

La conversion photovoltaïque de l'énergie solaire : Etat de l'art et perspectives

Daniel Lincot, Sébastien Delbos

Institut de recherche et de développement sur l'énergie
photovoltaïque (IRDEP-UMR 7174 CNRS-EDF-ENSCP/ParisTech)

Daniel-lincot@chimie-paristech.fr





IRDEP

INSTITUTE OF R&D ON PHOTOVOLTAIC ENERGY



cnrs | dépasser les frontières



LEADING THE ENERGY CHANGE



ParisTech



Plan

La ressource

Le rendement

La production

la compétitivité

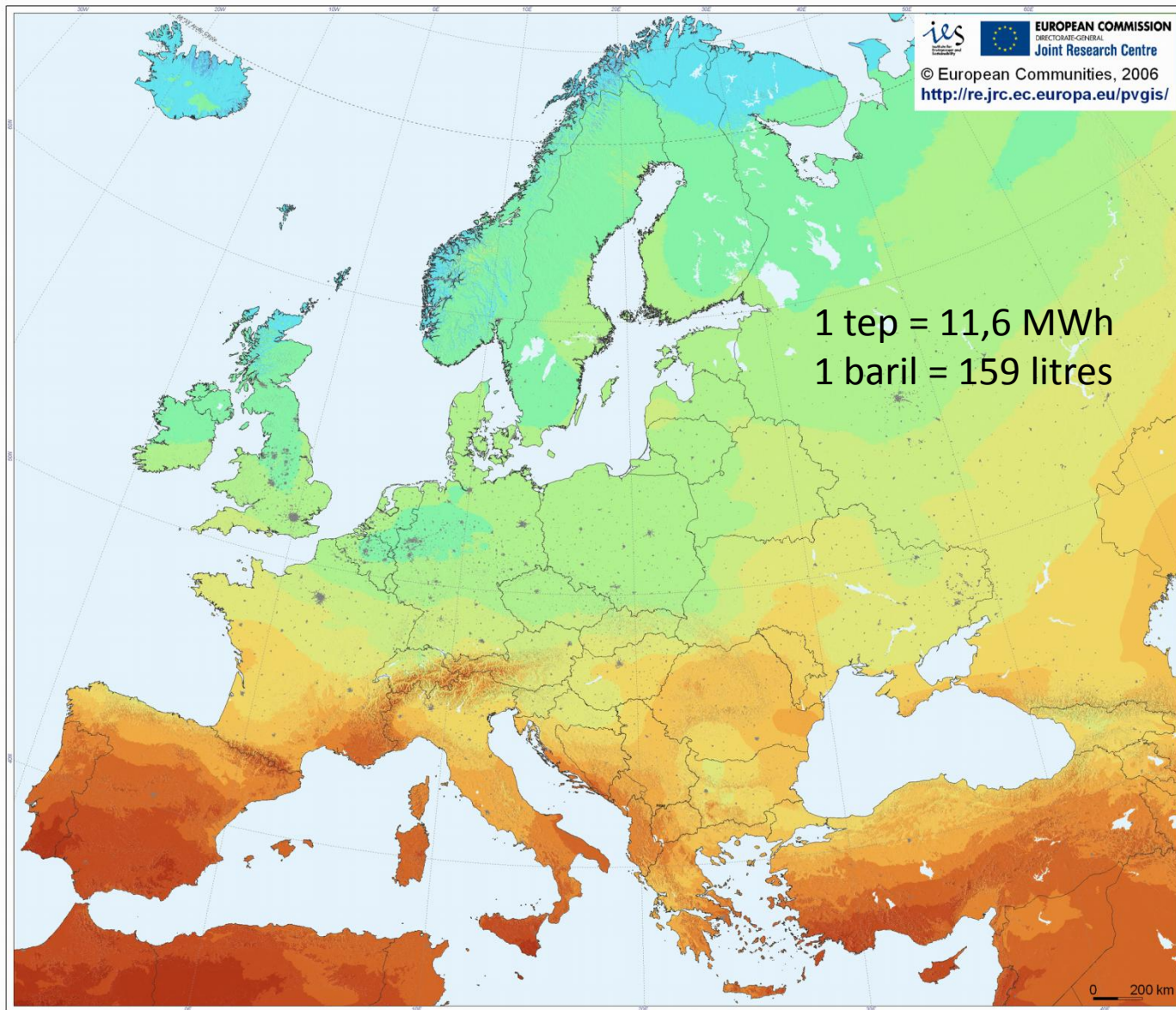
Les acteurs

Les filières

Les enjeux

La ressource

Photovoltaic Solar Electricity Potential in European Countries



Yearly sum of global irradiation incident on optimally-inclined south-oriented photovoltaic modules

Global irradiation [kWh/m²]
<600 800 1000 1200 1400 1600 1800 2000 2200>

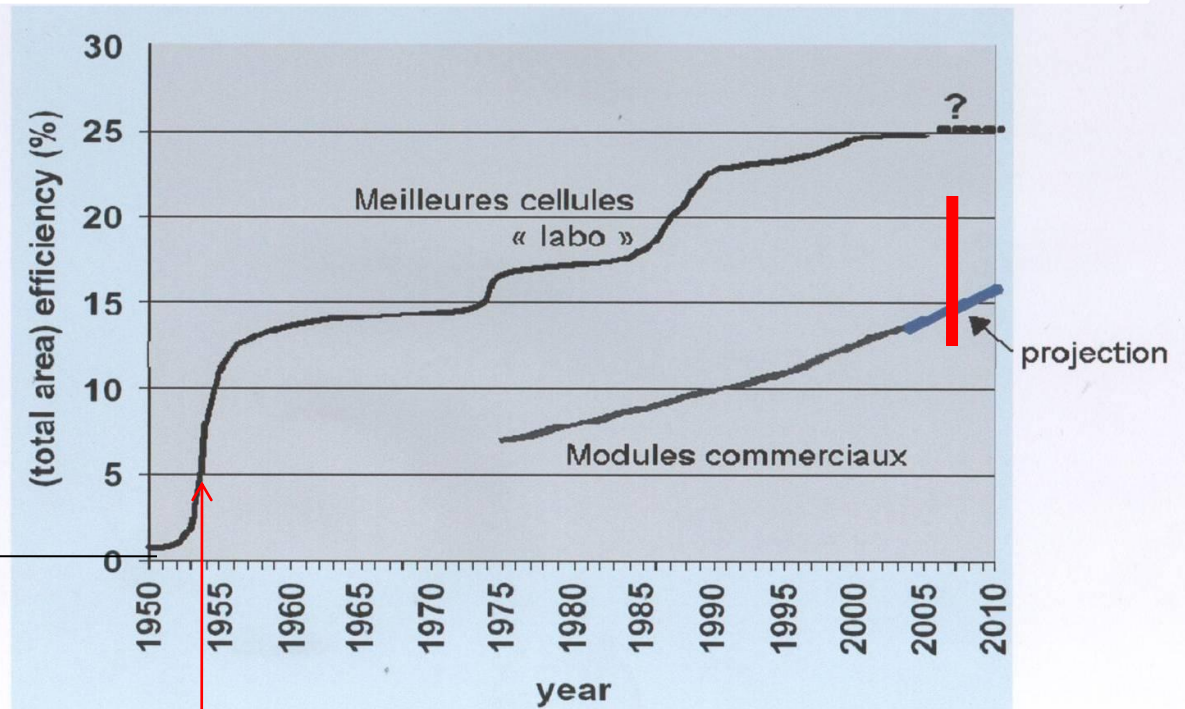
Yearly sum of solar electricity generated by 1 kWp system with optimally-inclined modules and performance ratio 0.75

