The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

Workshop on "Physics for Renewable Energy"
October 17 - 29, 2005

301/1679-25

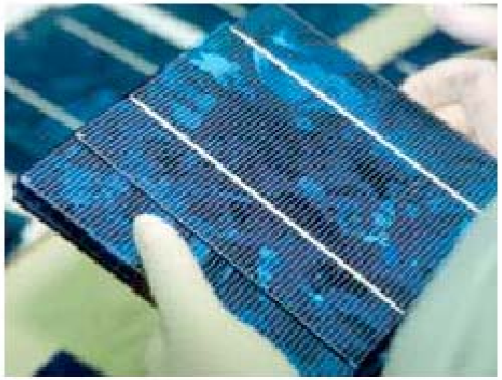
"Current Status of Photovoltaics"

F. Ferrazza
EniTechnologie
Nettuno (Rome)
Italy

Current status of photovoltaics

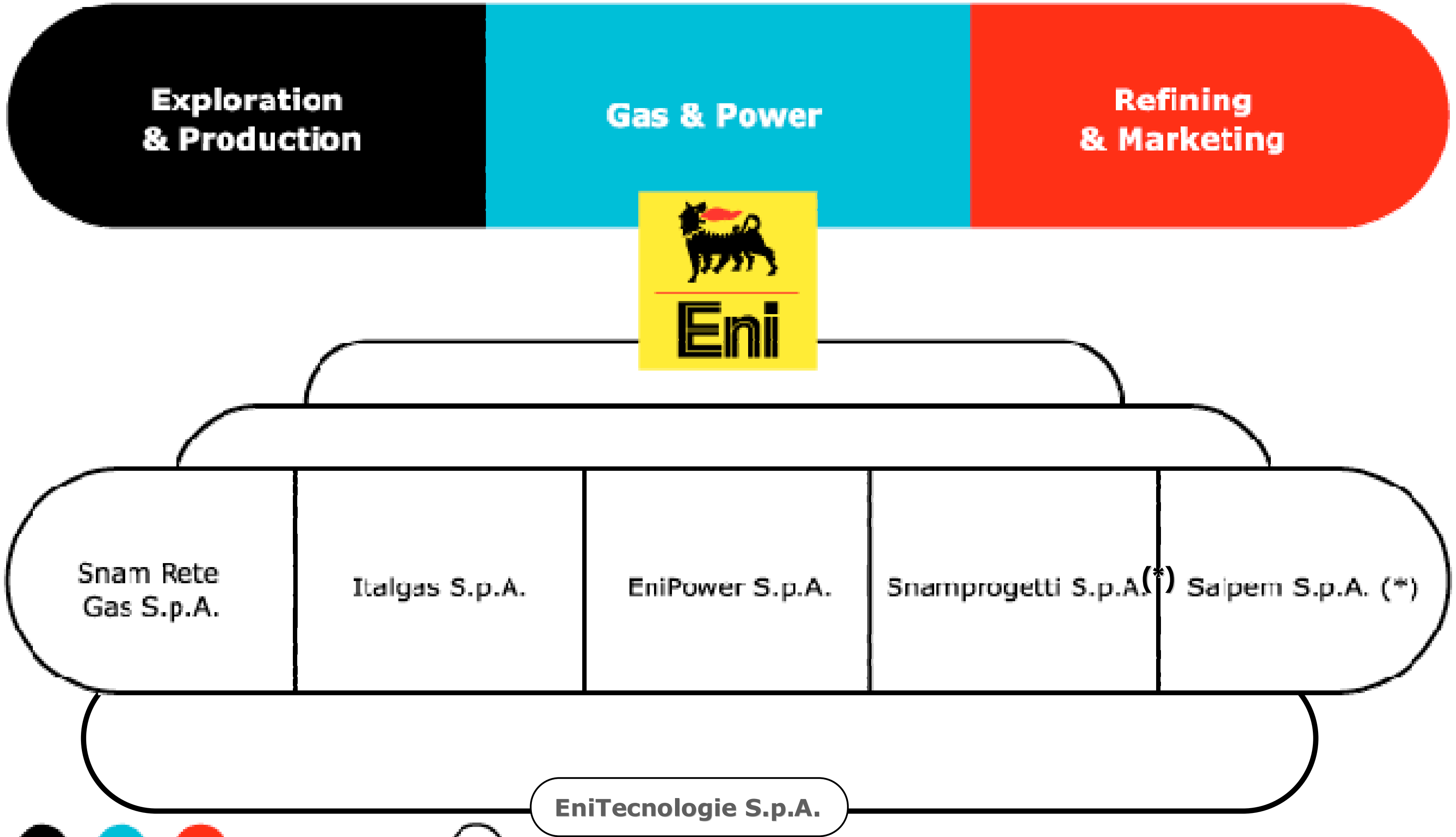
Francesca Ferrazza
EniTecnologie, Nettuno

Workshop on Physics for Renewable Energy



ICTP - Trieste
25 october 2005

Eni Organization



Divisioni — Divisions

Controllate — Controlled

(*) Le società sono attive rispettivamente nei settori

Engineering & services for the oil industry

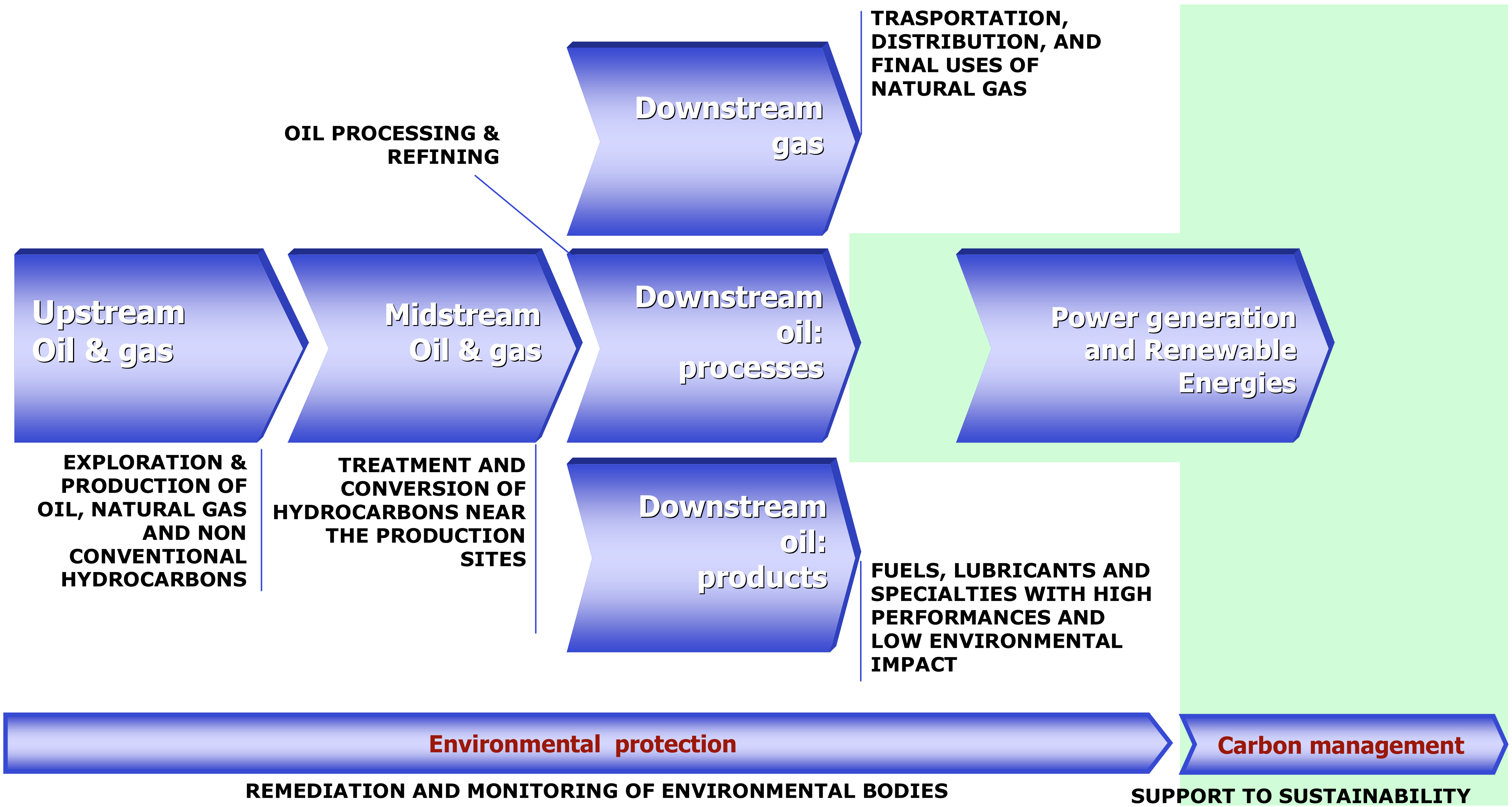
EniTecnologie is the "Corporate Technology Company" of Eni

EniTecnologie operates in the sectors of energy, hydrocarbon derived products and alternative sources, innovating while fully respecting the environment and with a view to sustainability.

EniTecnologie researches frontier technological ideas in sectors linked to the oil and gas, power generation, renewable energies, fuels and derived products value chains.

EniTecnologie safeguards technological know-how and industrial property in strategic energy sectors and maintains an observatory on the future of technologies and on technological innovation strategies at an international level.

SECTORS OF INTEREST FOR ENI



EniTecnologie, the Corporate Technology Company of Eni, is one of the major centres of excellence for the industrial research. It works in the oil and gas whole technology chain and in renewable sources, while safeguarding the environment, in a sustainable development perspective.

EniTecnologie took over Eurosolare, the Eni company that develops, produces and markets photovoltaic modules.

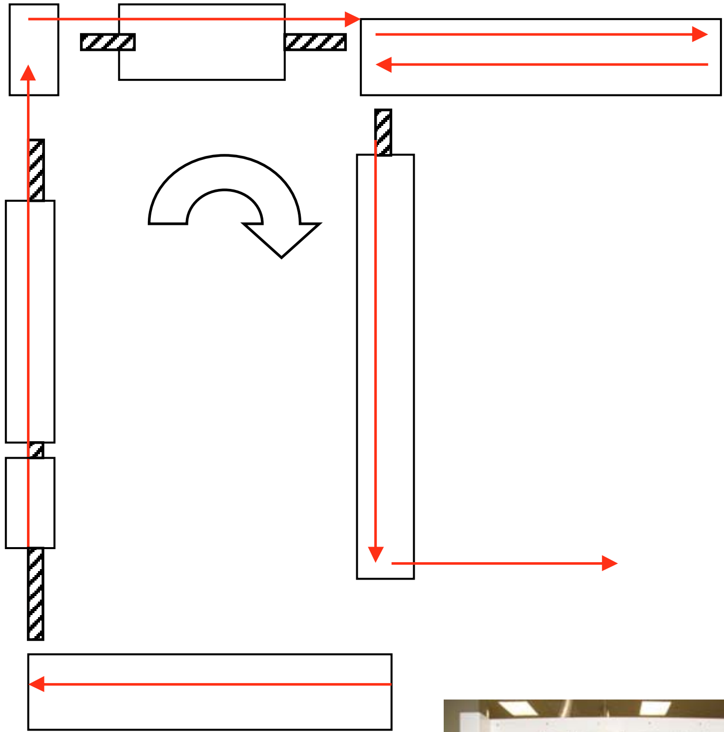
Inner Mongolia, 2004
Rural electrification

Italy, petrol station
Grid connected

EniTecnologie research centres

More information available on www.enitecnologie.it

The solar cell production line at EniTecnologie, Nettuno



- in line spray-on doper
- in line ceramic roller furnace
- SiN ARC
- screen printed metallization
- automation in progress

Full capacity 12 MW/yr

Contents

"Photovoltaics literally means light-electricity: photo comes from the Greek *phos*, meaning light, and volt from the Italian scientist *Alessandro Volta*; a pioneer in the study of electricity. This technology, originally developed for space applications in the 1950s, has many advantages: it is modular, clean, easy to maintain, and can be installed almost anywhere to suit the needs of the user. The electricity produced can be used directly, stored locally or fed into an existing electricity grid."

Source: A Vision for PV 2030 and beyond, PV TRAC report 2005

http://europa.eu.int/comm/research/rtdinfo/index_en.html

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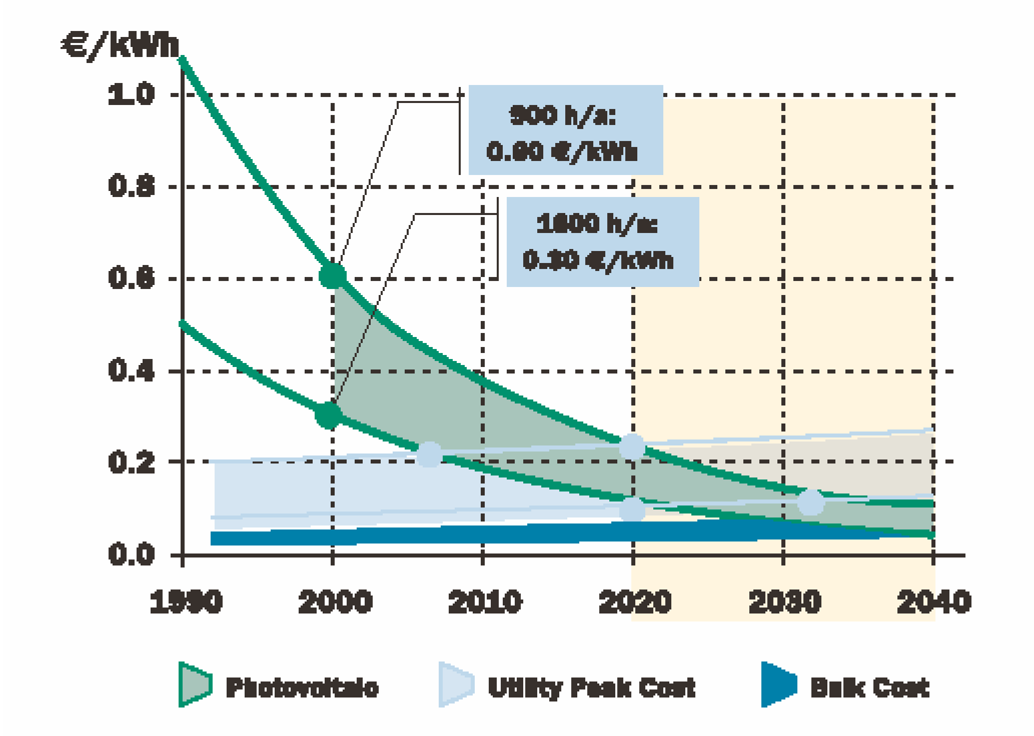


€/kWh
1.0
0.8
0.6
0.4
0.2
0.0
900 h/a:
0.60 €/kWh
1800 h/a:
0.30 €/kWh
1990
2000
2010
2020
2030
2040
Photovoltaic
Utility Peak Cost
Bulk Cost

Table 3: Electricity production from renewable sources, technical potential of RES and electricity generation costs

