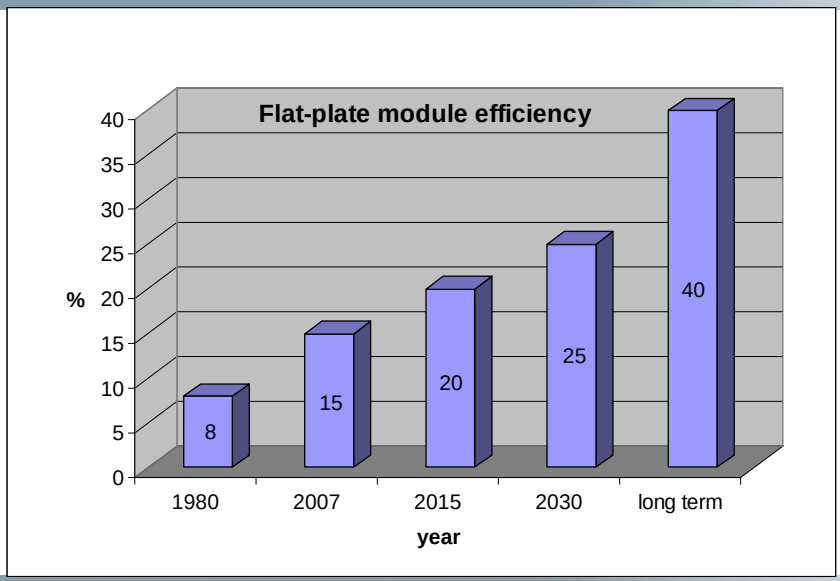
imec Source: European Technology Platform 2007 Joachim John | 24

European Research Agenda



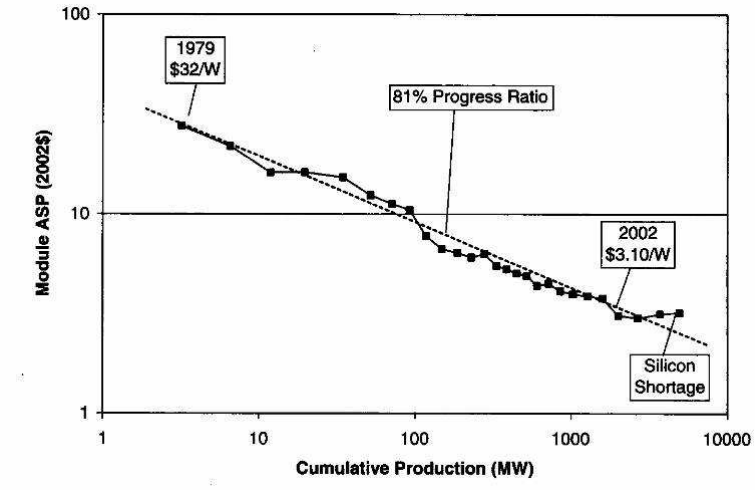
imec Source: European Technology Platform 2007

European Research Agenda



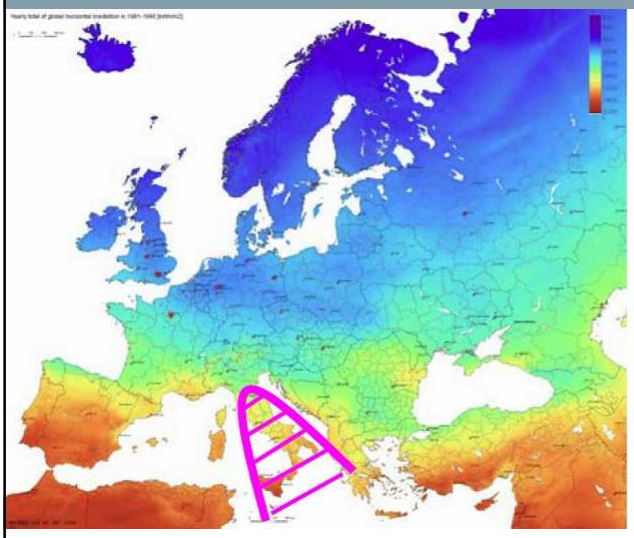
imec Source: European Technology Platform 2007

Learning curve



1. Module price decrease by 20% for every doubling of the cumulative Production
2. Keeping the dynamics, 1$/Module price will be reached at 10GW cumulative production in 2008