Solar electricity [kWh/kWp]
<450 600 750 900 1050 1200 1350 1500 1650>



Les rendements

Historique



1839

E. Becquerel
Le découvreur

1877

W.G. Adams
& R.E. Day
Cellules
Se 1%

Chapin & Fuller
& Person
Si(6%)

Source : J.C. Muller

La production

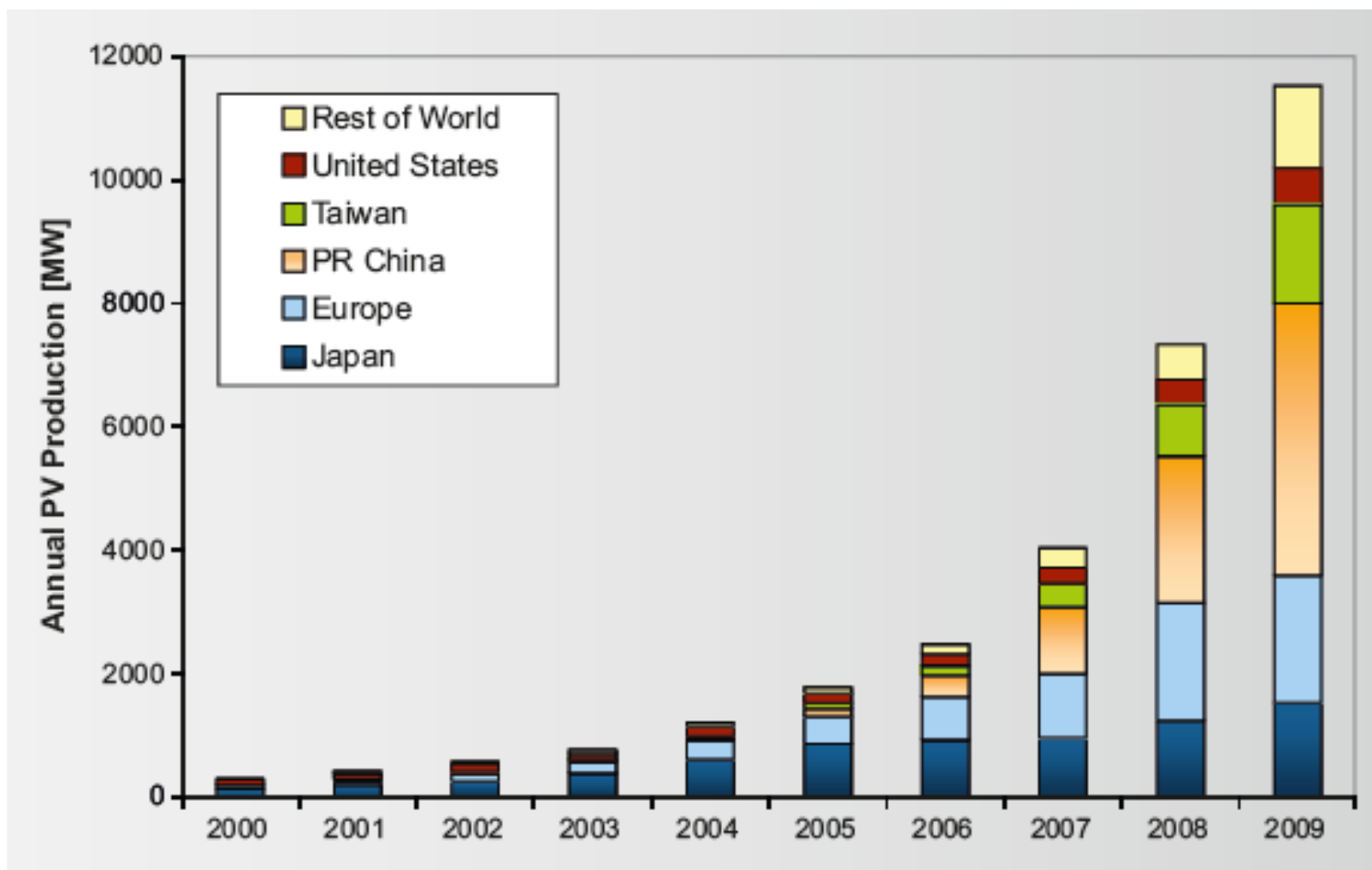


Fig. 1: World PV Cell/Module Production from 1990 to 2009
(data source: Navigant [Min 2010, a], PV News [Pvn 2010] and own analysis)

Fig. 3: Cumulative Photovoltaic Installations from 2000 to 2009
(data source: EPIA [Epi 2010],
Eurobarometer [Sys 2010]
and own analysis)

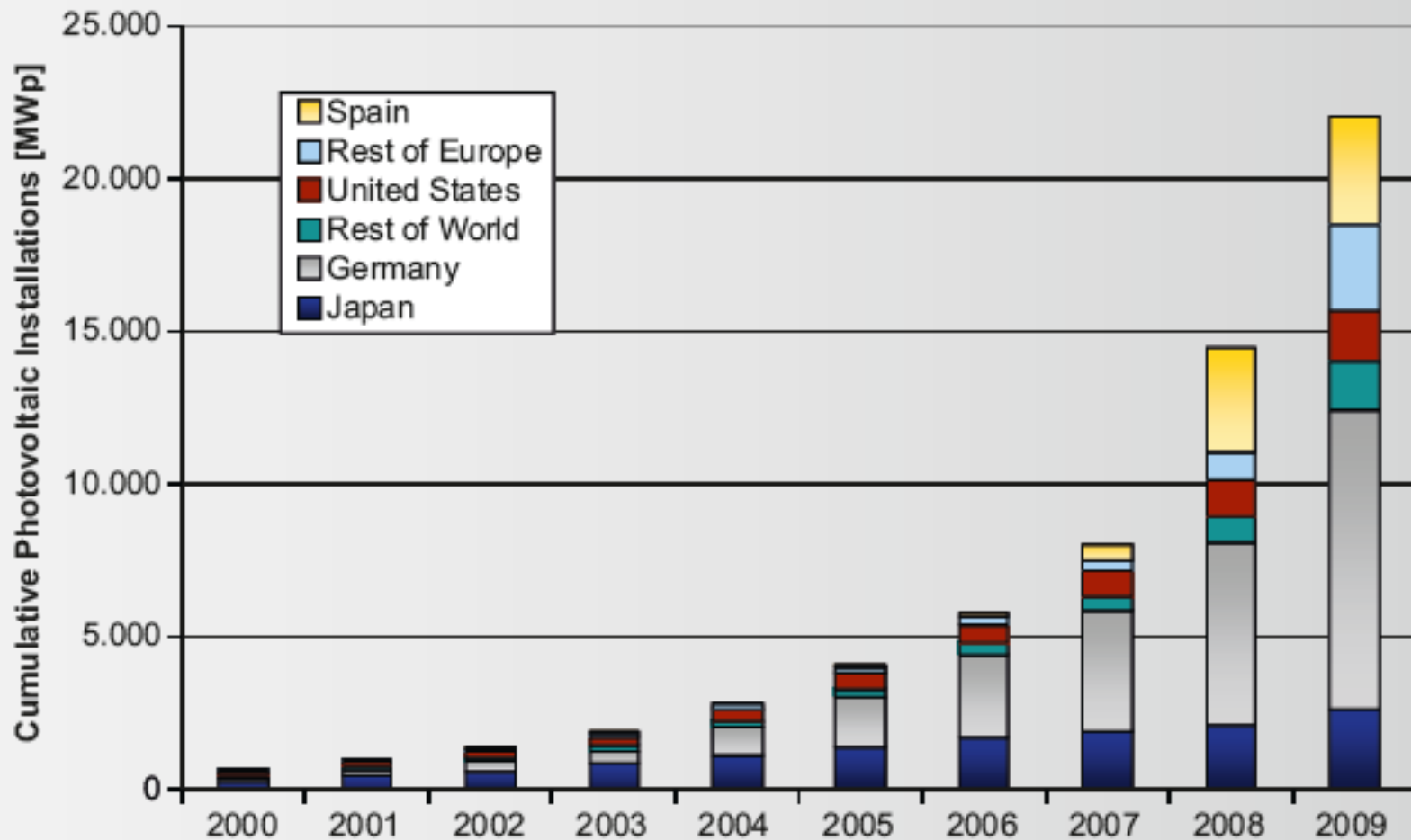


Fig. 2: Annual Photovoltaic Installations from 2000 to 2009
(data source: EPIA [Epi 2010], Euroobserver [Sys 2010] and own analysis)