	World electricity production 2003 (TWh)	World energy technical potential heat and electricity (x 1 000 TWh/year[16])	Electricity generation costs 2003 (€cents/kWh)
Hydroelectricity	2 631	14	2 - 8
Bio-energy	175	>77	5 - 6
Wind energy	75	178	4 - 12
Geothermal power	50	1400	2 - 10
Marine energy	0.8	32	[8 - 15]*
Solar thermal energy	0.5	>440	12 - 18
PV	2,5		25 - 65
Total renewable electricity production	2 969	>2 100	
Total world consumption	Electricity ~ 16,700 Total primary energy ~ 120,000		

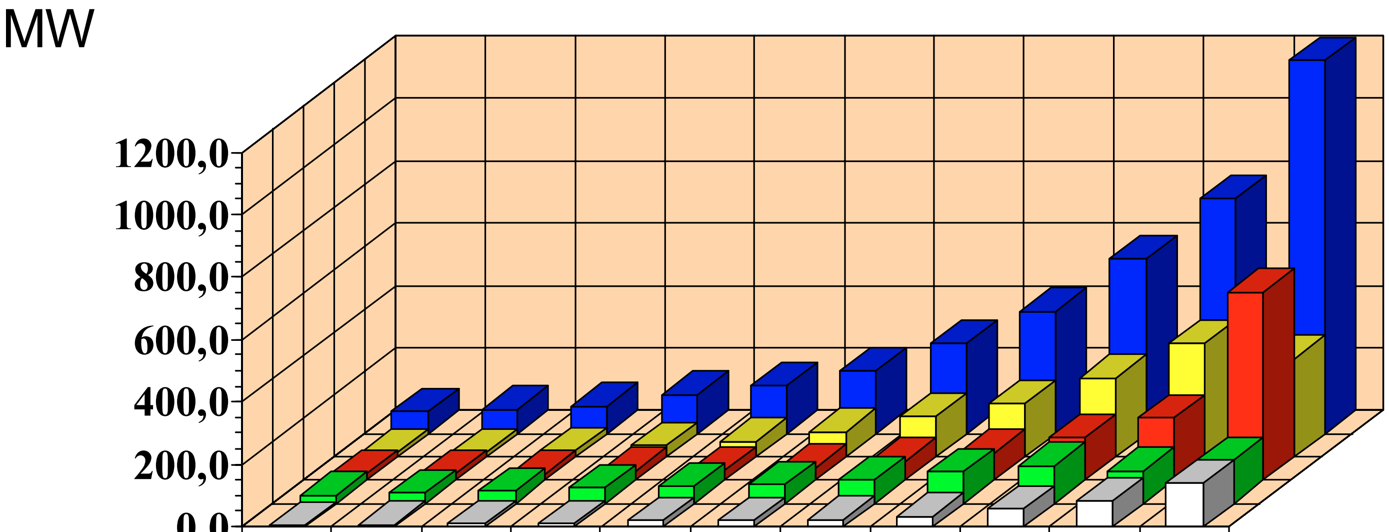
* estimated costs

World Energy Assessment: Energy and the challenge of Sustainability, UNDP, New York, ISBN 92-1-1261-0 (Chapter 5: Energy Resources)

World Market

Average growth 2000-2003: 40%/year
Turnover: 6 b €/year
Investments : ≈ 400 m€/year
Employed: ≈ 40.000

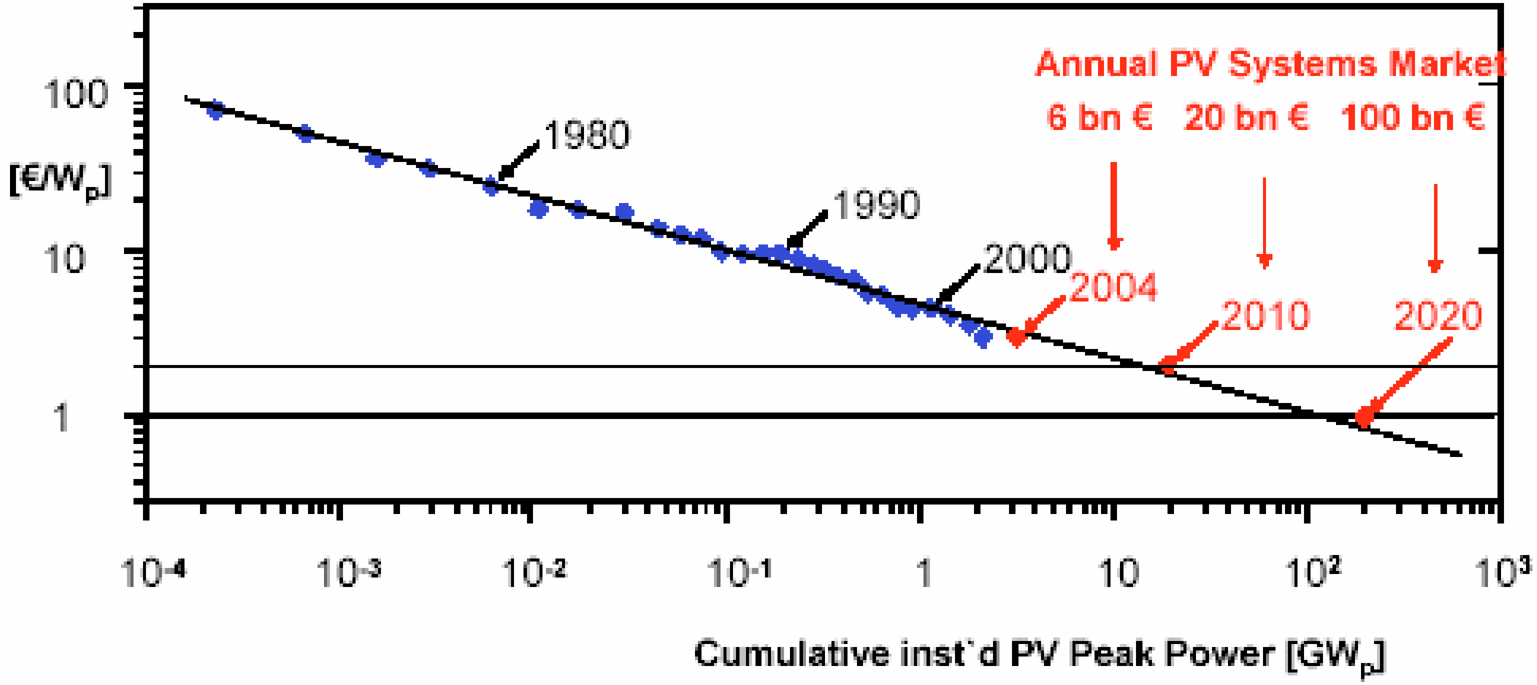
Potential at 2010
5.3 GW
25 b€



	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Rest of World	5,6	6,4	9,8	9,4	18,7	20,5	23,4	32,6	55,5	83,8	139
United States	25,6	34,8	38,9	51,0	53,7	60,8	75,0	100,0	120,6	104,2	139
Europe	21,7	20,1	18,8	30,4	33,5	40,0	60,7	86,4	135,1	199,4	602
Japan	16,5	16,4	21,2	35,0	49,0	80,0	128,6	171,2	251,1	363,9	314
Total	69,4	77,6	88,6	125,8	154,9	201,3	287,7	390,2	561,8	753,0	1195

Fonte: IEA, PPSP, SolarBuzz, PV News, PV Status report JRC 2005

Price Experience Curve of Crystalline Si PV Modules



Fraunhofer Institut Solare Energiesysteme

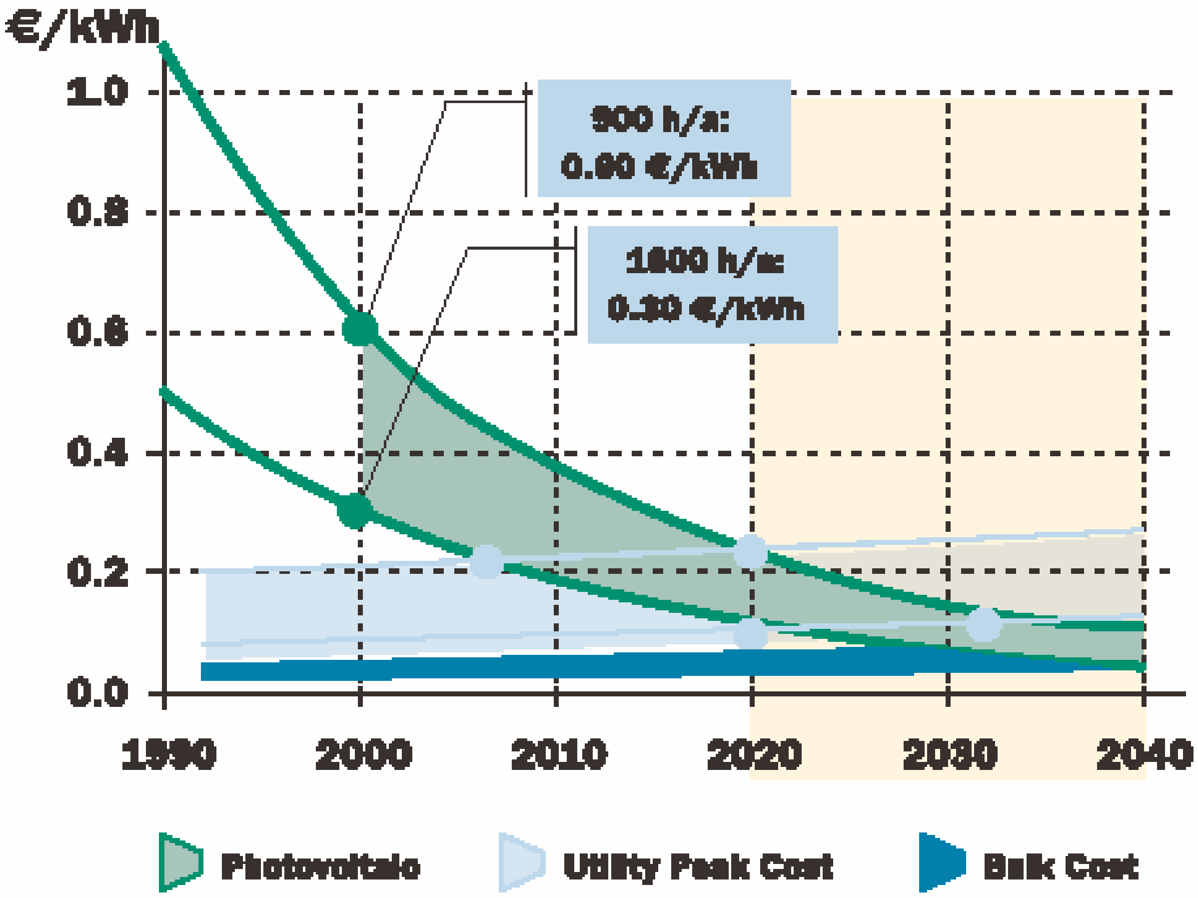
Incentives for PV in Europe (grid connected)

Country	Feed in tariff	capital incentives	loans	tax incentives	Notes
Austria	●				Installations 2003-04
Belgio	●				15c€/KWh
Cipro	●				12 - 26 c€/KWh
Rep. Ceca	●				20 c€/KWh
Danimarca					Green tariff under discussion
Estonia				●	
Finlanda		●			
Francia	●			●	15c€/KWh
Germania	●				55 c€/KWh
Grecia	●		●	●	7,8 c€/KWh
Irlanda					Under discussion
Italia	●				45 - 49 c€/KWh
Lituania	●				56 c€/KWh
Lussemburgo	●	●			25 - 45 c€/KWh
Malta				●	
Paesi Bassi	●				6,8 c€/KWh
Polonia			●	●	
Portogallo	●		●	●	22,4- 41 c€/KWh
Regno Unito			●	●	
Slovacchia				●	
Slovenia	●				6,5-37 c€/KWh
Spagna	●				21.6-39.6 c€/KWh
Svezia				●	
Svizzera	●				10 c€/KWh
Ungheria	●				60 c€/KWh

Market players

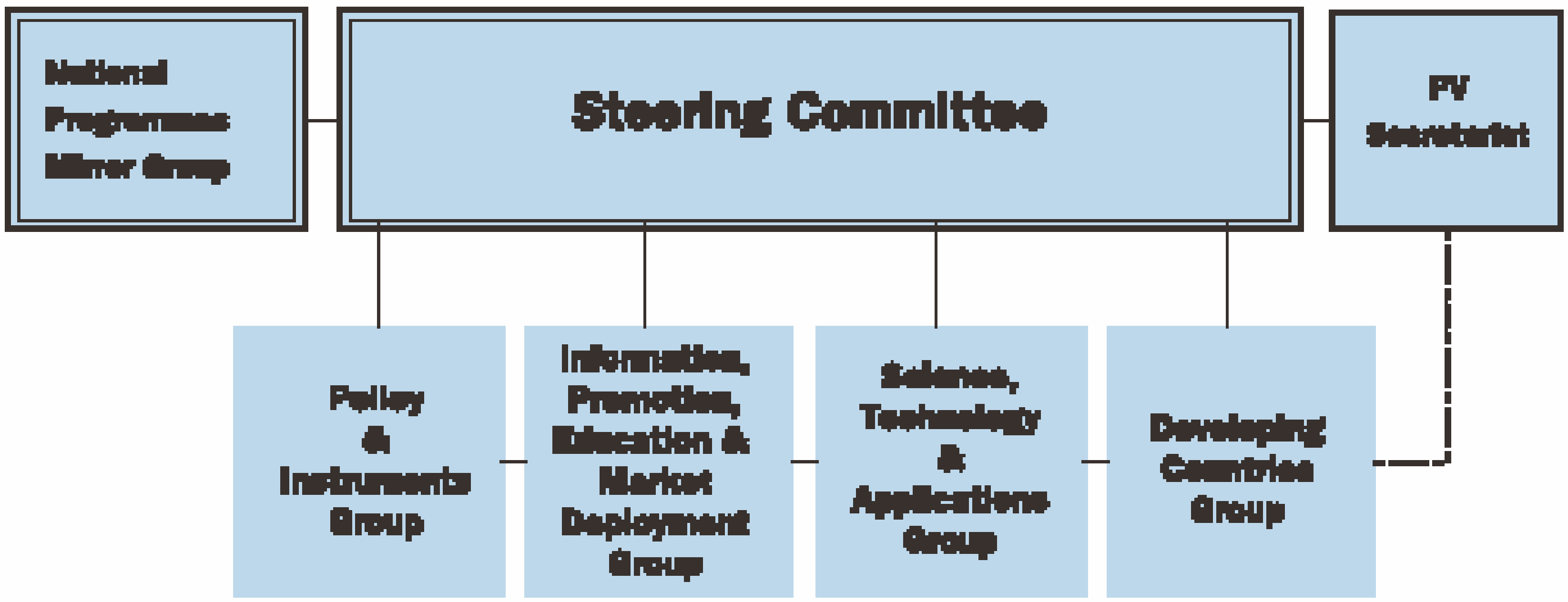
	2004	Production	Share	Ave growth		Capacity 2006/7
		(MW)		1999-2004		(estimates)
1	Sharp	314	26,3%	80%		800
2	Kyocera	105	8,8%	37%		480
3	BP Solar	85	7,1%	30%		202
4	Shell Solar	72	6,0%	35%		149
5	Mitsubishi	73	6,1%	64%		230
6	Rwe Schott Solar	64	5,4%	59%		202
7	Sanyo	64	5,4%	52%		398
8	Isofoton	54	4,5%	81%		202
9	Q-cells	73	6,1%	69%		499
10	Motech	35	2,9%	37%		230
11	General Electric	25	2,1%	(**)		70
12	Suntech	28	2,3%	(***)		202
	Total top ten	992	83,0%			
	others	203	17,0%			1138
	Total sales	1195	100,0%			4800