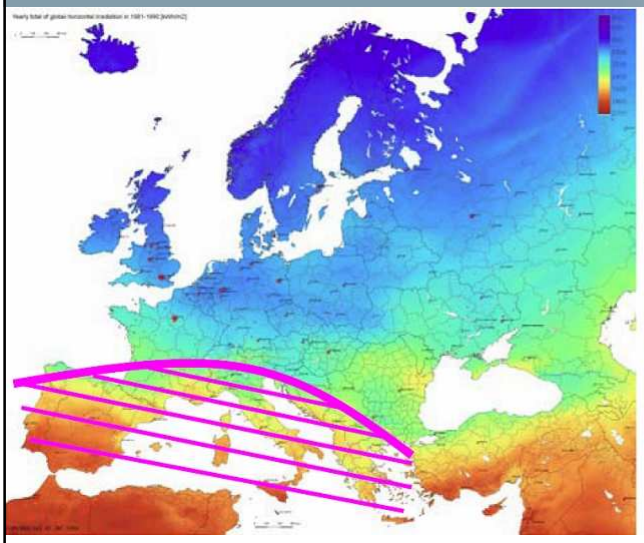
Grid Parity in Europe 2010



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

Courtesy of A. Jaeger-Waldau
JRC, ISPRA

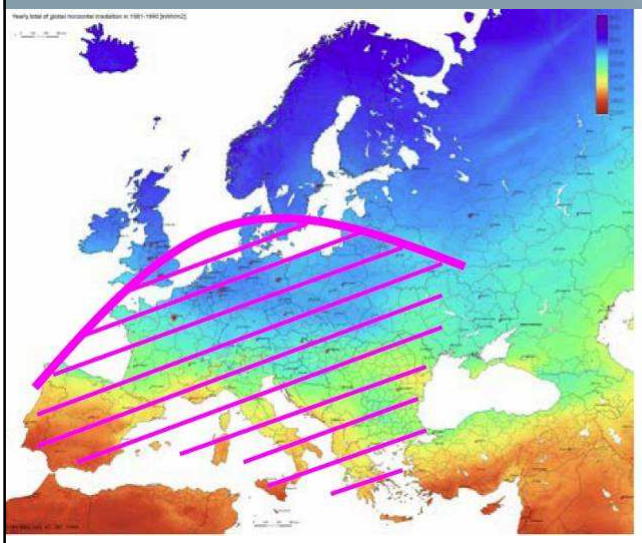
Grid Parity in Europe 2015



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

Courtesy of A. Jaeger-Waldau
JRC, ISPRA

Grid Parity in Europe 2020



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

Courtesy of A. Jaeger-Waldau
JRC, ISPRA

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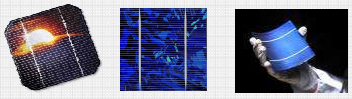
SOLAR+ Roadmap: 1 sun

Silicon Solar Cell Program

Thin crystalline Si (200 → 80 μm)

Higher efficiency (15→20%)
Si-ribbons
Thin-film crystalline Si (<20 μm)



Organic Photovoltaics

Higher efficiency
Stability

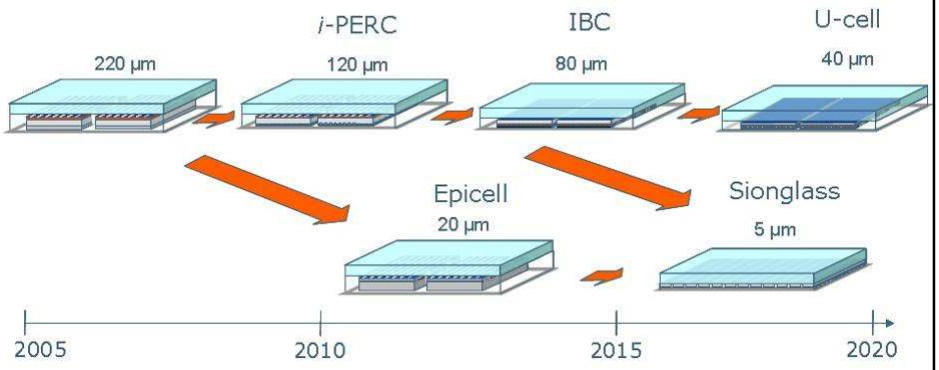
Consumer applications
Ambient intelligence

Large-scale application?