PV Status report 2010

http://www.eurosfair.prdd.fr/7pc/documents/1283851543_pv_report_2010.pdf

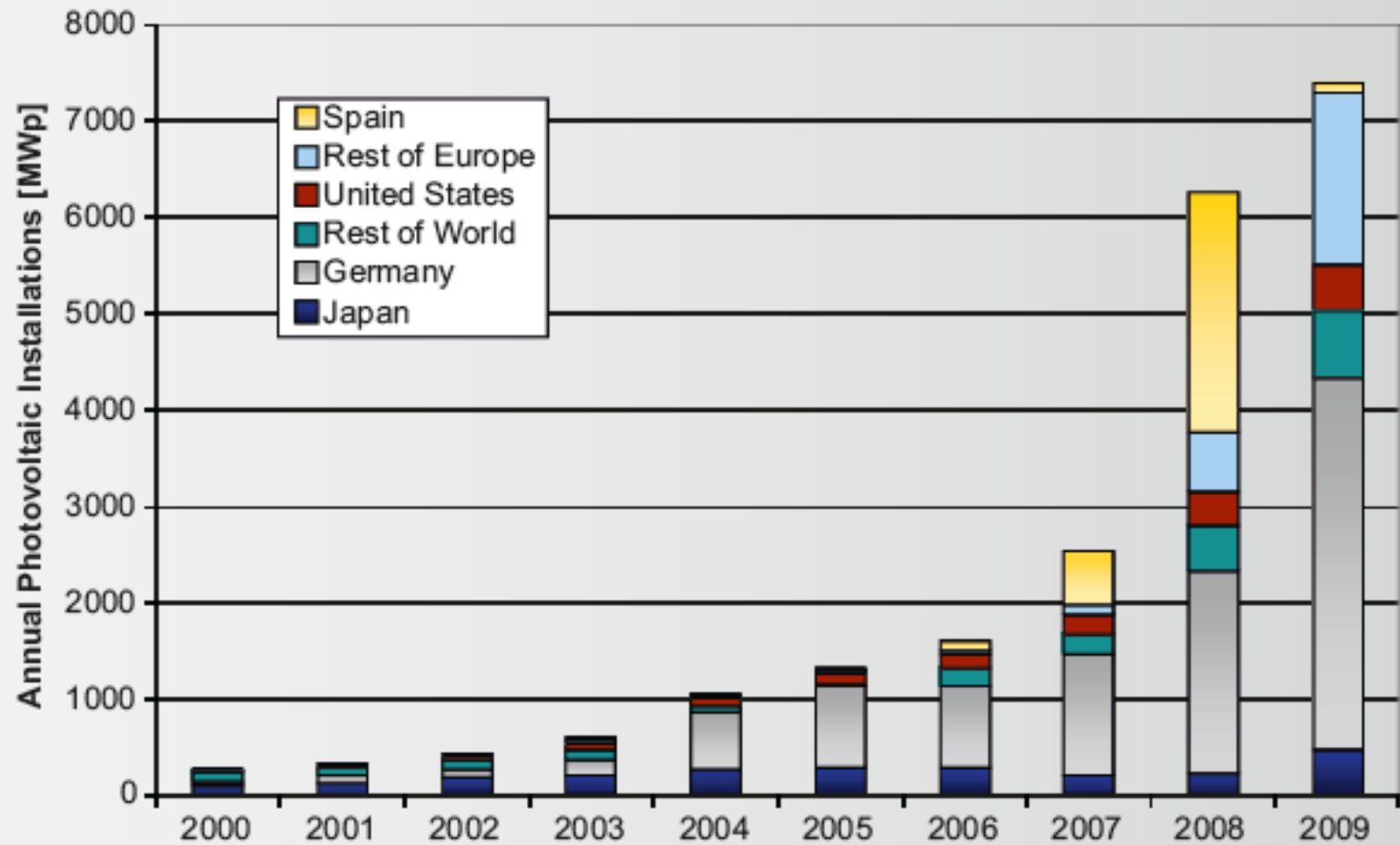
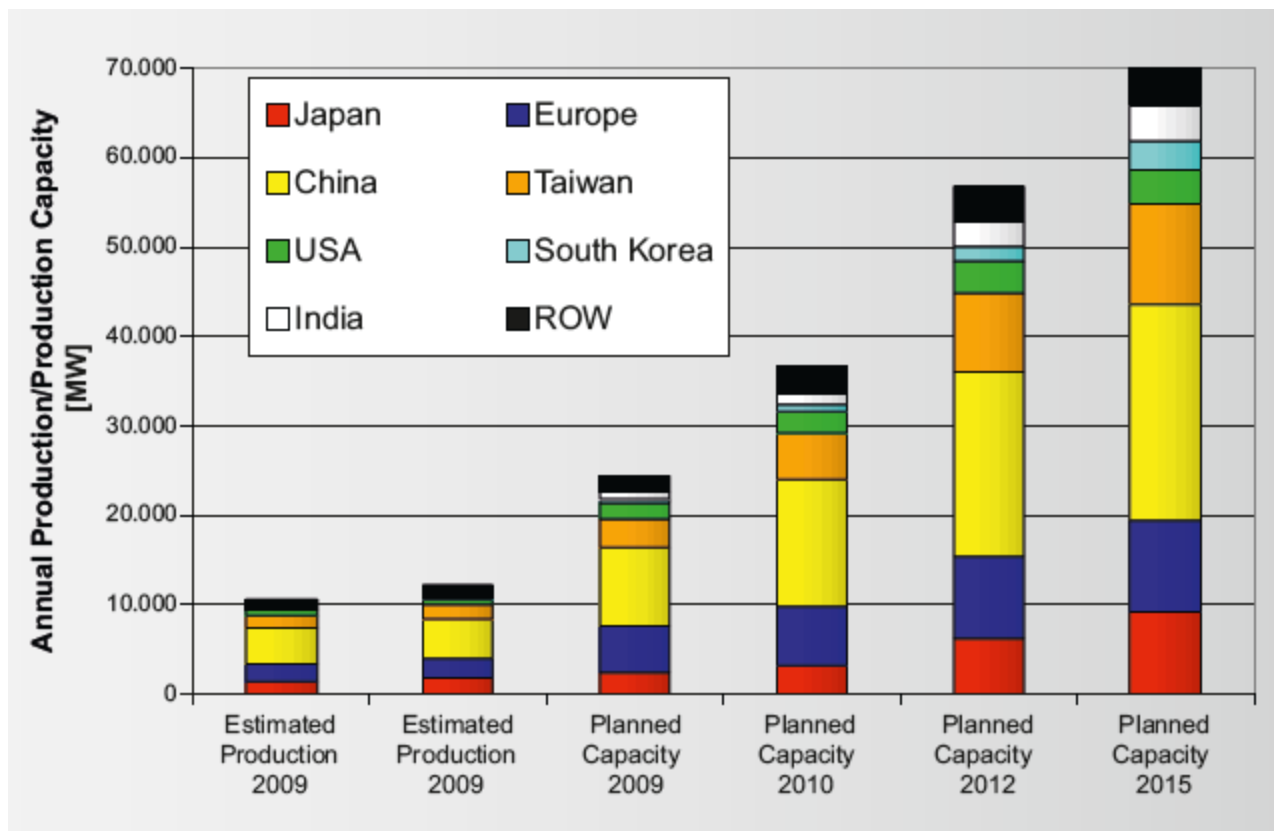