Figure 5: Generation costs of PV electricity[25]



[25] EPIA: Towards an Effective Industrial Policy for PV (RWE Schott Solar)

Figure 6: PV Technology Platform structure as proposed by PV-TRAC

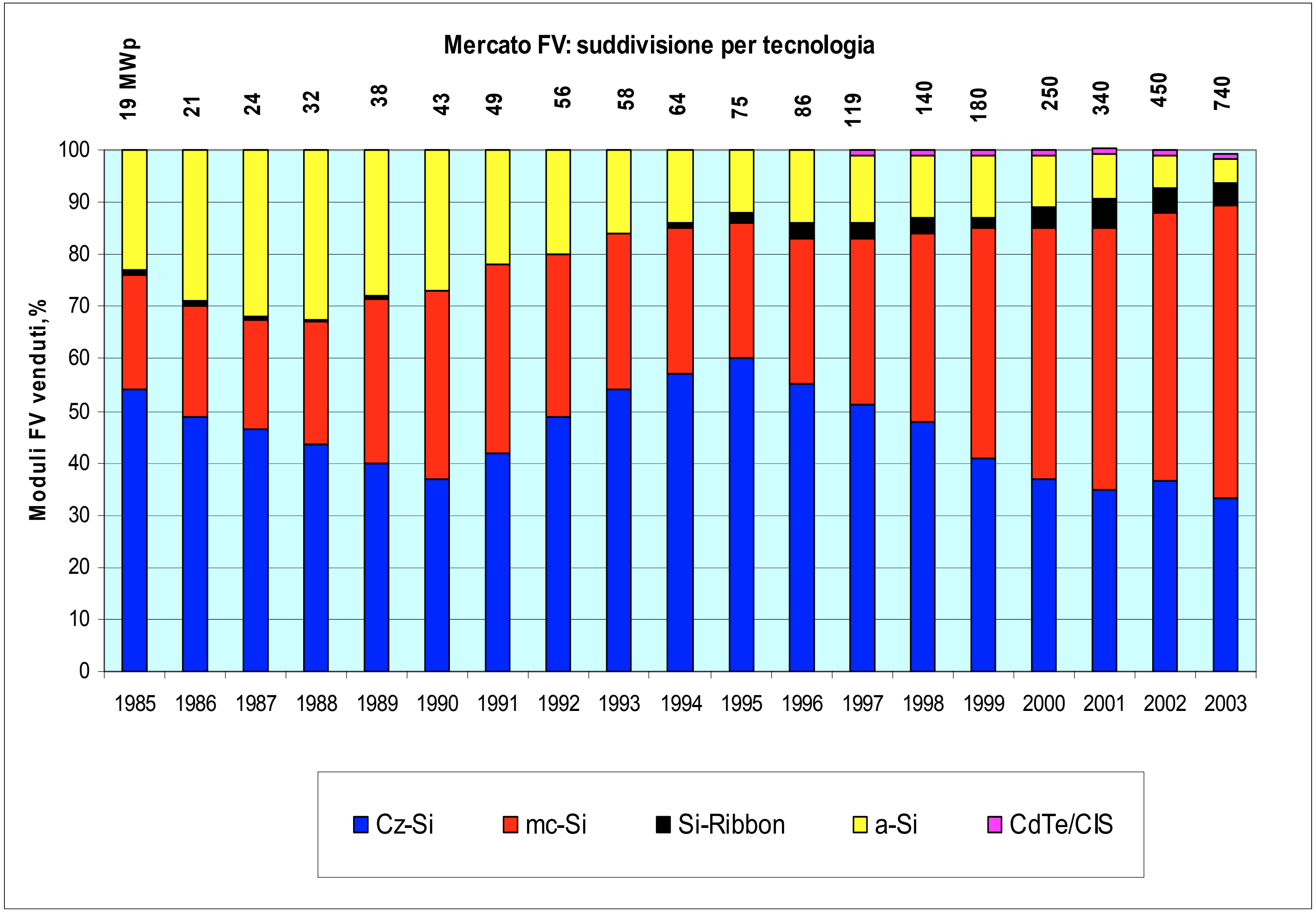


Contents

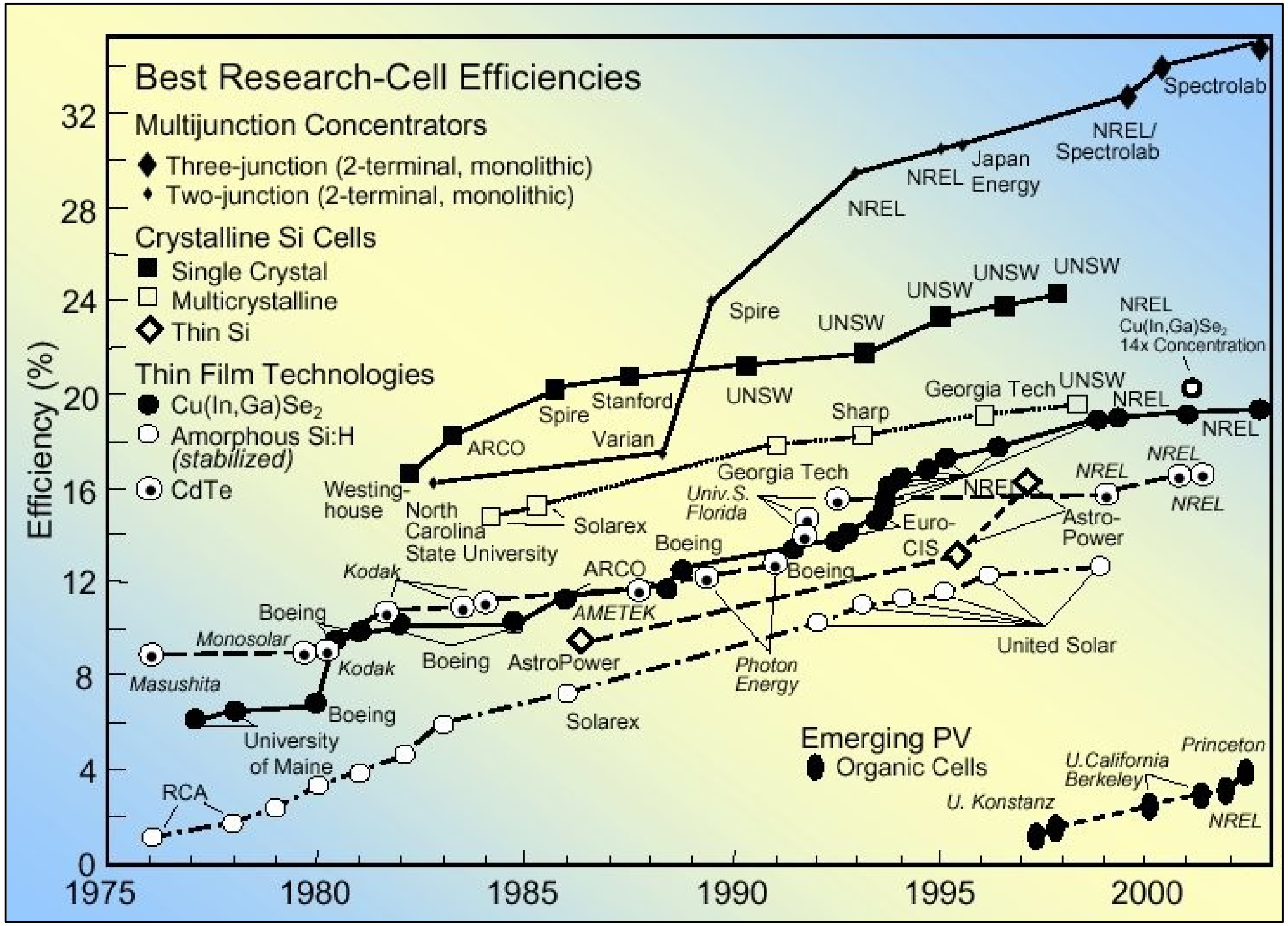
- Market
- Technology
- Future developments
- Conclusions

Bell Labs, 1955

Market by technology

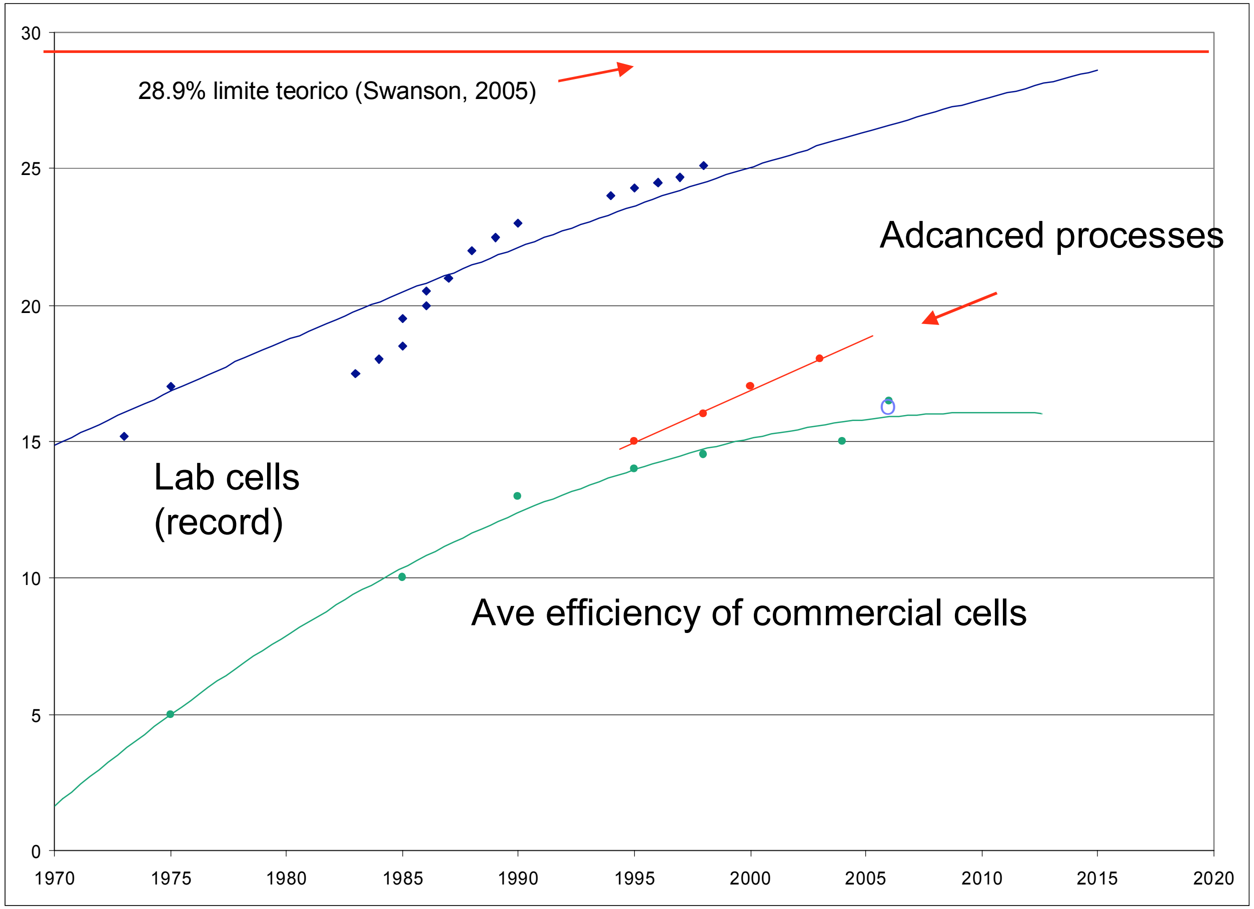


Cell record chart



Source – NREL, US

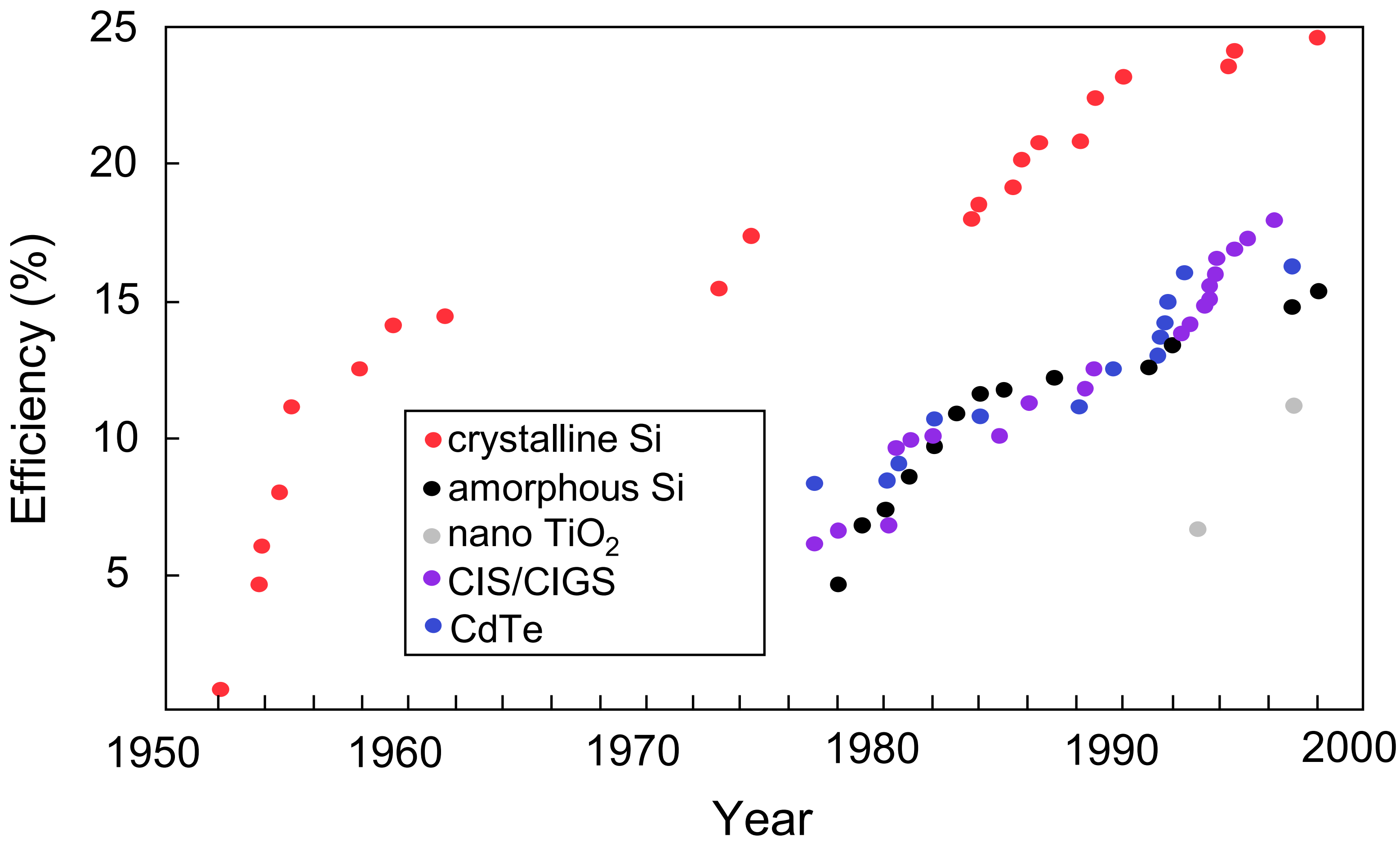
The case of silicon: Lab records and commercial cells