Direct cost (€/W_p) on module level

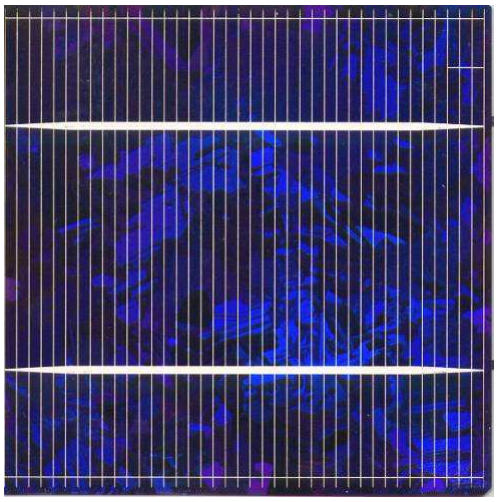
3 | 2 | 1 | 0.75 | < 0.5

Evolutionary scenario for crystalline Si PV



- Sustained decrease in active layer thickness
- Five technologies
- Only one major transition for introduction of each technology

Present value chain : Cell processing



Wafer Cutting/Separation
↓
Saw damage removal + texturing
↓
$POCl_3$ Diffusion
↓
Parasitic Junction Removal
↓
PECVD SiNx:H ARC layer
↓
Screen Printed Metallisation
↓
Co-firing

Average efficiency in production :
Multi ~ 15 %, Mono ~ 16 %

IMEC solar cell scientific highlights 2007

- Concentrator cells N+1
- i-PERC
- IBC N+2
- Thin film N+3

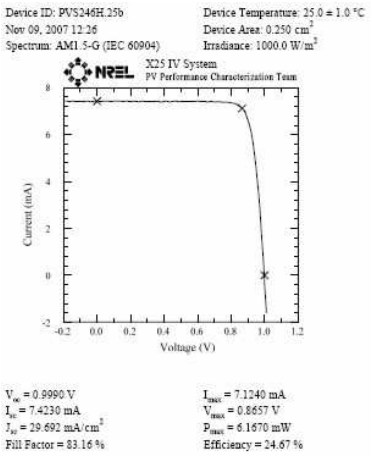
Presented at the

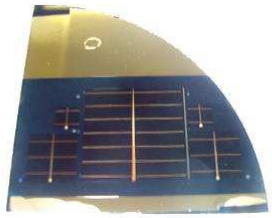
22nd European Photovoltaic Solar Energy Conference and Exhibition, Milano, Italy 2007

3000 participants and 520 Exhibitors

Single junction GaAs solar cell on Ge substrate

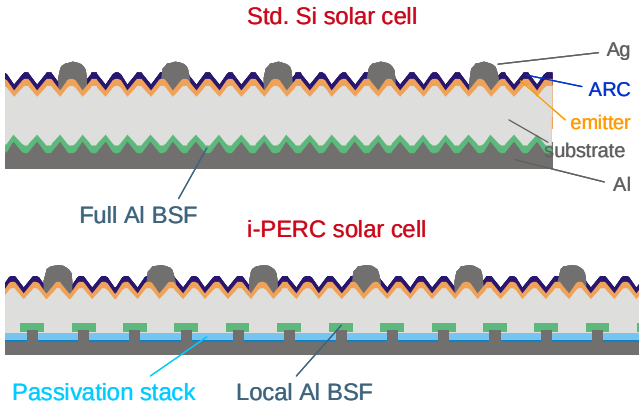
New world record efficiency achieved: 24.7%





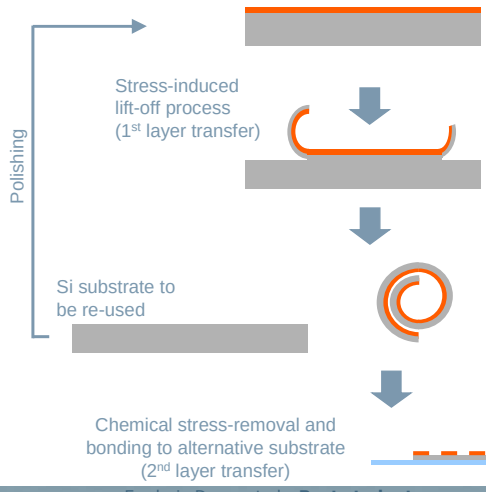
Achieved in ESA-IMAGER project, on germanium substrate with improved micro-defect distribution

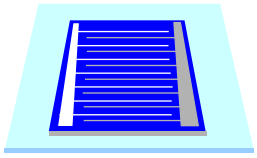
i-PERC cells on very thin substrates



130 µm mc-Si	Area (cm²)	J_{sc} (mA/cm²)	V_{oc} (mV)	FF (%)	Eff (%)
i-PERC(best)	156	34.8	623	77.1	16.7
i-PERC (av)	156	34.5	623	77.0	16.6
Full Al BSF (av)	156	32.8	614	74.6	15.0