Fig. 6: World-wide PV
Production 2009 with future
planned production capacity
increases



<http://www.epia.org/>

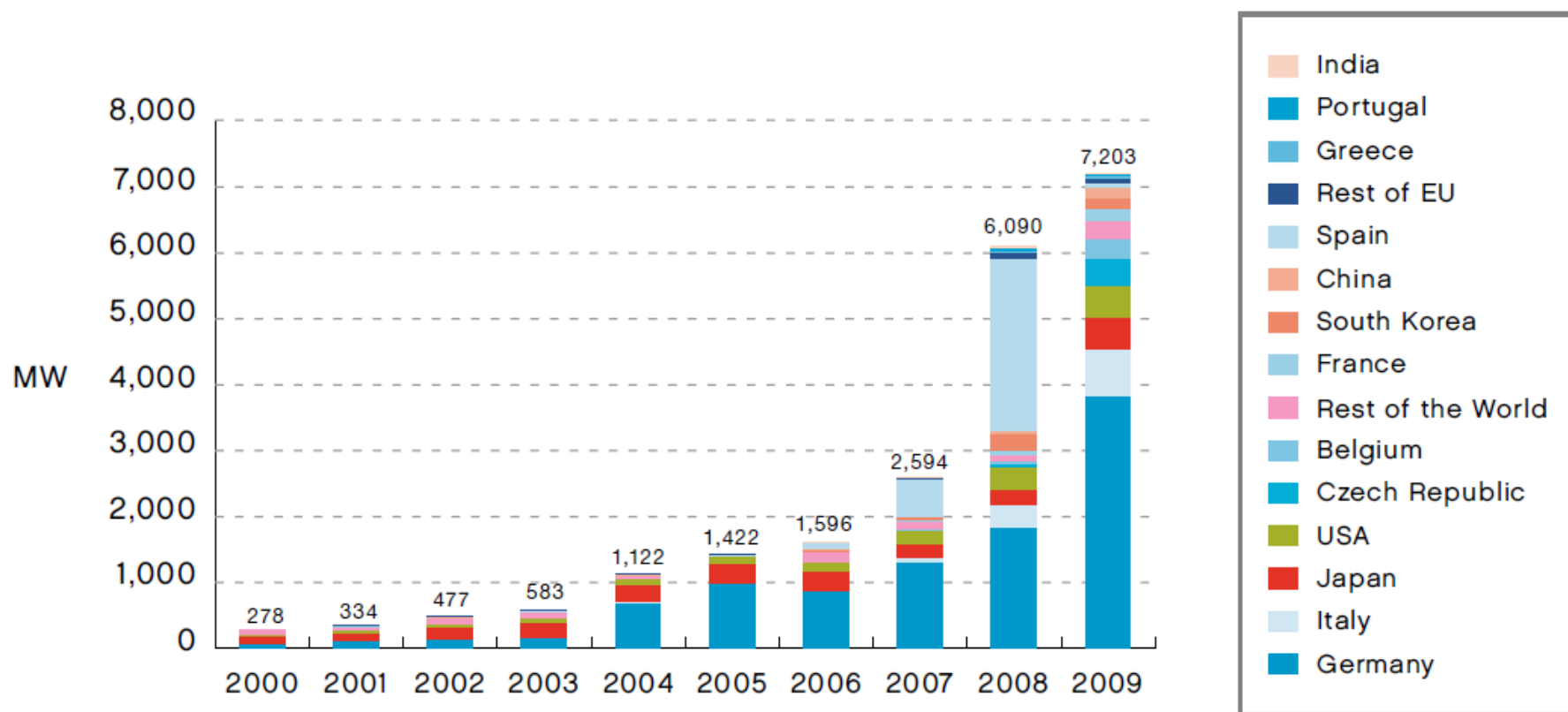
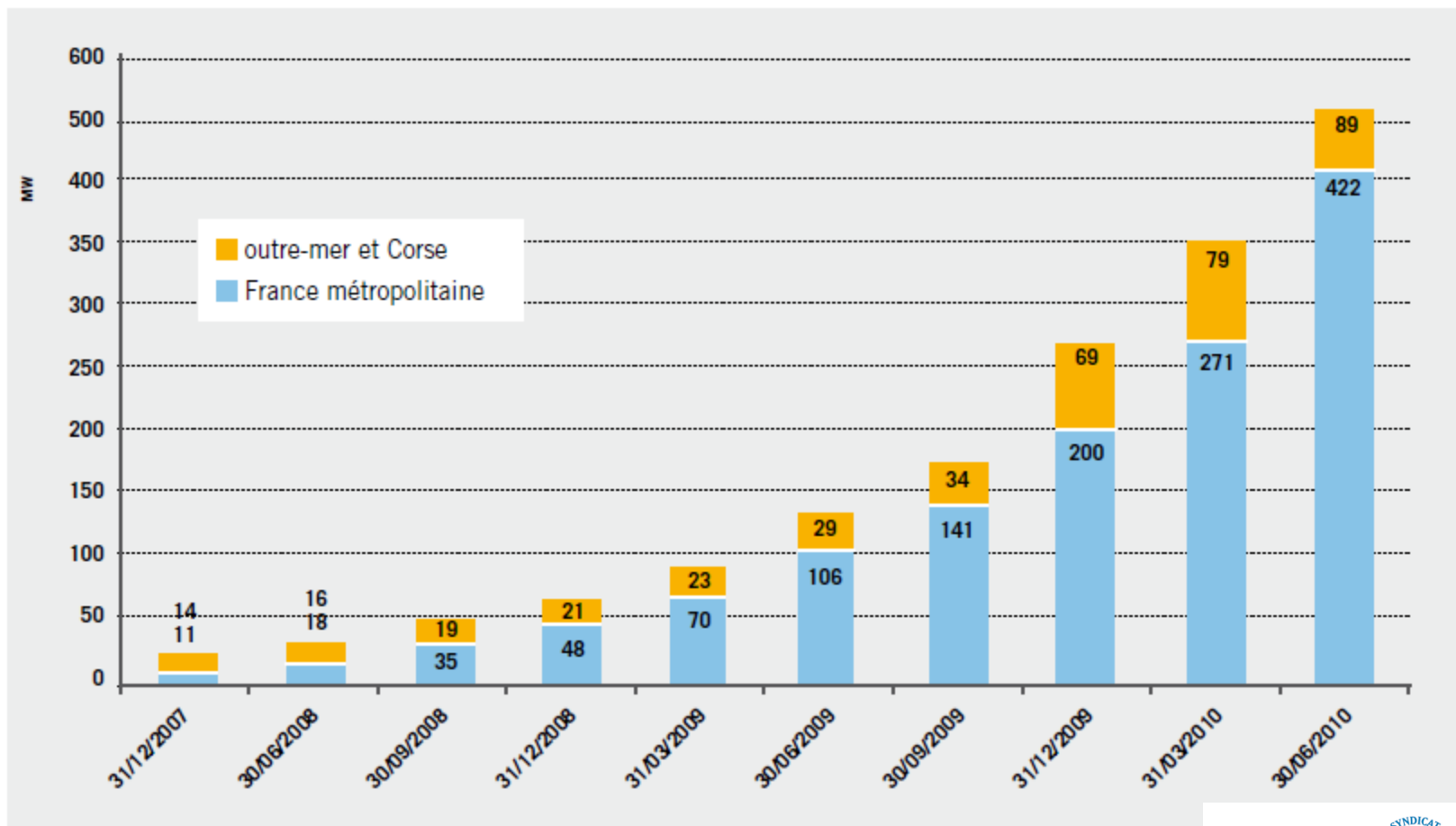