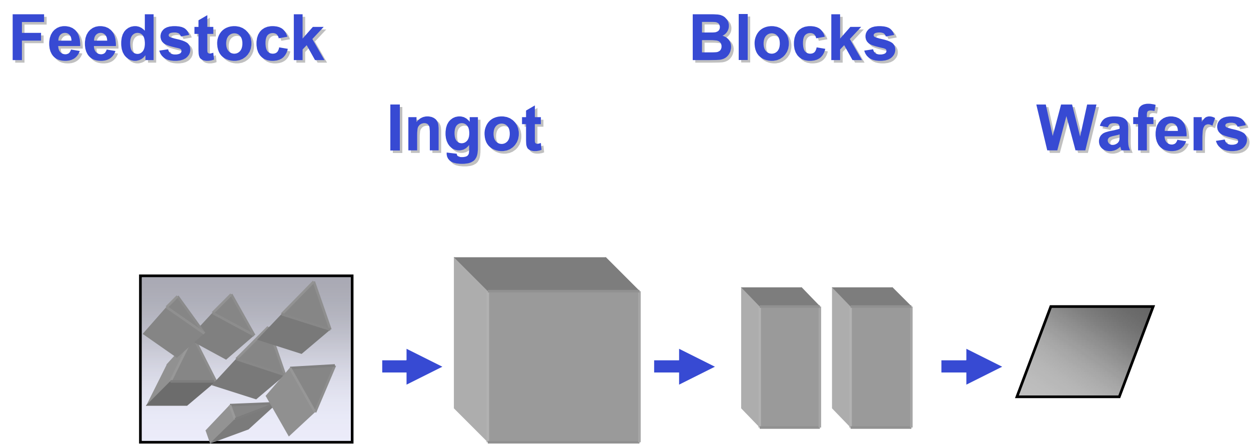
Fonte: Progress in Photovoltaics,UNSW web site, Conf records

ET 2005

Efficiency of Photovoltaic Devices



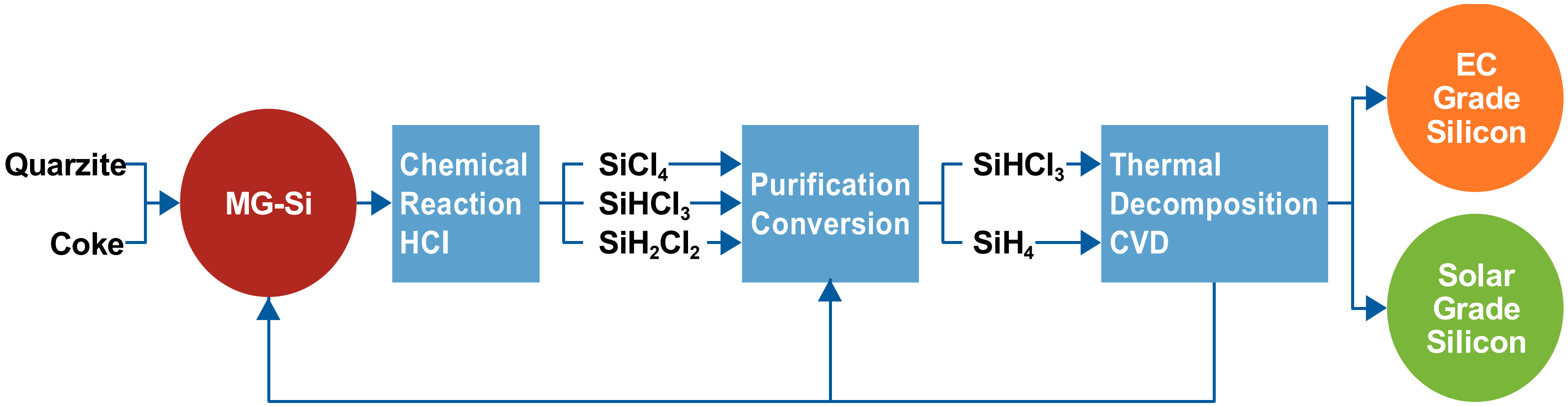
Silicio - material yield



Resa in materiale (%)		96	60	50
Costo (€/Kg)	30	60	100	250

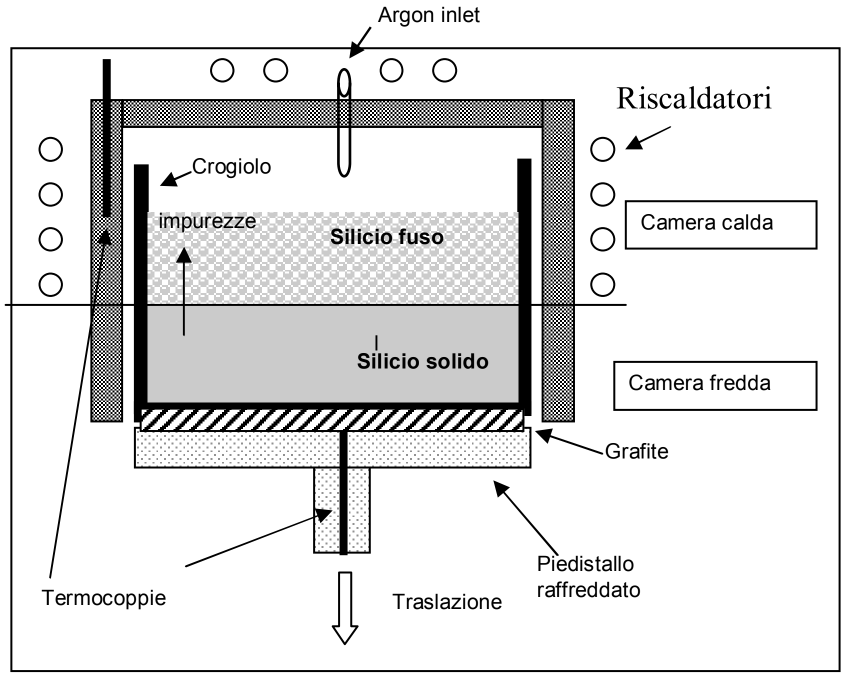
1 wafer = (3 ± ,3) €
(125 mm^2 270 μm)

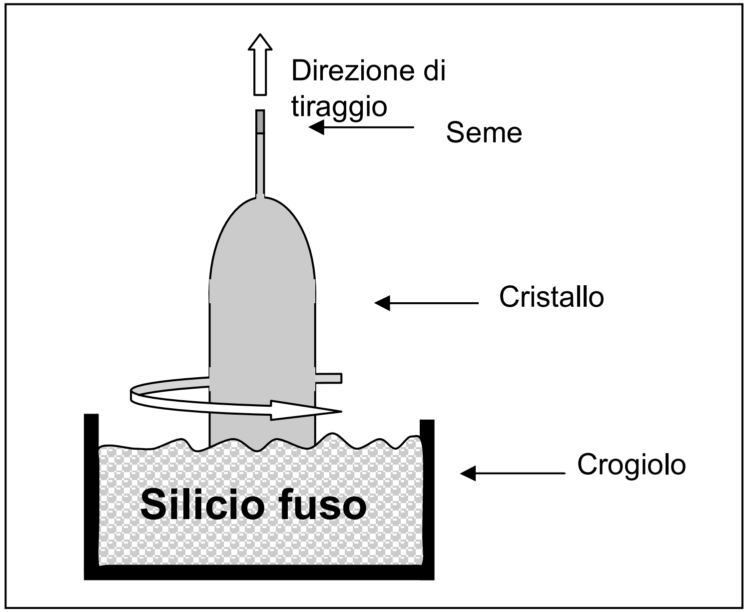
Il silicio per uso fotovoltaico - I



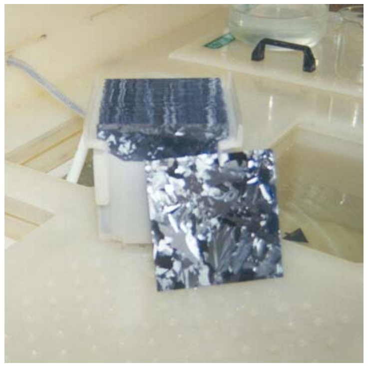
Shortage in feedstock supply

Silicon for PV – ingot growth



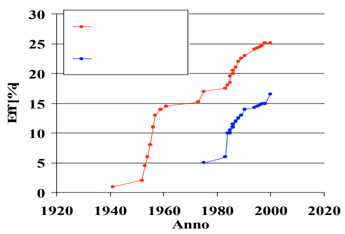


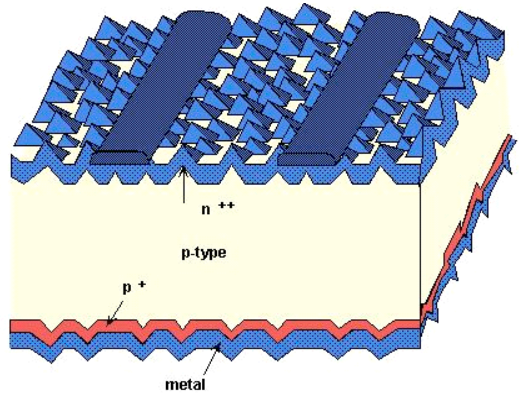
Schematic of Directional Solidification
For mutlicrystalline silicon



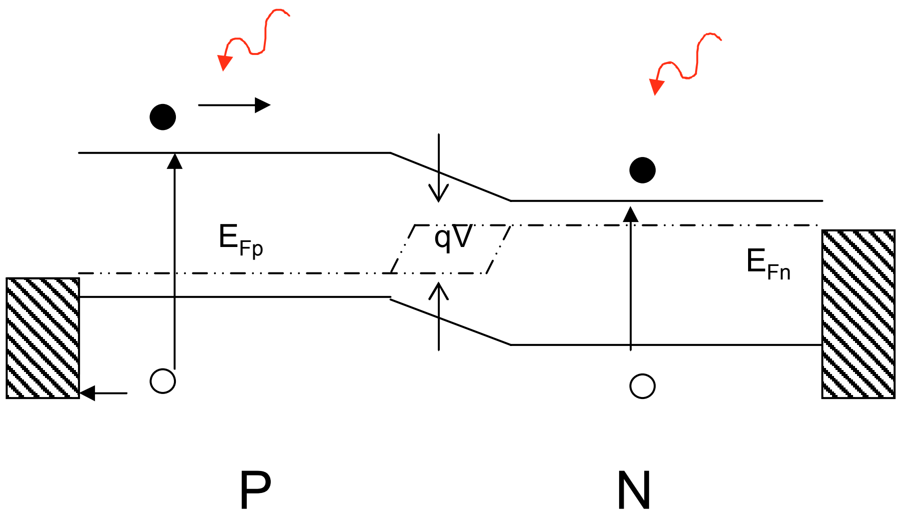
Schematic of Czochralski growth

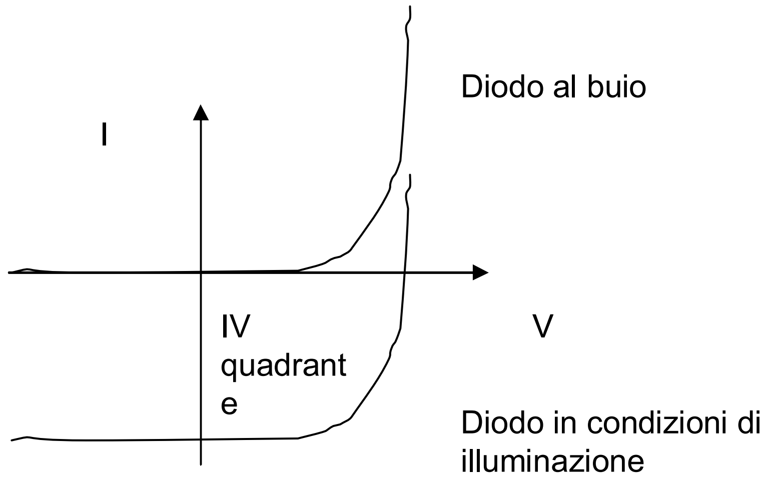
Solar cells



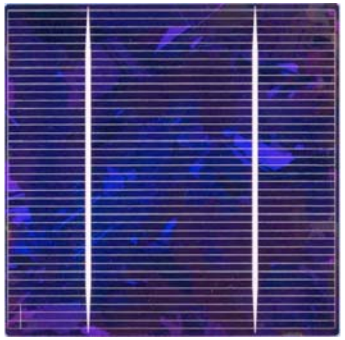


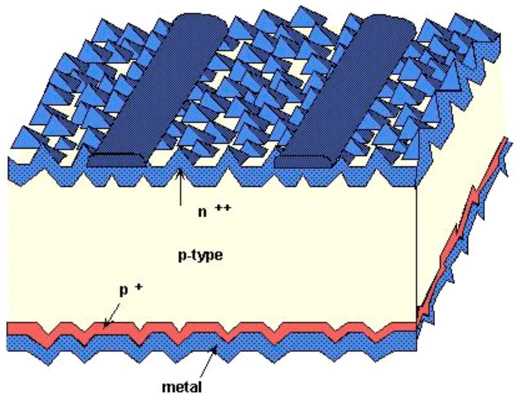
Commercial solar cells ar p-n diodes on thin silicon substrates. The metal contacts are realized by screen printing metal pastes.