Stress-induced lift-off process





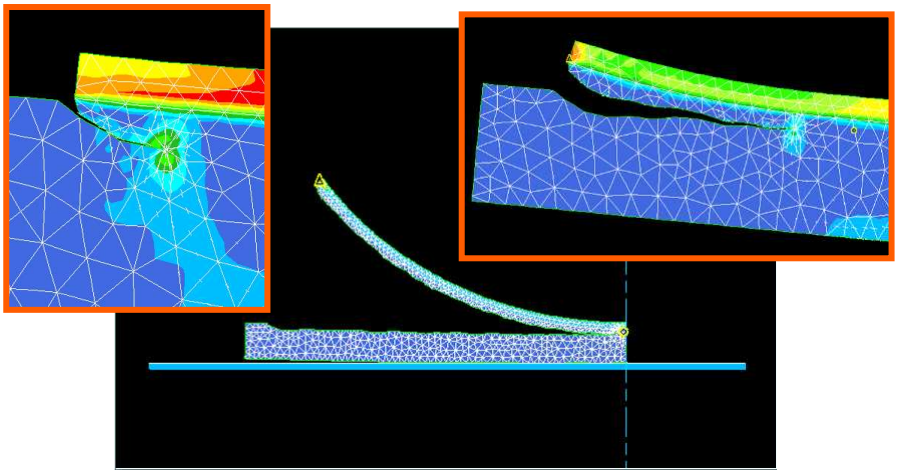
First solar cell

Rear-side cell processing (IBC)

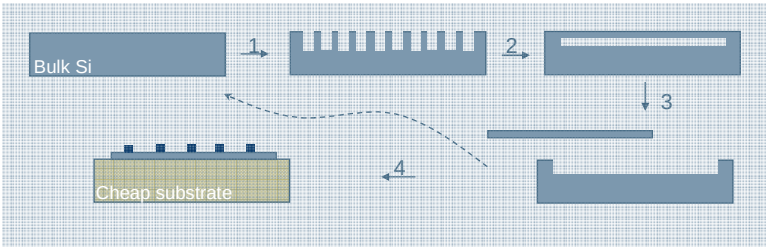
J_{sc}	26.7 mA.cm^{-2}
V_{oc}	550 mV
FF	67.8 %
R_{series}	980 mΩ.cm²
R_{shunt}	4300 Ω.cm²
Efficiency	**10.0 %**

Frederic Dross et al., **Best student paper award,**
22nd European Photovoltaic Solar Energy Conference and Exhibition, Milano, Italy 2007

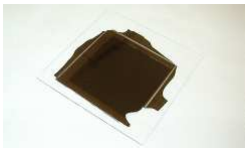
Simulation of stress-induced lift-off

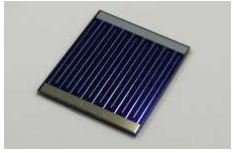


Epi-free lift-off approach



- lift-off and transfer to glass using anodic bonding
- a-Si:H/c-Si heterojunction structure implemented on bonded layers
- Proof-of-concept cell !





Valerie Pauw et al., **Best poster award**,
22nd European Photovoltaic Solar Energy Conference and Exhibition, Milano, Italy 2007

Crystalline Si solar cells: Benchmarking

Technology	Uniqueness / recent achievements	Main competitors
i-PERC	• Unique process (patented by IMEC) • Closest to industrial implementation of all potential local-BSF approaches • Highest efficiency results on thin large-area substrates (16.7%, 130 µm multi)	ISE (LFC), but their process still relies on high-quality thermal oxide at rearside
IBC	• Link with manufacturer of ultra-thin ribbons (SolarForce) • Rearside HIT-emitter	UKON, ISE, ECN
Epitaxial cells	• Unique process based on porous Si reflector (patented by IMEC) and high-T CVD • Highest efficiency results obtained on large area substrates – epitaxial emitter (14.9%)	ISE Uni.Neuchatel – Juelich microcrystalline Si (low deposition rates)
SionGlass	• Best worldwide results obtained with AIC-process (patented for use on ceramics) -8% • Highest efficiency potential for thin crystalline Si films on non-Si carrier	UNSW, HMI

Summary

- Face the challenge:
  - Energy supply for 10 Billion people by using a carbon free and environment friendly energy generation
- The answer can only come from renewable energy
- Industry has understood that renewable energy is a chance and not a threat
- Europe has defined a strategic research agenda
  - Clear commitments to a carbon free economy based on renewable energy generation.
- PV Aim:
  - Reach grid parity as fast as possible by increasing the efficiency and reduce the cost of the solar cell.

Outlook

- IMEC
  - Backside passivation of thin bulk silicon solar cells
  - Thin film silicon solar cells
  - Innovative new concepts like quantum dots or nano structures
- Europe
  - PV Grid parity of whole Europe until 2030
  - System energy pay back time: 1year (2015)
  - Turn key system price: 2.5 €/Wp (2015)
  - Solar energy generation cost: 0.15 €/kWh (2015)
  - Flat plate efficiency: 20% (2015)