Figure 2 - Evolution of the World annual PV market 2000-2009

Evolution de la répartition du parc raccordé au réseau



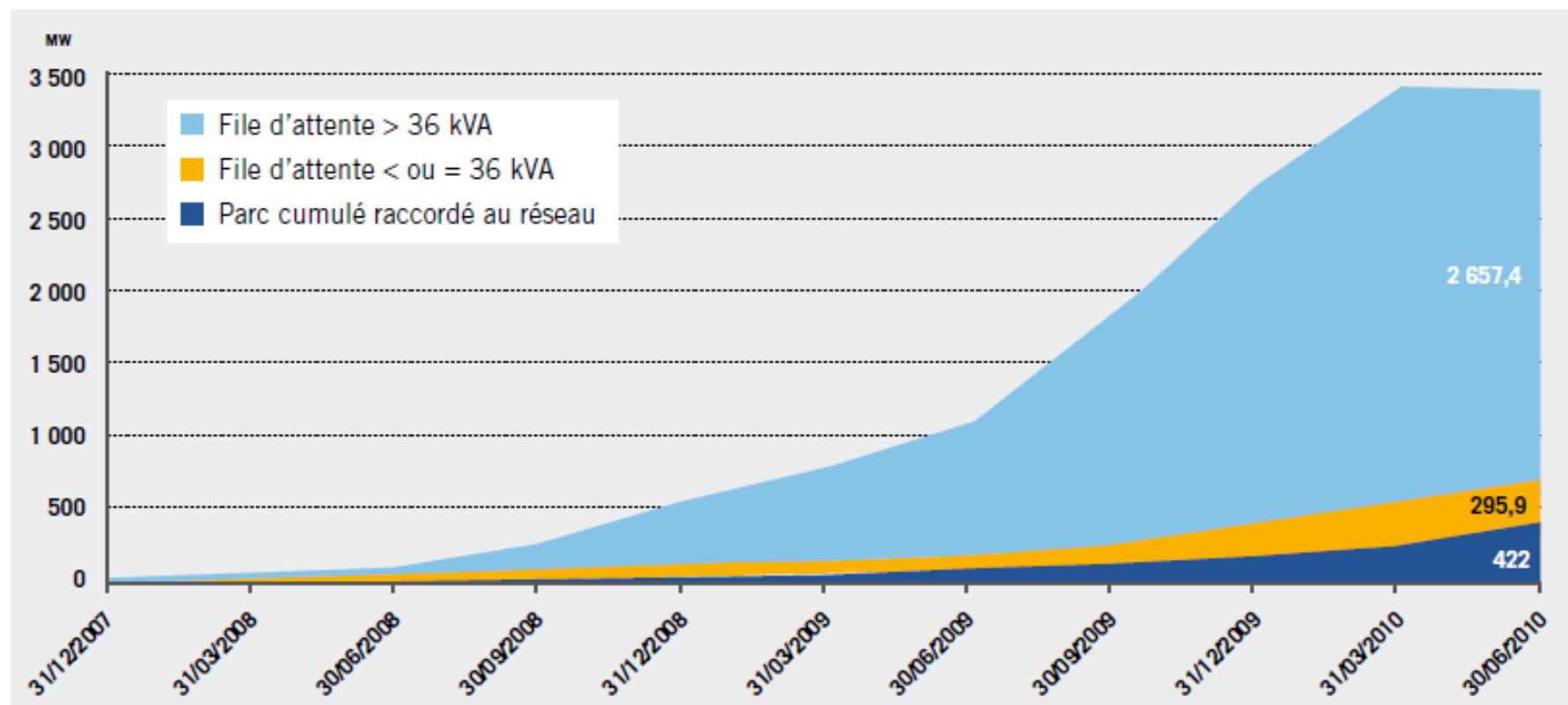
(Source : estimations SER-SOLER, d'après ERDF, EDF-SEI)



GROUPEMENT FRANÇAIS
SOLER
DES PROFESSIONNELS DU
SOLAIRE PHOTOVOLTAÏQUE

Etat des lieux
du parc photovoltaïque français
au 30 juin 2010

Evolution de la répartition de la file d'attente en MW (France métropolitaine)



(Source : SER-SOLER, d'après ERDF-EDF SEI)



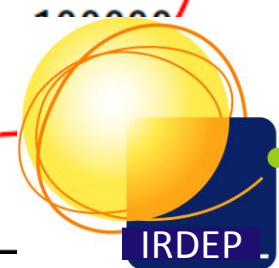
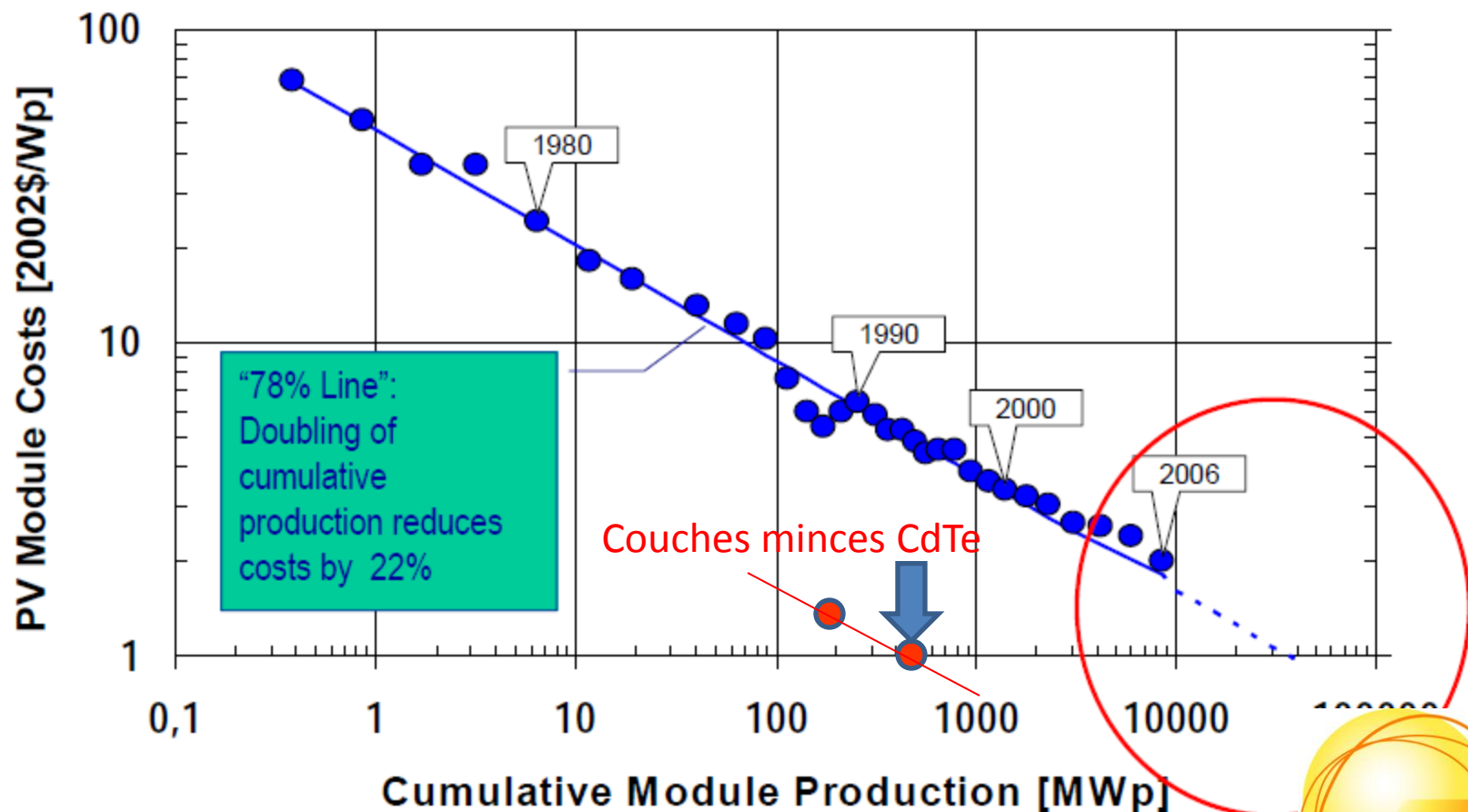
GRUPPEMENT FRANÇAIS
SOLER
DES PROFESSIONNELS DU
SOLAIRE PHOTOVOLTAÏQUE