Solar cells



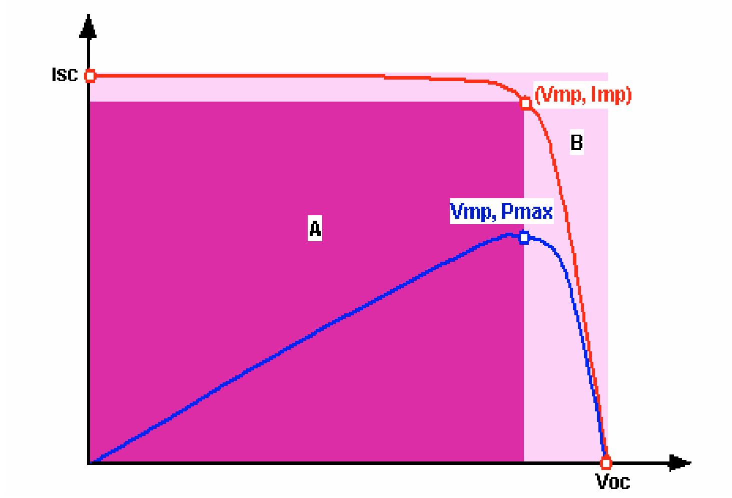


Efficiency
14 -15% on multicrystalline silicon
15 –16% on CZ Si

Eff=Pcell/P standard Sun
Standard Sun = 1000W/m^2
spectrum AM1.5G

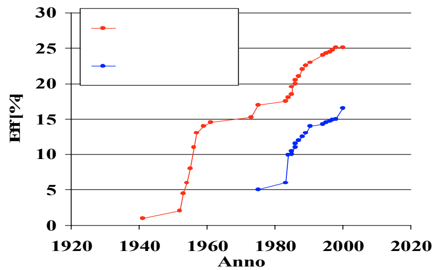
Typical wafer dimensions 100 cm^2, 150 cm^2,

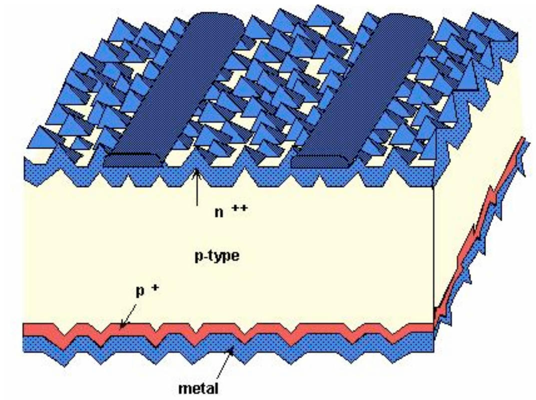
Thickness <270 μm

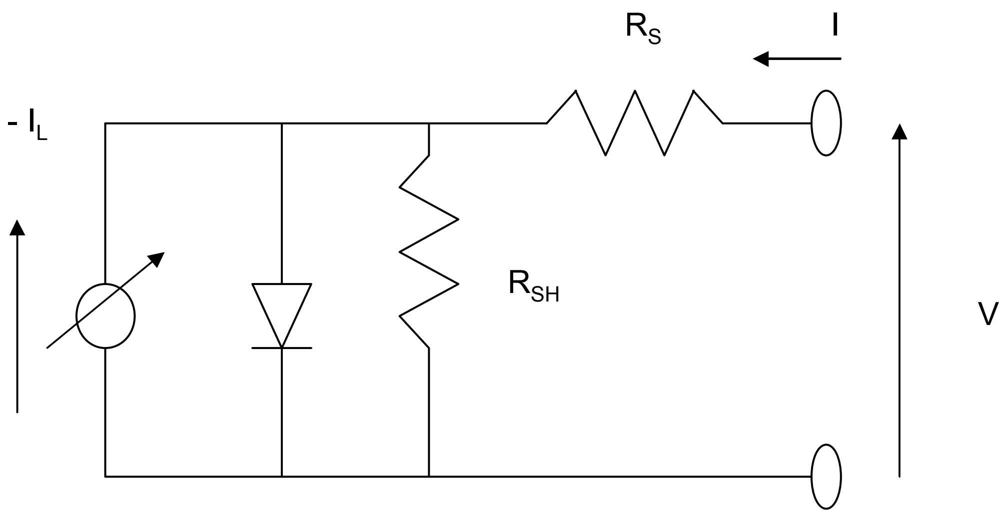


$$FF = I_{mp}V_{mp}/I_{sc}V_{oc}$$

Solar Cells

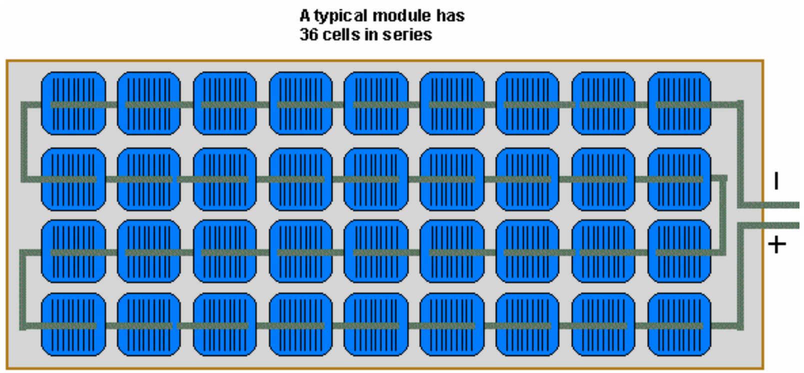


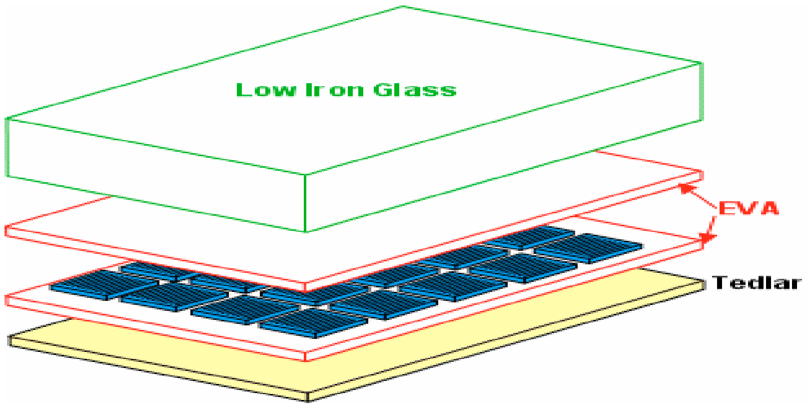




Simplified circuit schematic of a pn solar cell

Schematic of a PV module

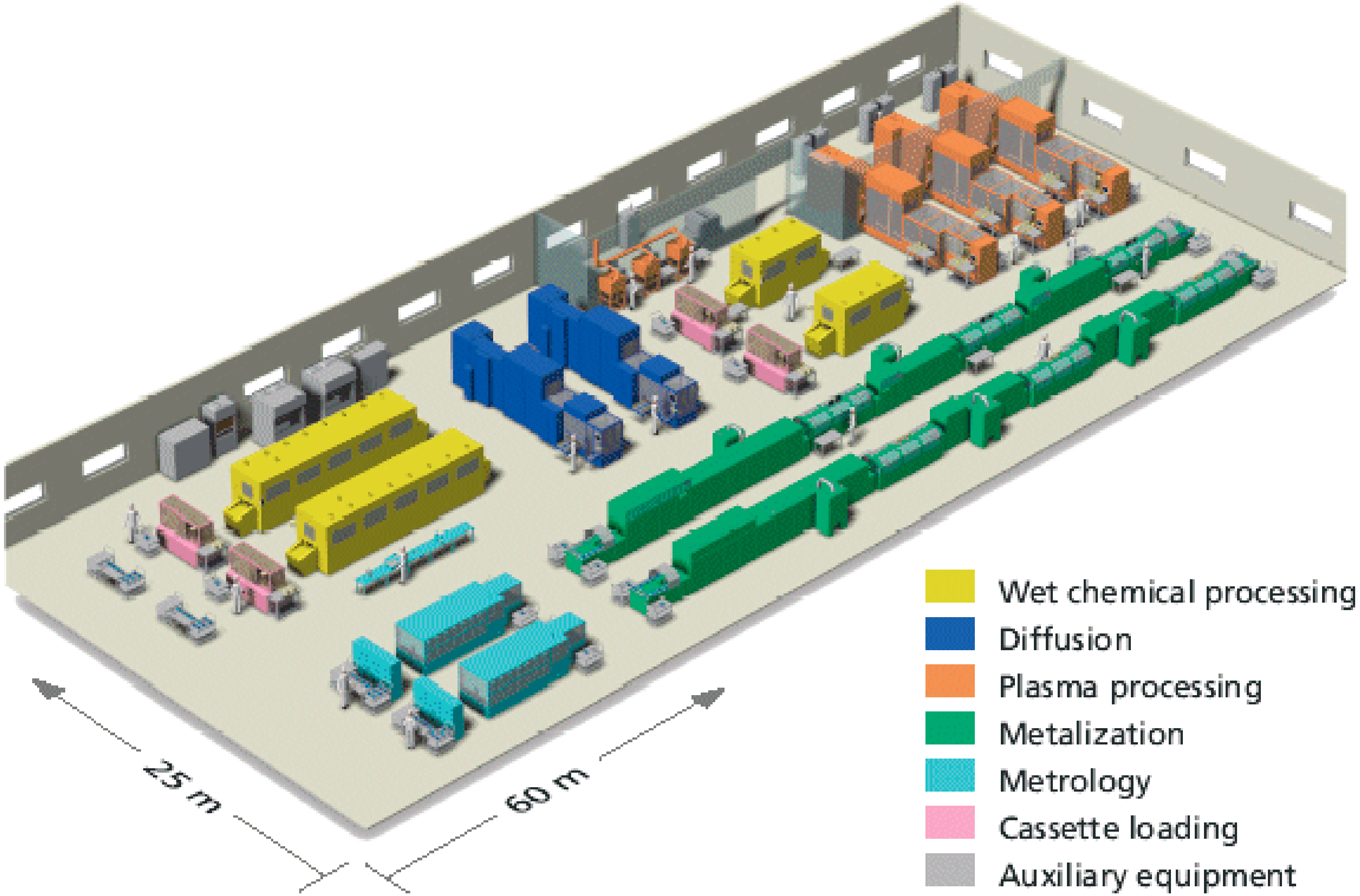




Lifetime >20 years
Type certification (IEC 61215)

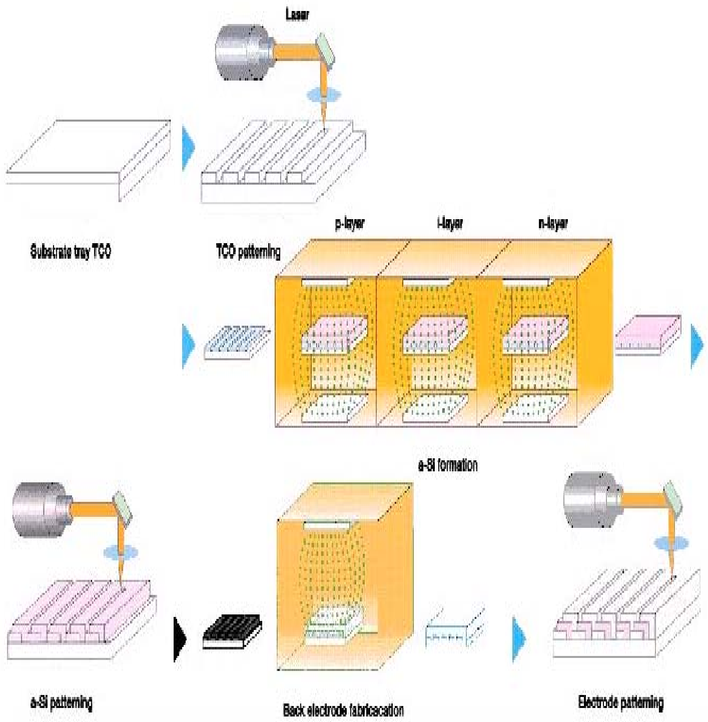
Semi-automatic line 5 MW/year - 1990

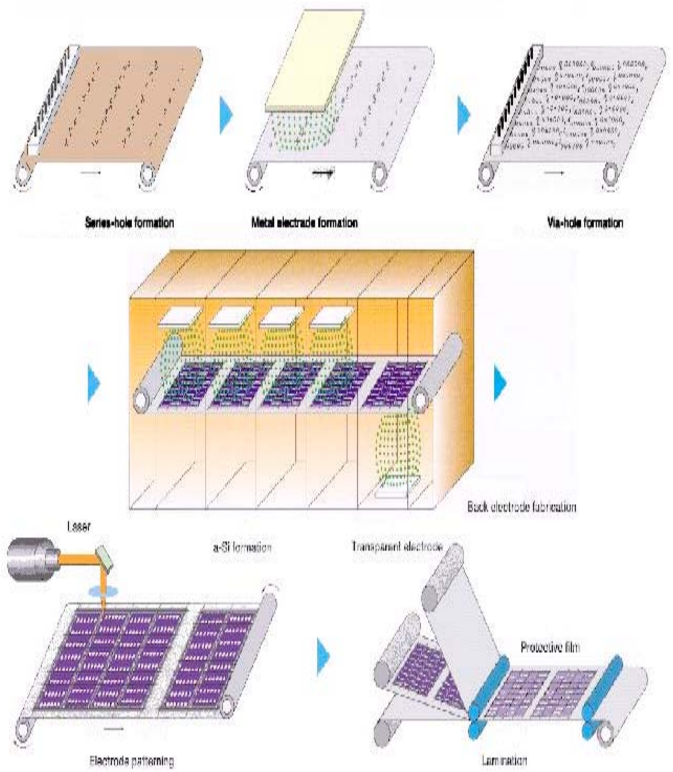
Strongly automated batch line – 40 MW/year - 2001



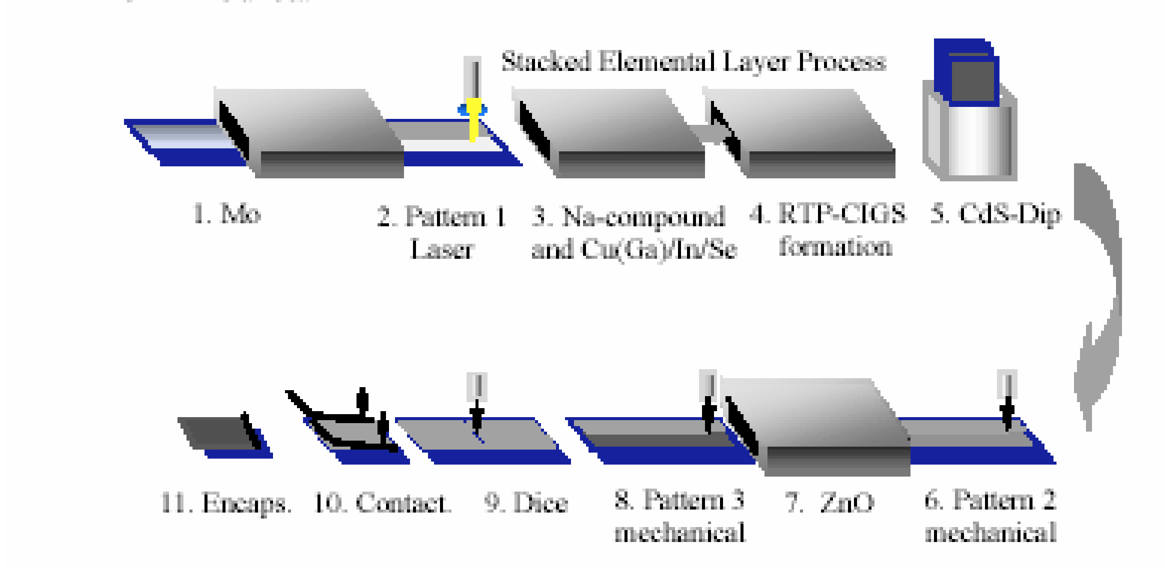
50MW/year, 2003

Thin films


Laser
Substrate tray TCO
TCO patterning
p-layer
i-layer
n-layer
a-Si formation
a-Si patterning
Back electrode fabricacation
Electrode patterning


Series-hole formation
Metal electrade formation
Via-hole formation
Back electrode fabrication
Laser
a-Si formation
Transparent electrode
Protective film
Electrode patterning
Lamination

Thin films – what's the situation?