Etat des lieux
du parc photovoltaïque français
au 30 juin 2010

Les coûts



PV Technology Learning Curve since '76



Les champions actuels : First Solar, technologie CdTe



0.65 \$/W in 2010 annouced

La compétitivité

Coût total système : Modules + systèmes électriques

2010 : 4-7 Euros /W installé

Fermes solaires : 2-3 Euros /W

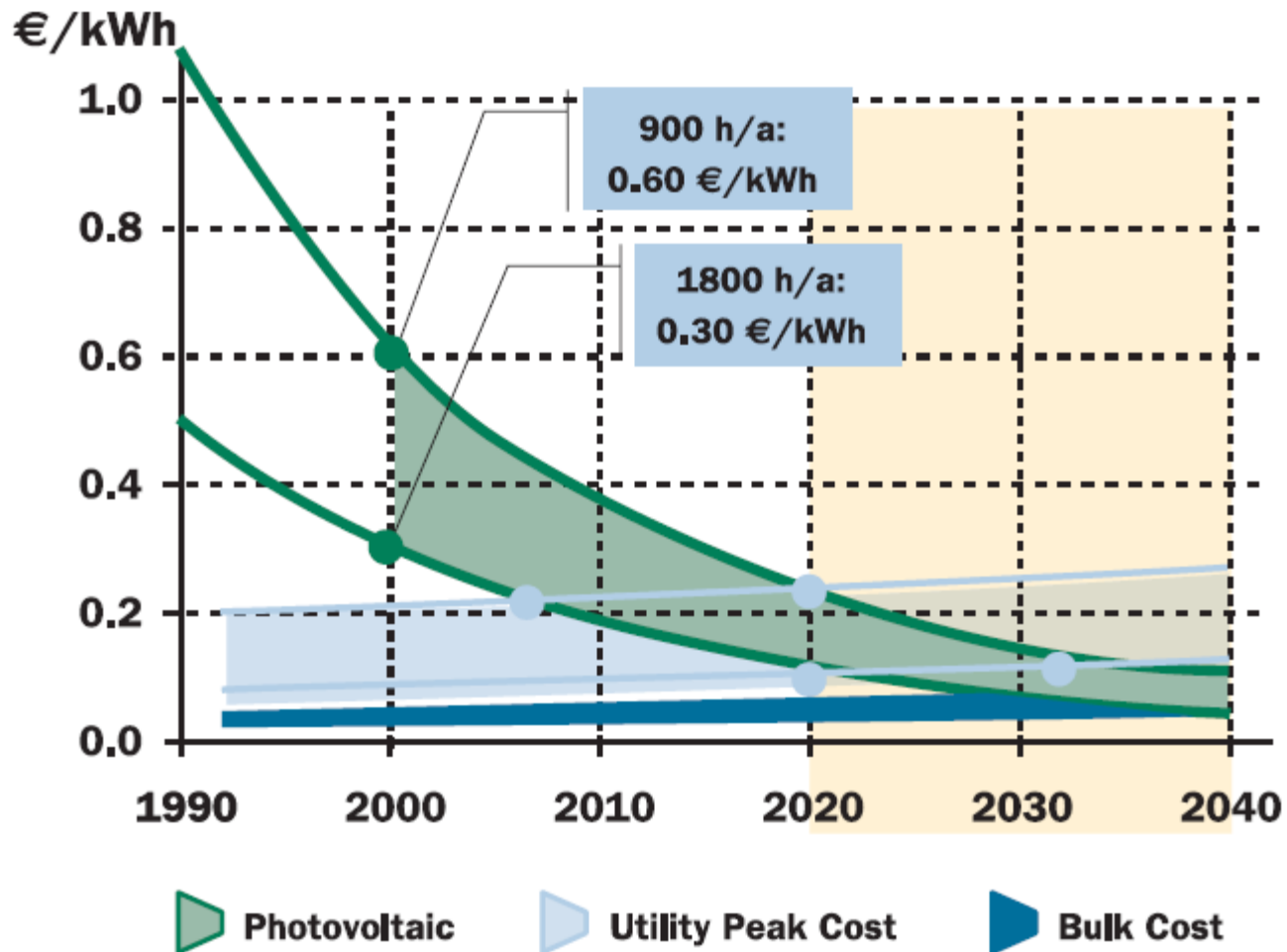
Productible : 100-150 kWh/m² par an sur 20 ans

→ Coût du kWh photovoltaïque

→ Concept de parité réseau : coût PV = prix de détail classique

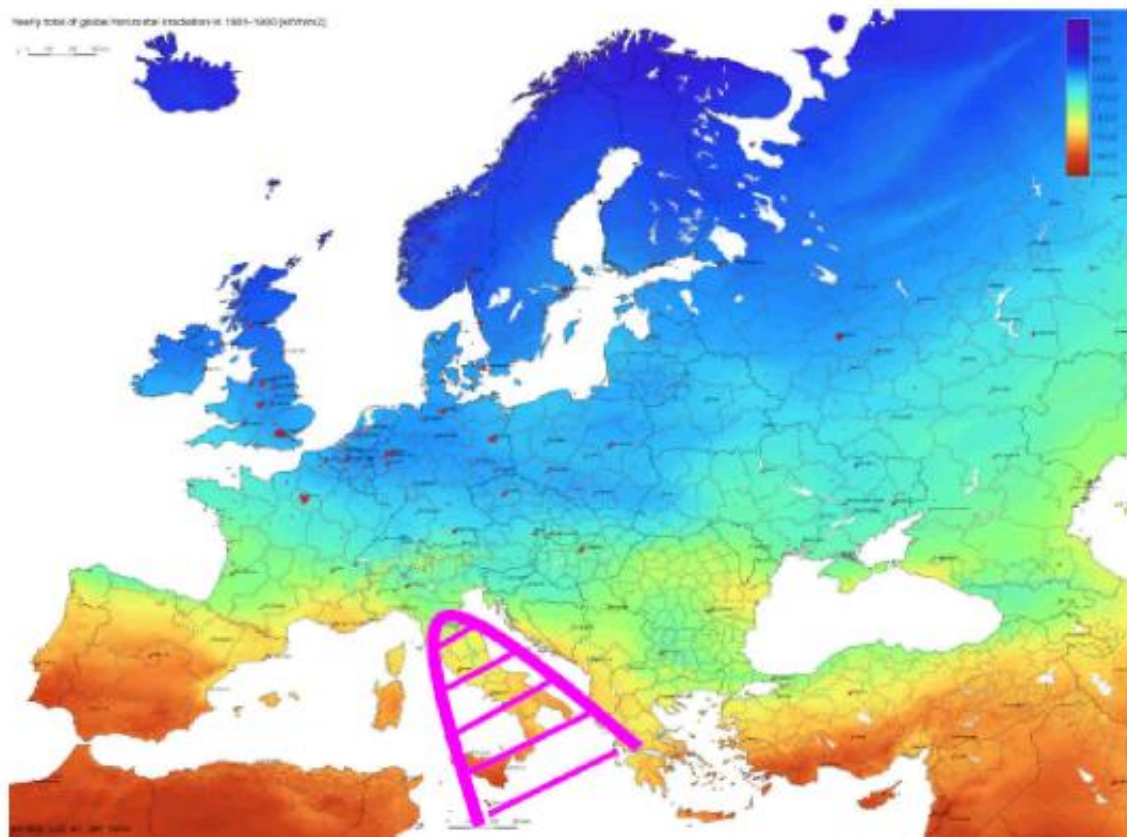
PV Platform

Figure 5: Generation costs of PV electricity²⁵



Grid parity in Europe – 2010

(lines to guide the eye)



irradiation (kWh/m ² ·yr)	PV generation cost (€/kWh)
---	-------------------------------

600	0.50
-----	------

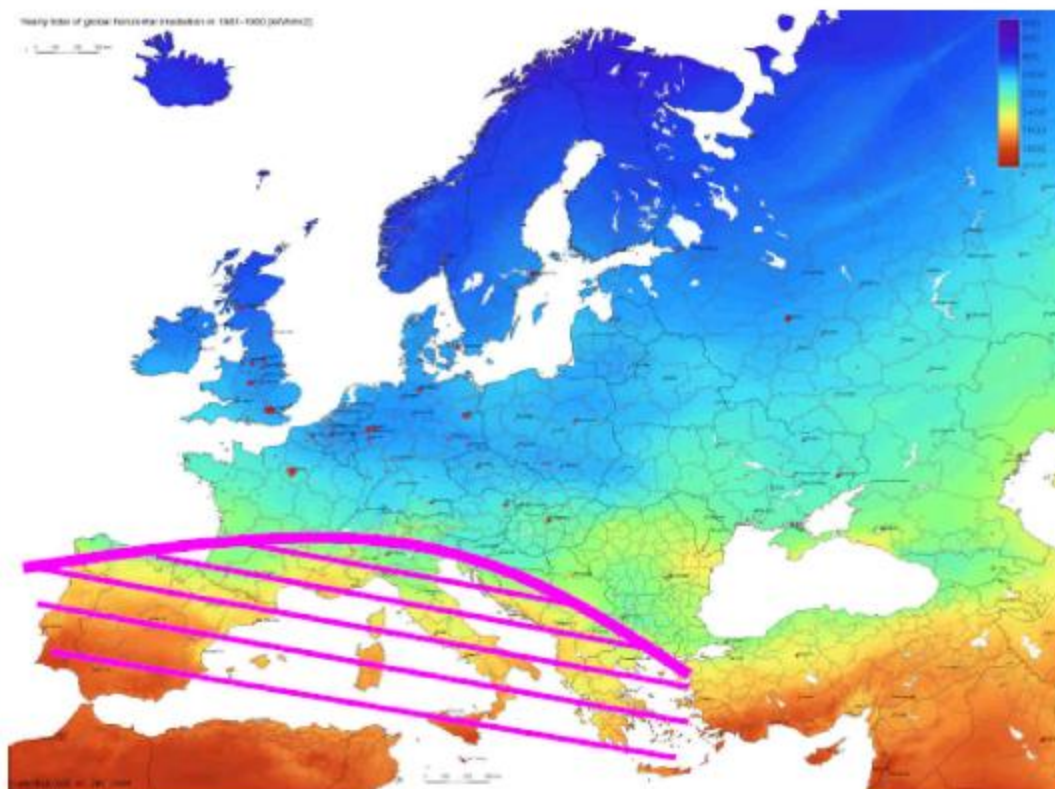
1000	0.30
------	------

1400	0.21
------	------

1800	0.17
------	------

Grid parity in Europe – 2015

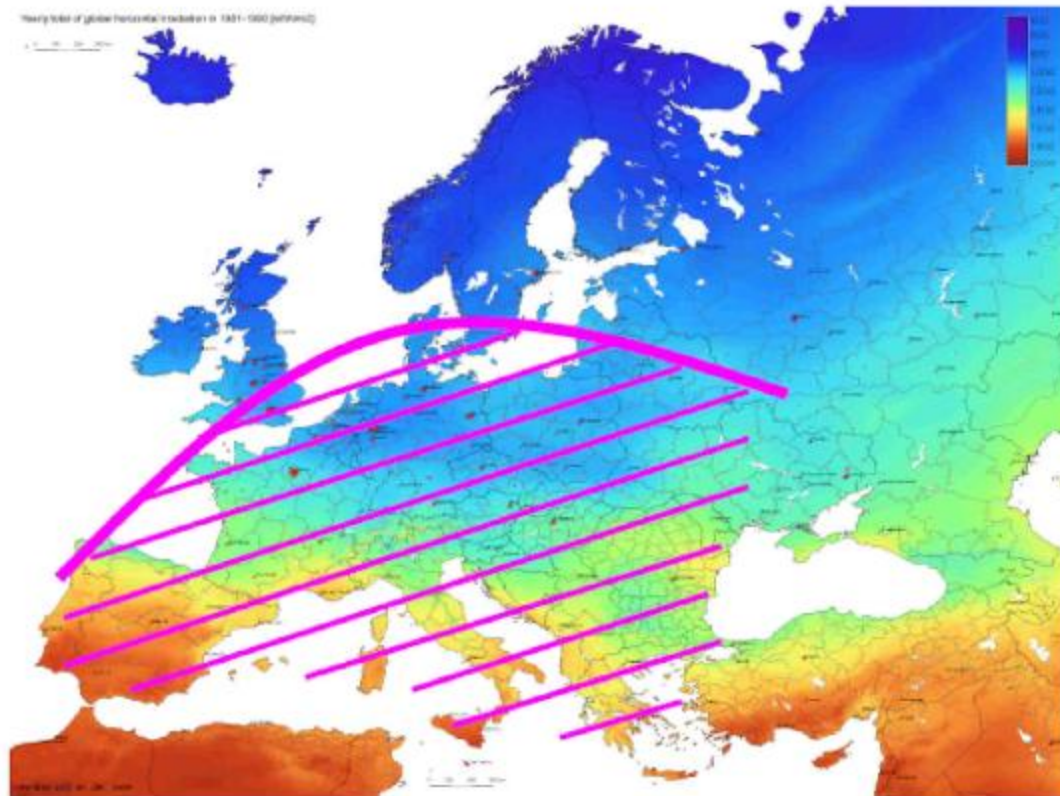
(lines to guide the eye)



irradiation (kWh/m ² .yr)	PV generation cost (€/kWh)
600	0.42
1000	0.25
1400	0.18
1800	0.14

Grid parity in Europe – 2020

(lines to guide the eye)



irradiation (kWh/m ² .yr)	PV generation cost (€/kWh)
600	0.33
1000	0.20
1400	0.14
1800	0.11