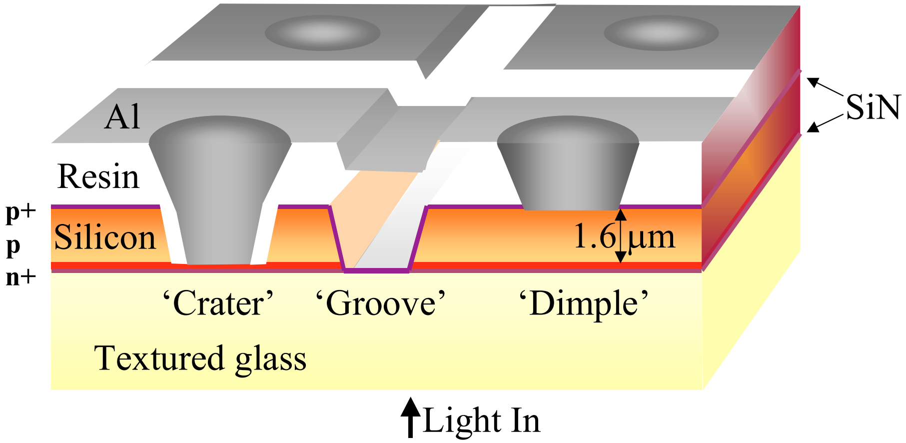
Open problems

- Low efficiency (<10%)
- Stability
- Toxic or rare materials
- Complex technologies
- Expensive equipment

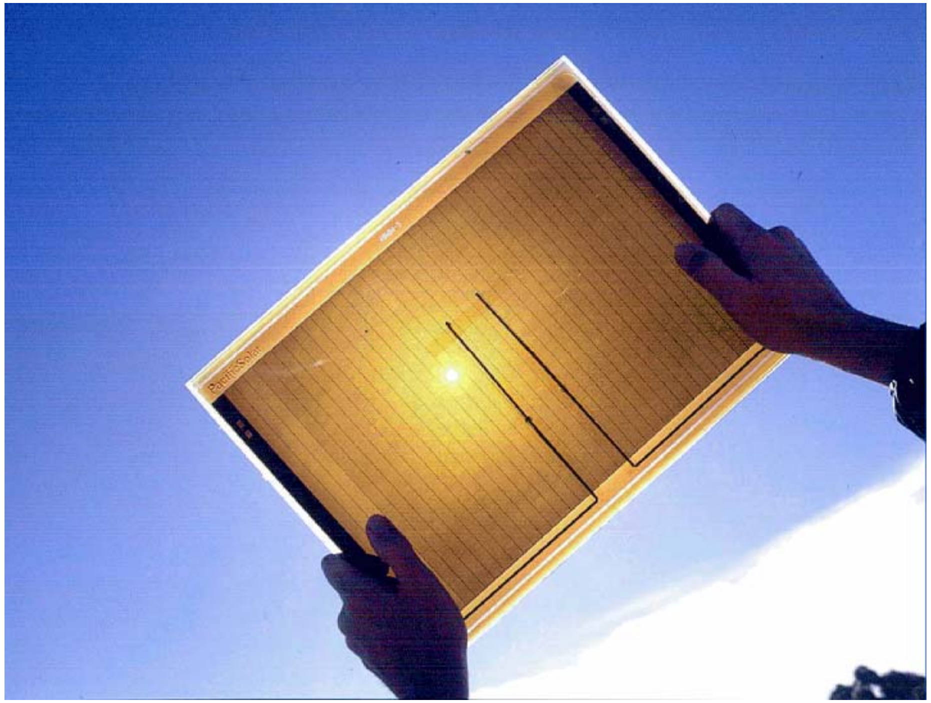
Advantages

- Low material usage => potential low cost
- Cell and module in the same sequence
- High industrial potential
- Aesthetical aspect

Thin Polycrystalline silicon on glass:
Ave eff 7.5%
(Pacific Solar, now CSG Solar)

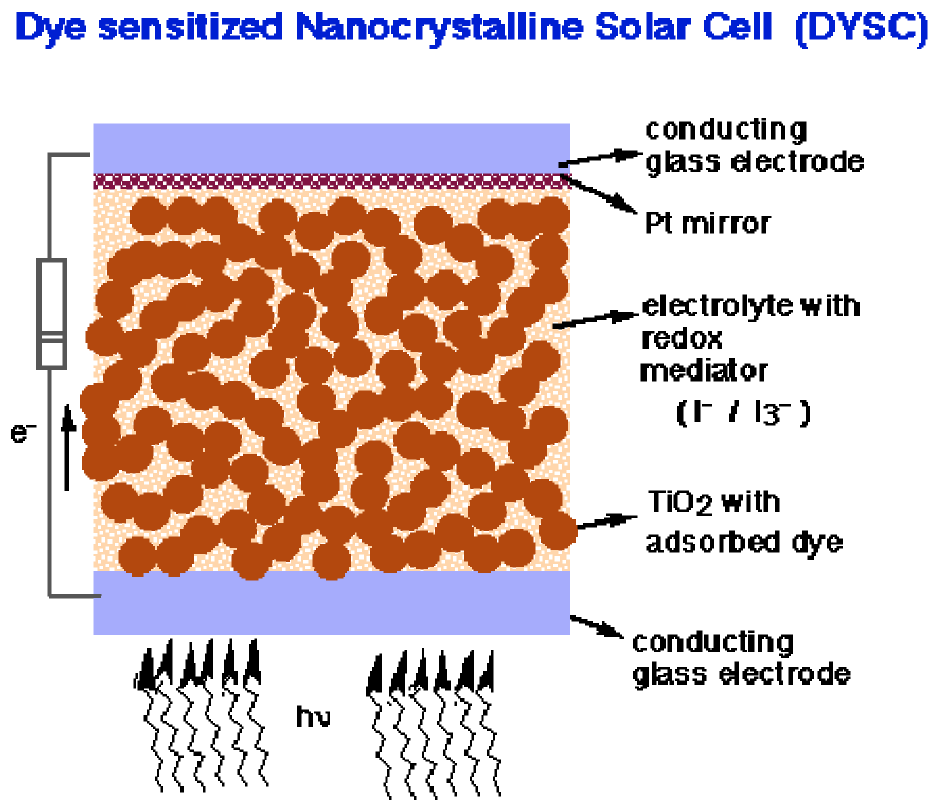


Schema di una sezione



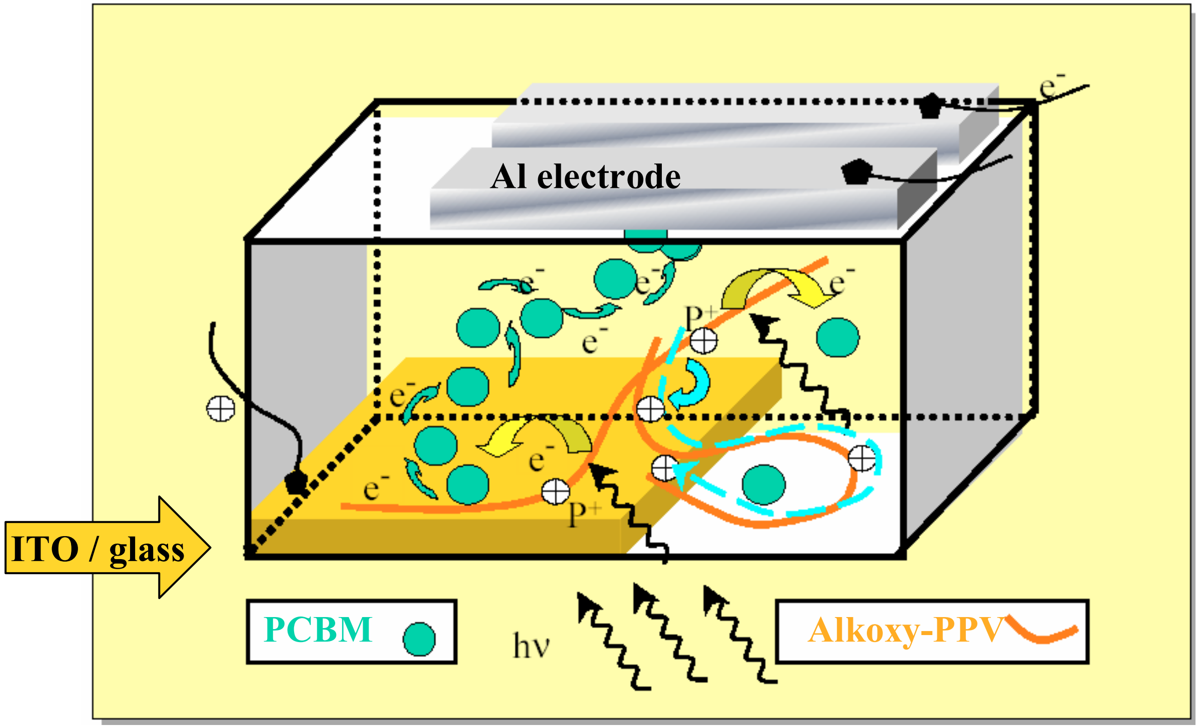
Other thin films: a-Si, CdTe, CIS

Nanotecnologies:



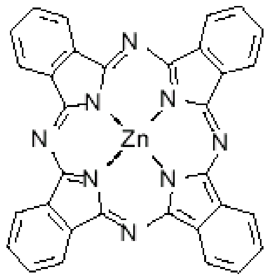
Efficiency up to 10% on small area

Polimeric cell – University of Linz

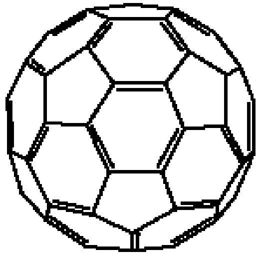


Schema di funzionamento della Cella polimerica
MDMO = PPV 3,7-dimethyloctyloxy methyloxy PPV
PCBM = 1-(3-methoxycarbonyl) propyl-1-phenyl [6,6] $\mathbf{C_{61}}$

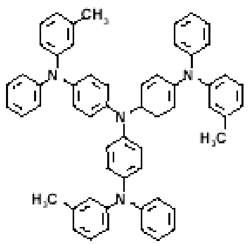
Polimer solar cells - Dresden



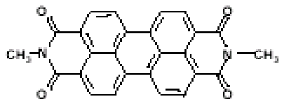
ZnPc



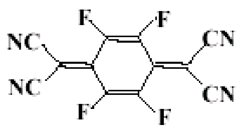
C_{60}



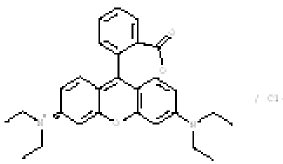
m-MTDATA



MPP



F_4-TCNQ



Rhoda B

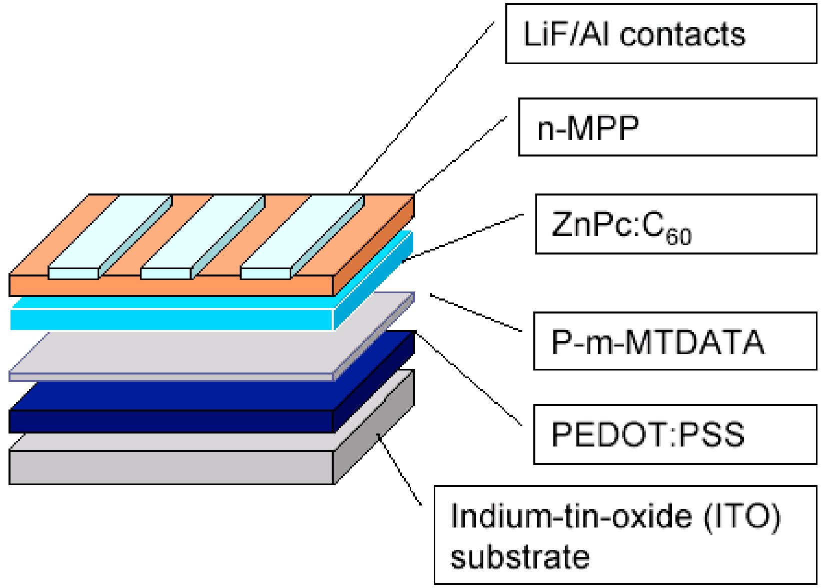
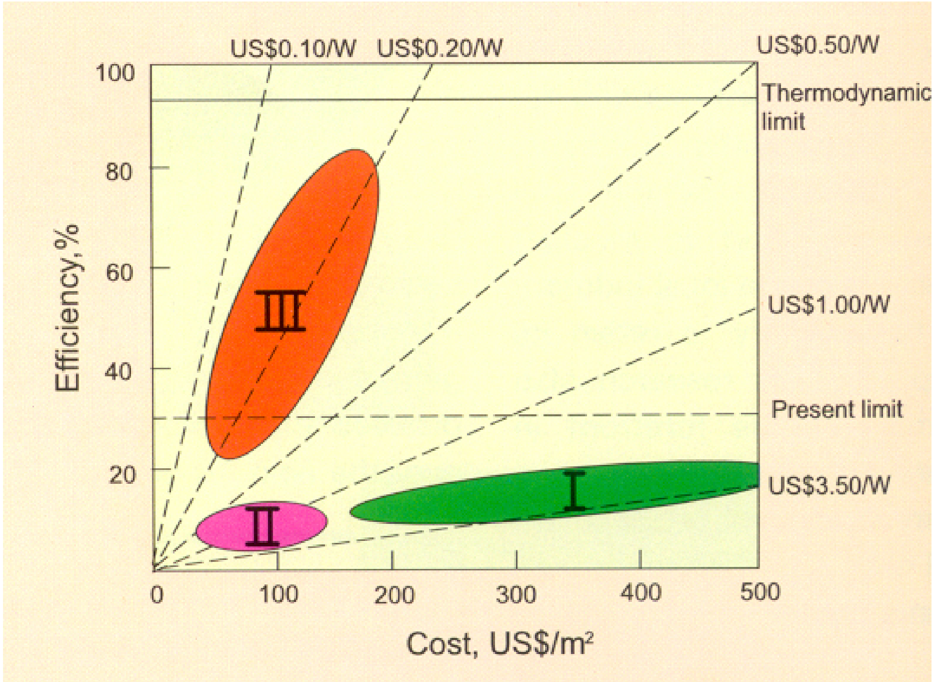


Fig. 1: Schematic diagram of the device configuration and molecular structures of the materials used.

Contents

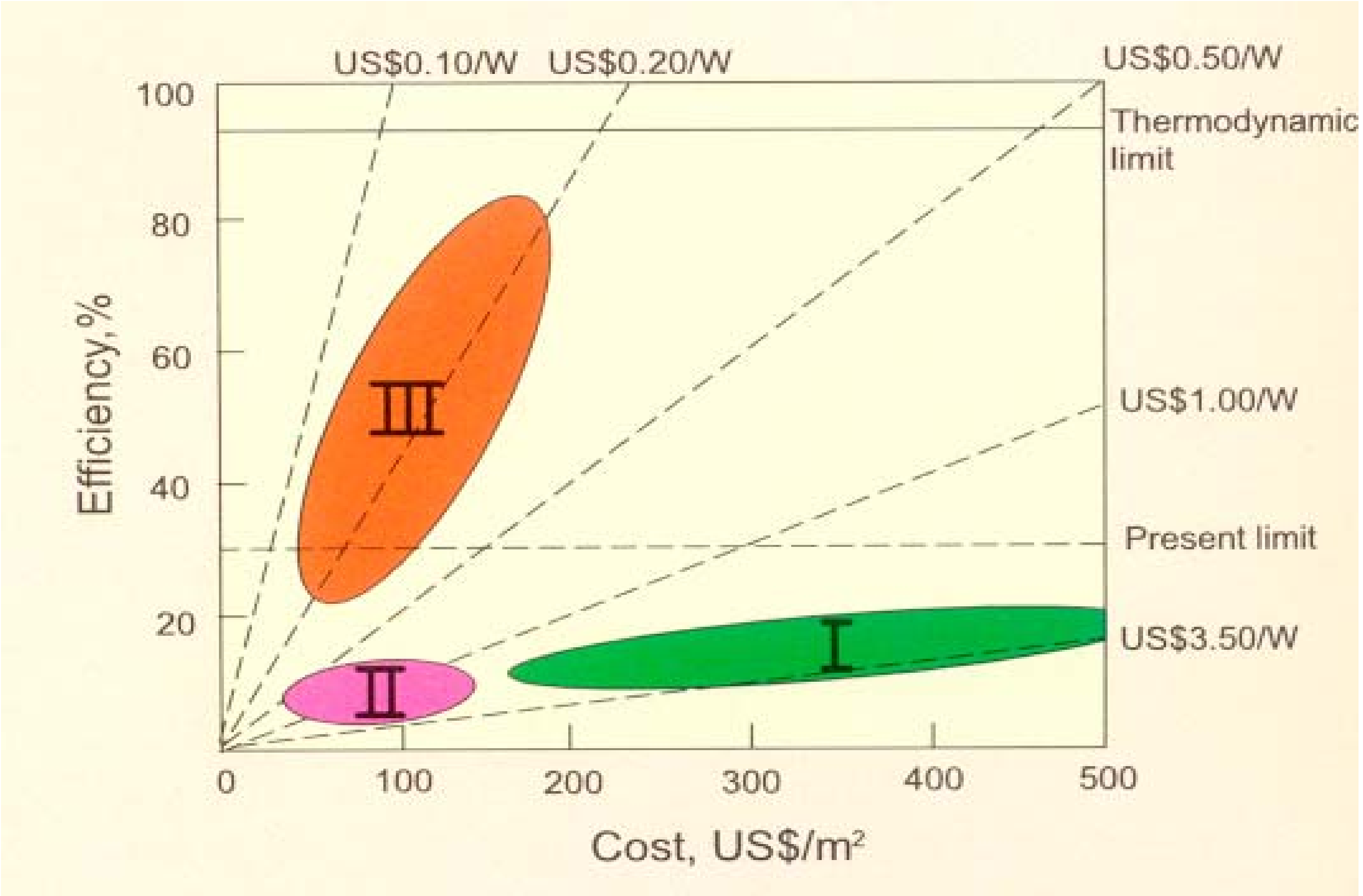


US$0.10/W
US$0.20/W
US$0.50/W
Thermodynamic limit
US$1.00/W
Present limit
US$3.50/W
III
II
I
Efficiency, %
100
80
60
40
20
0
100
200
300
400
500
Cost, US$/m²

Medium-long term developments

- High efficiency cells on thin (< 250 μm) large areas (>200 cm^2)
- Possible industrial relevance of > 20% efficient processes
- thin films
- nanotecnologies
- very high efficiency cells

High efficiency or low cost?



Record chart (1 sun)

Table I. Confirmed terrestrial cell and submodule efficiencies measured under the global AM1·5 spectrum (1000 Wm^{-2}) at 25°C

Classification[a]	Effic.[b] (%)	Area[c] (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF[d] (%)	Test centre[e] (and date)	Description
Silicon							
Si (crystalline)	24·7 ± 0·5	4·00 (da)	0·706	42·2	82·8	Sandia (3/99)	UNSW PERL[6]
Si (multicrystalline)	19·8 ± 0·5	1·09 (ap)	0·654	38·1	79·5	Sandia (2/98)	UNSW/Eurosolare[6]
Si (thin film transfer)	16·6 ± 0·4	4·017 (ap)	0·645	32·8	78·2	FhG-ISE (7/01)	U. Stuttgart (45 μm thick)[7]
III-V cells							
GaAs (crystalline)	25·1 ± 0·8	3·91 (t)	1·022	28·2	87·1	NREL (3/90)	Kopin, AlGaAs window
GaAs (thin film)	23·3 ± 0·7	4·00 (ap)	1·011	27·6	83·8	NREL (4/90)	Kopin, 5 μm CLEFT[8]
GaAs (multicrystalline)	18·2 ± 0·5	4·011 (t)	0·994	23·0	79·7	NREL (11/95)	RTI, Ge substrate[9]
InP (crystalline)	21·9 ± 0·7	4·02 (t)	0·878	29·3	85·4	NREL (4/90)	Spire, epitaxial[10]
Polycrystalline thin film							
CIGS (cell)	18·4 ± 0·5[f]	1·04 (ap)	0·669	35·7	77·0	NREL (2/01)	NREL, CIGS on glass[11]
CIGS (submodule)	16·6 ± 0·4	16·0 (ap)	2·643	8·35	75·1	FhG-ISE (3/00)	U. Uppsala, 4 serial cells[12]
CdTe (cell)	16·5 ± 0·5[f]	1·032 (ap)	0·845	25·9	75·5	NREL (9/01)	NREL, mesa on glass[13]
Amorphous/Nanocrystalline Si							
Si (nanocrystalline)	10·1 ± 0·2	1·199 (ap)	0·539	24·4	76·6	JQA (12/97)	Kaneka (2 μm on glass)[14]
Photochemical							
Nanocrystalline dye	8·2 ± 0·3	2·36 (ap)	0·726	15·8	71·2	FhG-ISE (7/01)	ECN[15]
Nanocrystalline dye (submodule)	4·7 ± 0·2	141·4 (ap)	0·795	11·3	59·2	FhG-ISE (2/98)	INAP
Multijunction cells							
GaInP/GaAs	30·3	4·0 (t)	2·488	14·22	85·6	JQA (4/96)	Japan Energy (monolithic)[16]
GaInP/GaAs/Ge	28·7 ± 1·4	29·93 (t)	2·571	12·95	86·2	NREL (9/99)	Spectrolab (monolithic)
GaAs/CIS (thin film)	25·8 ± 1·3	4·00 (t)	—	—	—	NREL (11/89)	Kopin/Boeing (4 terminal)
a-Si/CIGS (thin film)[g]	14·6 ± 0·7	2·40 (ap)	—	—	—	NREL (6/88)	ARCO (4 terminal)[17]

[a]CIGS = $CuInGaSe_2$; a-Si = amorphous silicon/hydrogen alloy.
[b]Effic. = efficiency.
[c](ap) = aperture area; (t) = total area; (da) = designated illumination area.
[d]FF = fill factor.
[e]FhG-ISE = Fraunhofer-Insitut für Solare Energiesysteme; JQA = Japan Quality Assurance.
[f]Not measured at external laboratory.
[g]Unstabilized results.

Efficiency limit for a single junction device

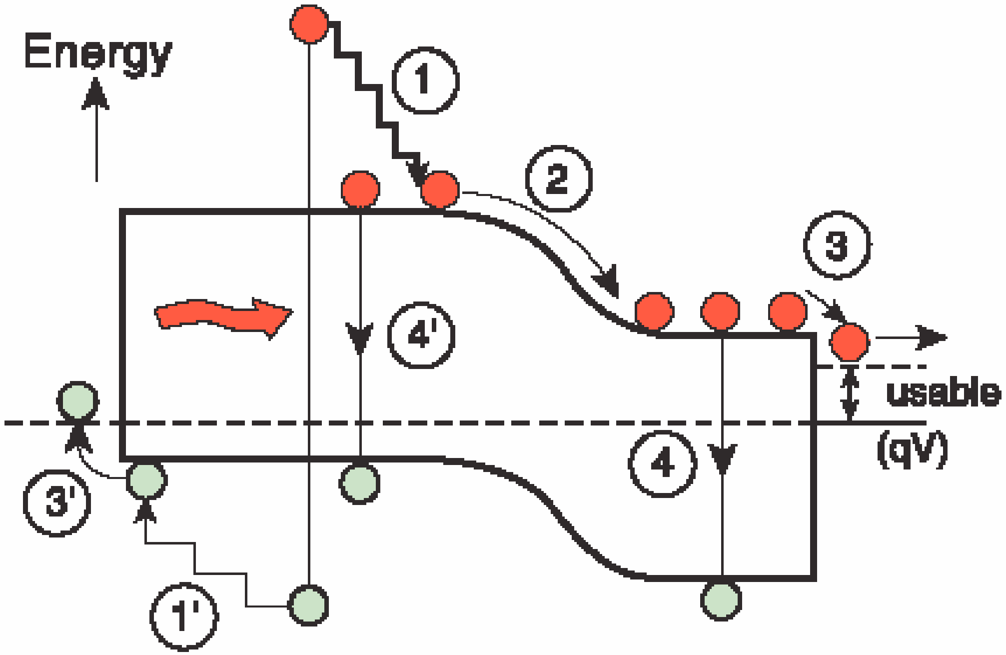


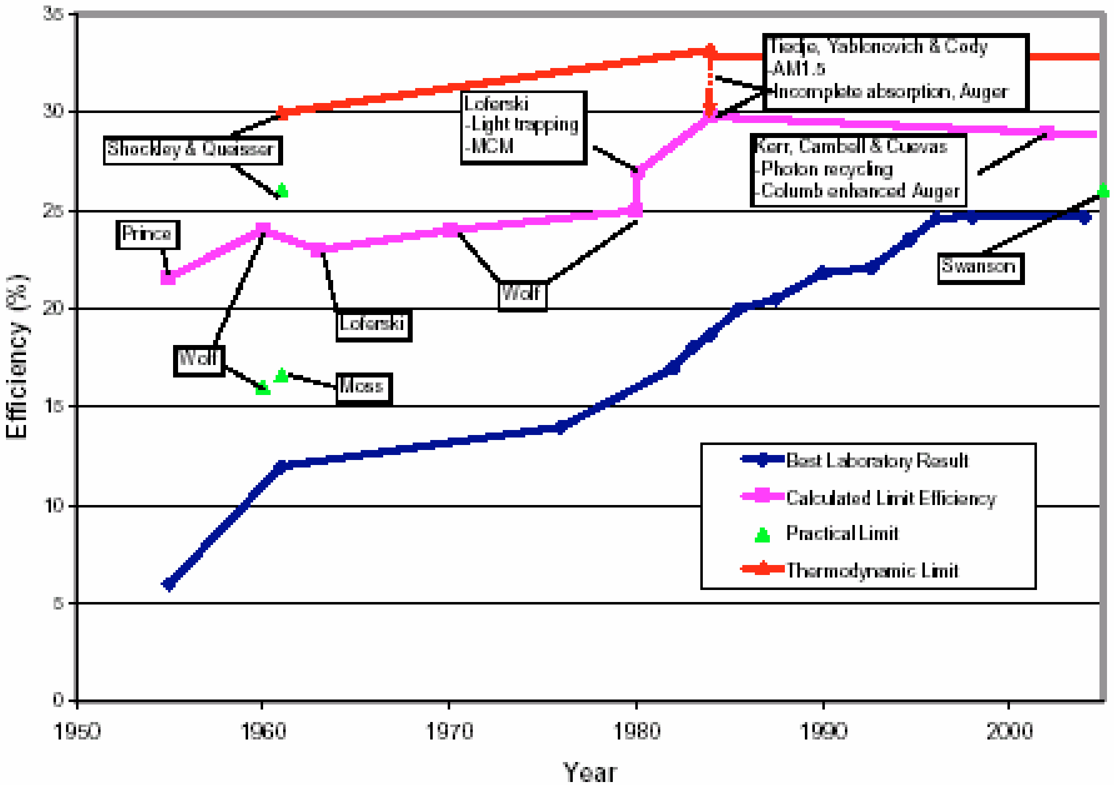
Fig. 6:1 Loss processes in a standard solar cell: (1) lattice thermalisation loss; (2) and (3) junction and contact voltage loss; (4) recombination loss.

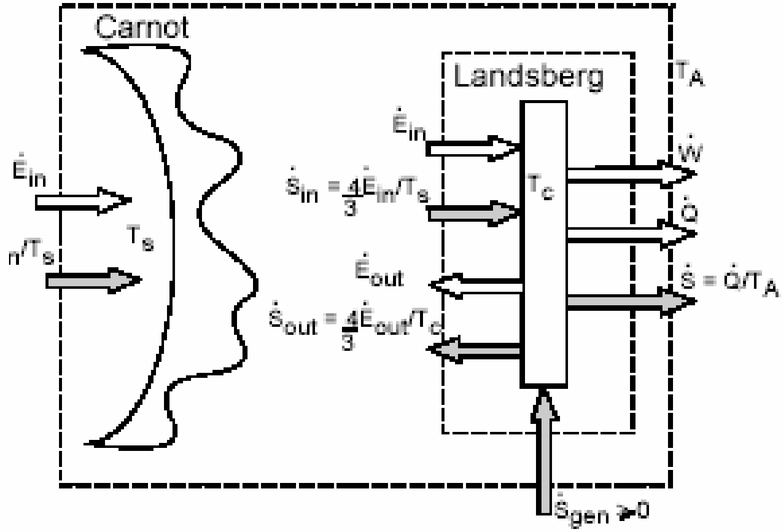
1. Photons E>> Eg 20%
2. Junction losses 10%
3. Non ohmic contacts 10%
4. Recombination 30%
5. Photons E<Eg 30%

Max 30.8% at 1 sun for silicon

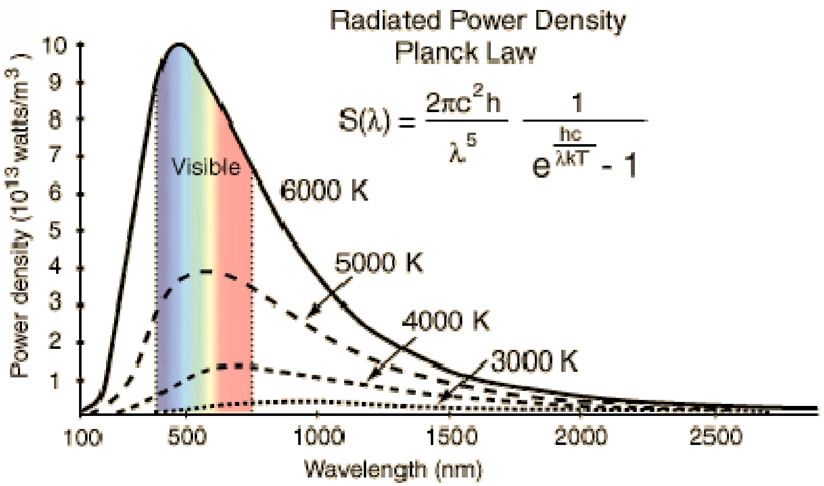
Practical limit about 26%

Efficiency : calculations and limits





$$\dot{W} = \dot{E}_{in} - \dot{E}_{out} - T_A(\dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen})$$



Efficiency : calculations and limits

Thermodinamic limit

η= 1-Ta/Ts = 95% Carnot efficiency

$\eta = [1-(T_c/T_s)^4][1-T_a/T_s]$ = 85.4% Müser

= 86.8% multiple converters

Quantum converter

$$\eta = \frac{x_g \int_{x_g}^{x_\infty} f(x)dx}{\int_0^\infty xf(x)dx}$$

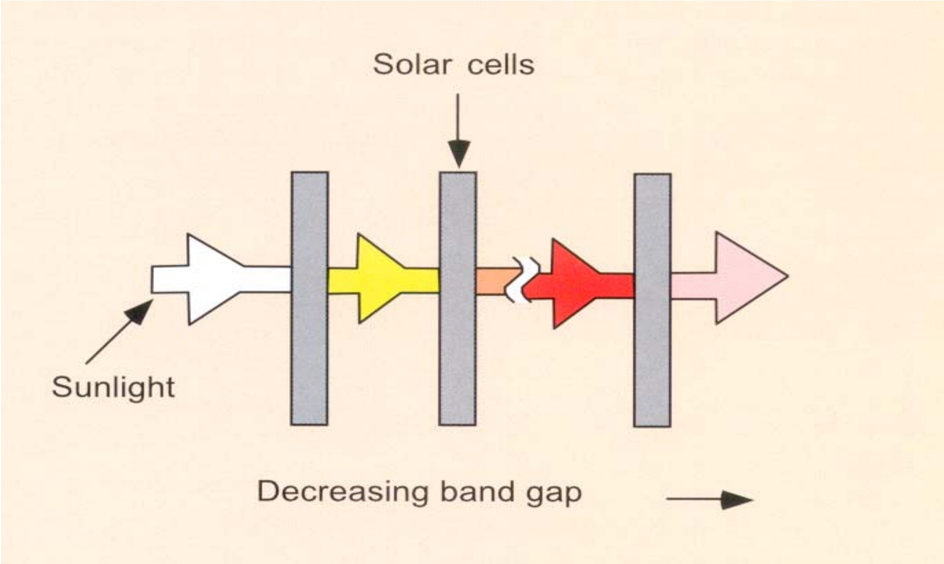
= 86.8% multiple converters

= 40.8% one converter,

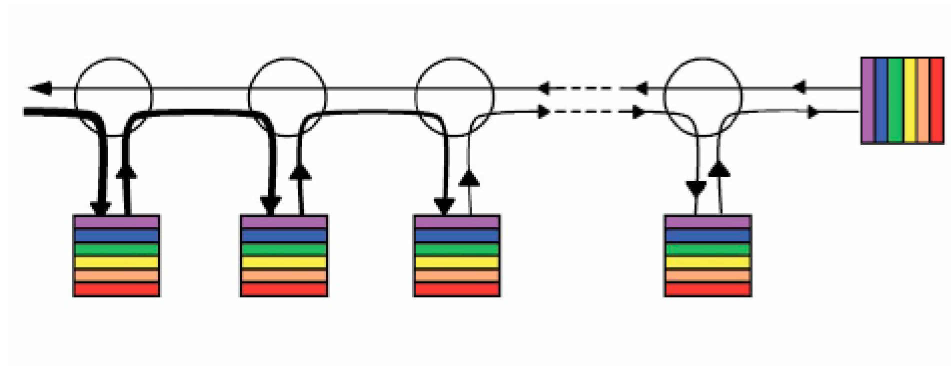
max concentration (1/fω = 45.872)

= 30.8% one converter, 1 sun.

$x = E/KT_s$ f(x) = generalized photon distribution function



Tandem Cells



86,8% **theoretical limit for infinite junctions (93.3% con l'uso di circolatori ottici)**

30% **triple junction (GaInP/GaAs/Ge)**

39 % under concentration

6-12% **amorphous silicon best modules**

Possible candidate for multigiunctions: InGaN => theoretical limit about 50% Material used for LEDs

Spectrolab Inc. 12500 Gladstone Avenue, Sylmar, California 91342 USA

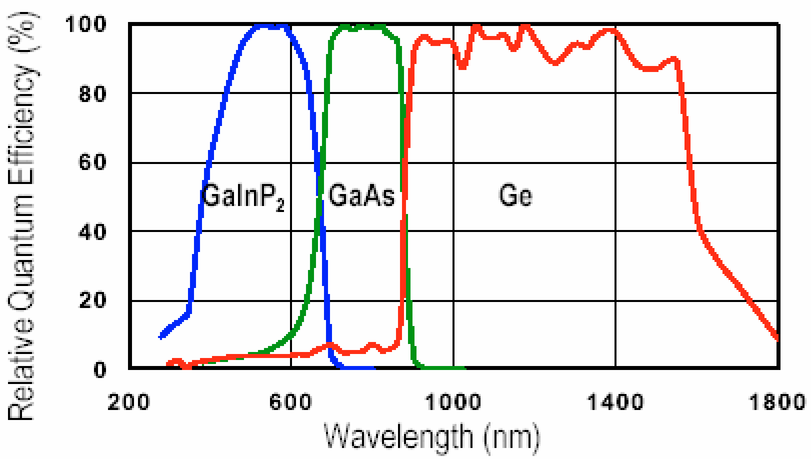
- High efficiency $GaInP_2$/GaAs/Ge triple junction monolythic, two-terminal design
- Greater than 30% AM1.5D min. avg. efficiency from 200 to 400 Suns concentration in production
- Compatible with point focus, dense array and linear concentrators
- High Reliability
  -No degradation with multiple assembly methods

Typical Cell Electrical Parameters

350 Suns, AM1.5D (37.2 W/cm²) 25°C

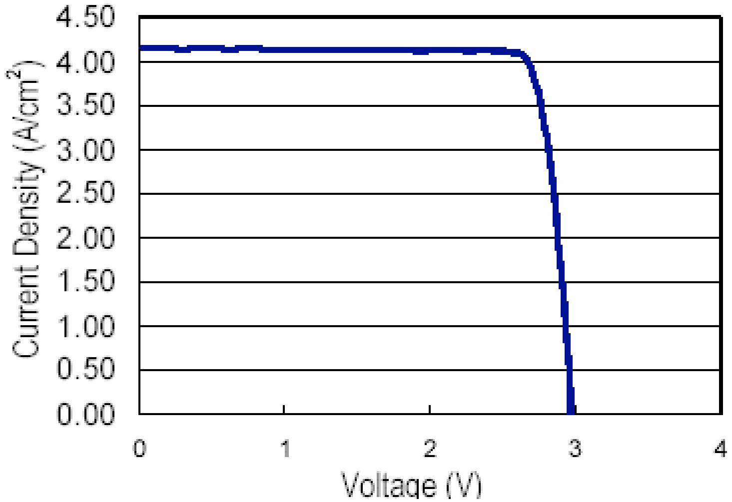
J_{sc}= 4.14 A/cm²	J_{mp}= 4.05 A/cm²
V_{oc}= 2.97 V	V_{mp}= 2.64 V
P_{mp}= 10.68 W/cm²	Cff = 86.9 %
Efficiency = 30.5 %	

Quantum Efficiency

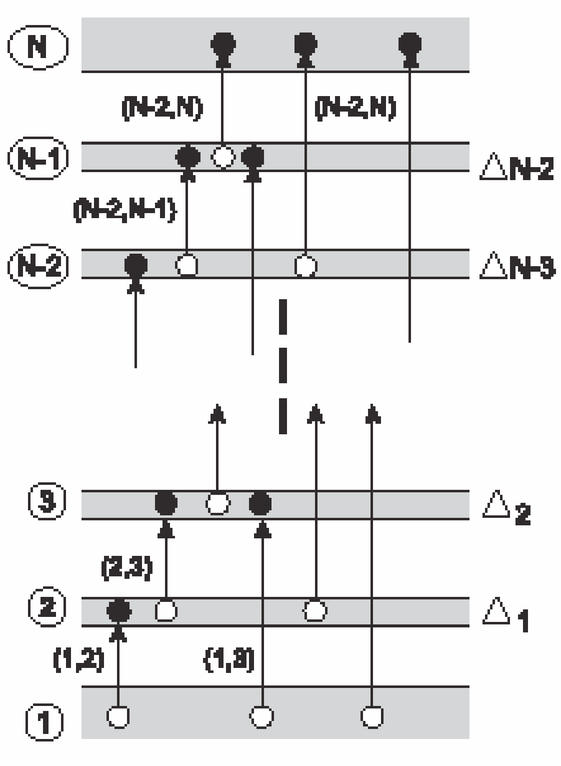


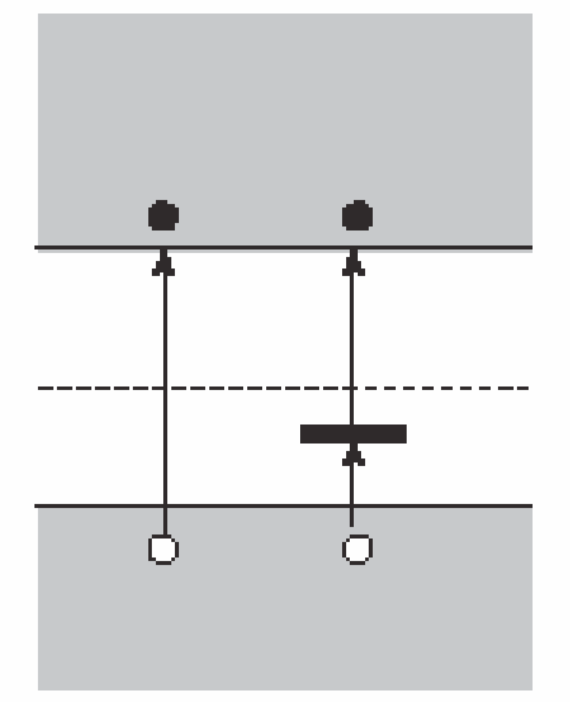
Typical Cell Light IV Characteristic

350 Suns, AM1.5D (35 W/cm²) 25°C



Multiband and impurity cells

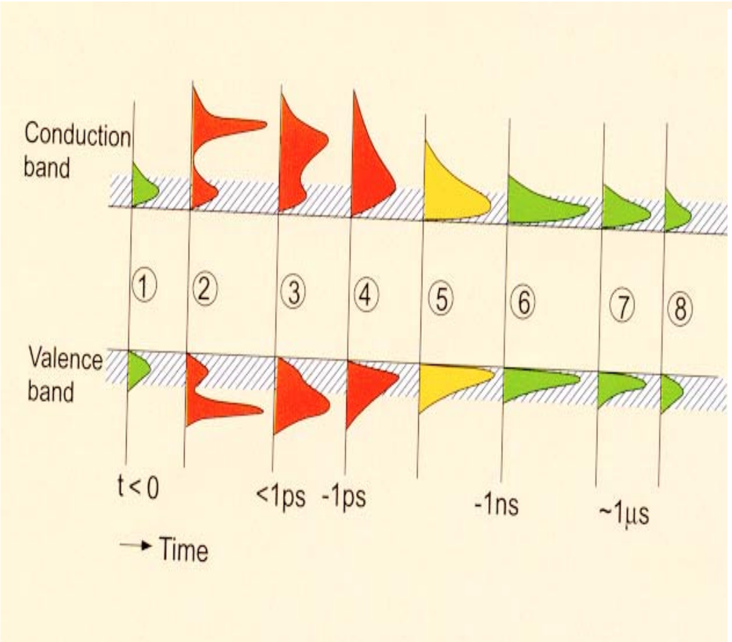


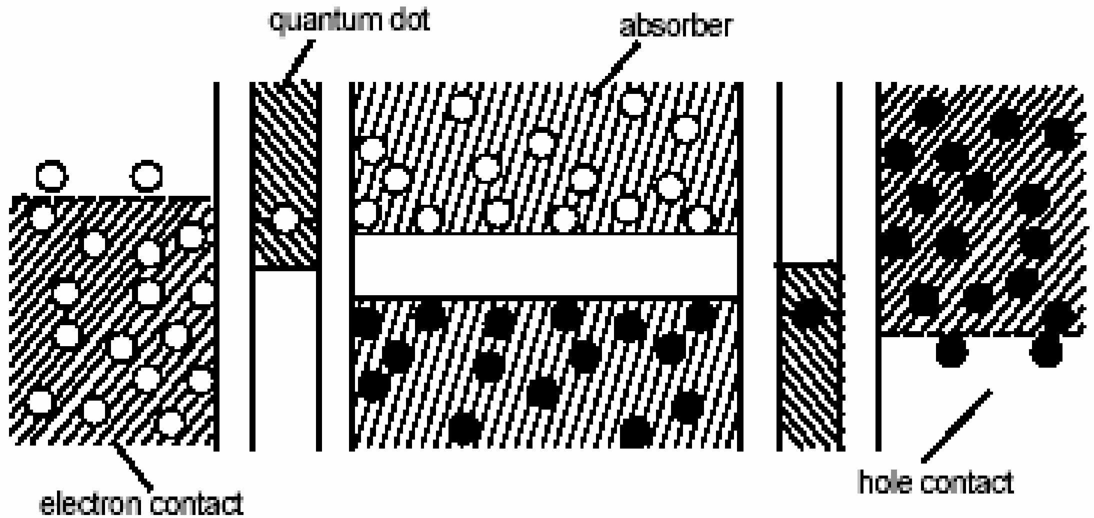


86,8%   limit for infinite bands

With Quantum Wells or Quantum dots

Hot Carriers





Problems to solve

- **Slow cooling system**
- **Selective contacts**

Conclusions

PV is a fast growing sector.

Silicon represents 90% of the market and has potential for further cost reductions, despite the current shortage situation

However, the theoretical efficiency limit is unlikely to be reached in eth near future. Other cell production technologies may be suitable for industrial applications, with efficiency values around 20%

Long term technologies include organic and polimeric cells, and terrestrial use of III-V compounds, which have demonstrated >39% under concentarted light. Higher efficeny structures are under study. Promising candidates are InGaN, used for LEDs, and QD structures such as hot carriers or multiband approaches.

FAQs

• What is the energy pay-back time of a commercial PV module?

In terms of energy, the largest component for the cell is in the realization of silicon. A rough calculation predicts about 1 year for energy recovery of the silicon. Other important components for the modules are teh frames and the glass sheets. This brings the total energy pay back time to 2-3 years for an efficient c-Si module

• How much does a home system cost, and how much space does it occupy?

25 sqm for a 3 kW system. About 22 k€. Annual production (in Rome): 3800 kWh. With the current Italian feed in tariff, return of the investment is in about 10 years.

Thank you!