PV Electricity will be competitive within the next years

Les acteurs

35 premiers 2009	Pays	2008	2009	Croiss.	Part	Cumul
First Solar Inc. (US)	US, De, Ma	504	1 100	118%	9,6%	1 896
Suntech Power (China)	China	497	704	42%	6,2%	1 824
Sharp (Japan)	Japan	473	595	26%	5,2%	2 939
Q-Cells (De)	De	570	551	-3%	4,8%	2 040
Yingli (China)	China	282	525	87%	4,6%	995
JA Solar (China)	China	300	520	73%	4,5%	985
Kyocera (Japan)	Japan	290	400	38%	3,5%	1 456
Trina (China)	China	210	399	90%	3,5%	638
SunPower (US)	Philippines	237	397	68%	3,5%	818
Gintech (Taiwan)	Taiwan	180	368	104%	3,2%	614
Motech (Taiwan)	Taiwan	272	360	32%	3,1%	1 030
Sanyo (Japan)	Japan	215	260	21%	2,3%	1 050
Ningbo Solar (China)	China	175	260	49%	2,3%	604
Solarfun (China)	China	170	260	53%	2,3%	430
Schott Solar (De)	US, De	149	229	54%	2,0%	790
Bosch-Ersol (De)	De	143	200	40%	1,7%	492
Solar World -DC (De)	De	160	200	25%	1,7%	649
REC Scancell (No)	Norway	135	130	-4%	1,1%	385
Mitsubishi El (Japan)	Japan	148	120	-19%	1,0%	741
DelSolar (Taiwan)	Taiwan	83	88	6%	0,8%	247
Isofoton (Sp)	Spain	130	70	-46%	0,6%	517
Ninghai Risen (China)	China	70	70	0%	0,6%	155
China Light Solar (China)	China	22	70	218%	0,6%	105
Suzhou Shenglong (China)	China	15	60	300%	0,5%	87
Shanghai Topsol (China)	China	48	60	25%	0,5%	108
Zhejiang Sun Valley (China)	China	38	55	47%	0,5%	99
Trony Science (China)	China	27	50	85%	0,4%	108
BP Solar (US)	US, Sp, Aus, In	75	49	-34%	0,4%	655
Photowatt (Fr)	Fr	58	49	-16%	0,4%	274
Jiangsu ShunFeng (China)	China	50	46	-8%	0,4%	121
Ningbo Shanshan Ulica (China)	China	30	42	40%	0,4%	102
Kaneka (Jp)	Japan	57	40	-30%	0,3%	229
Kymungdong (South Korea)	South Korea	25	35	40%	0,3%	85
Shangai ST Solar (China)	China	20	30	50%	0,3%	50
Polar Photovoltaics (China)	China	6	15	150%	0,1%	22
<i>Autres fabricants</i>		1 813	3 024	67%	26,5%	6 743
Cell World		7 676	11 432	49%	100%	30 302



Publiée par CYTHELLIA sarl,
La Maison ZEN, Chef Lieu, F-73 000 Montagnole
Tel+ 33(0)4 79 25 31 75 Fax+ 33(0)4 79 25 33 09
Editeur: Alain Ricaud, ar@cythelia.fr, Rédaction : Mamadou Kane

La Lettre du Solaire

Avril 2010 / Vol 10 N°4

Les 13 premiers en 2005

Sharp (Jp)
 Q-Cells (All)
 Kyocera (Jp)
 Sanyo(Jp)
 Mitsubishi(Jp)
 Schott Solar(All)
 BP Solar (UK)
 Suntech (China)
 Motech (Taiwan)
 Shell Solar (NL)
 Isophoton (Es)
 Deutsche Cell (All)
 Photowatt (Fr)

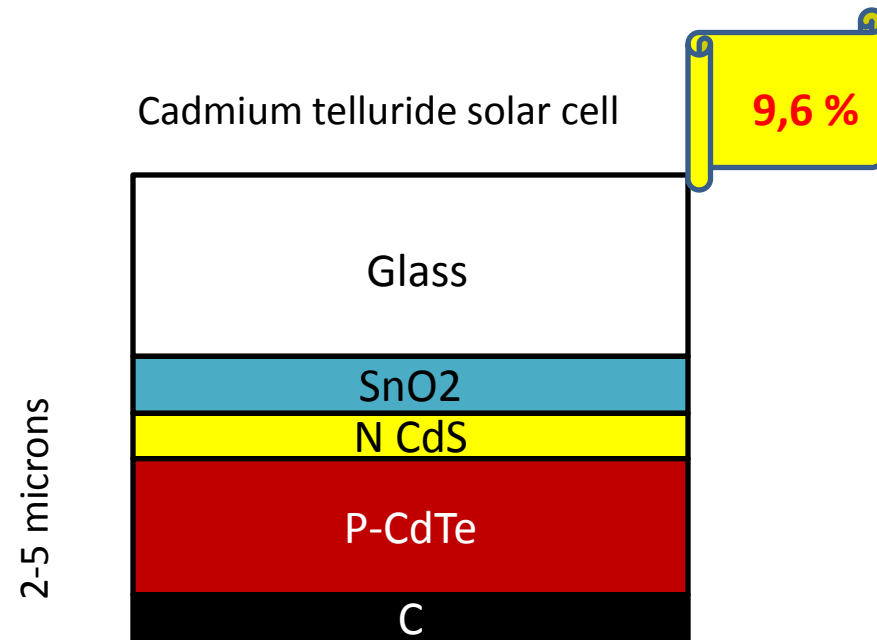
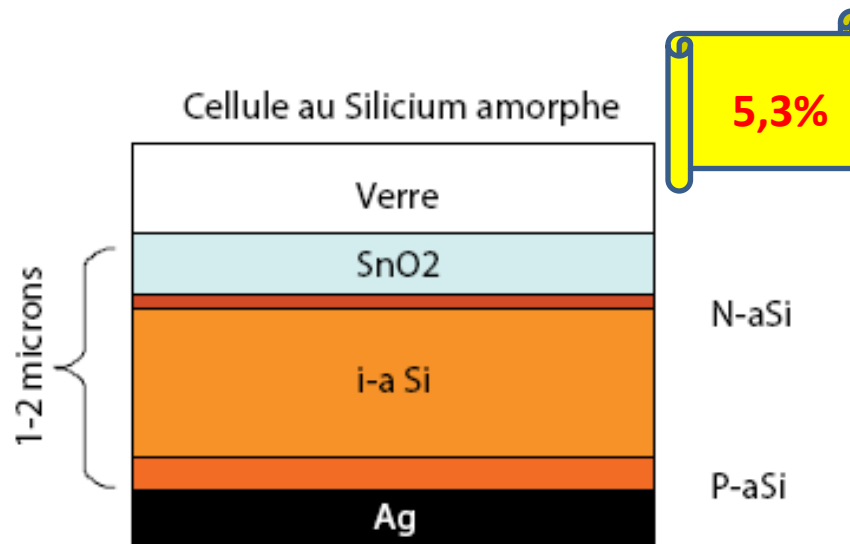
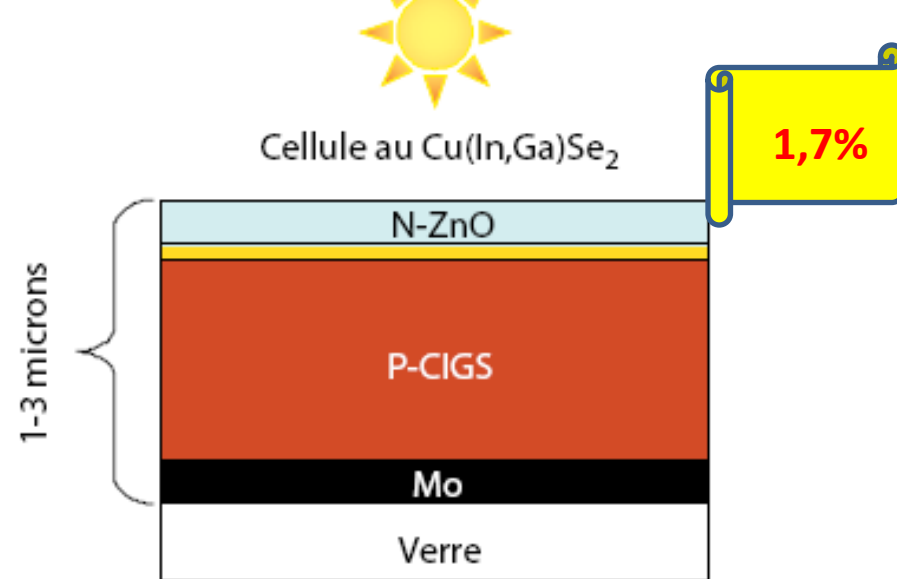
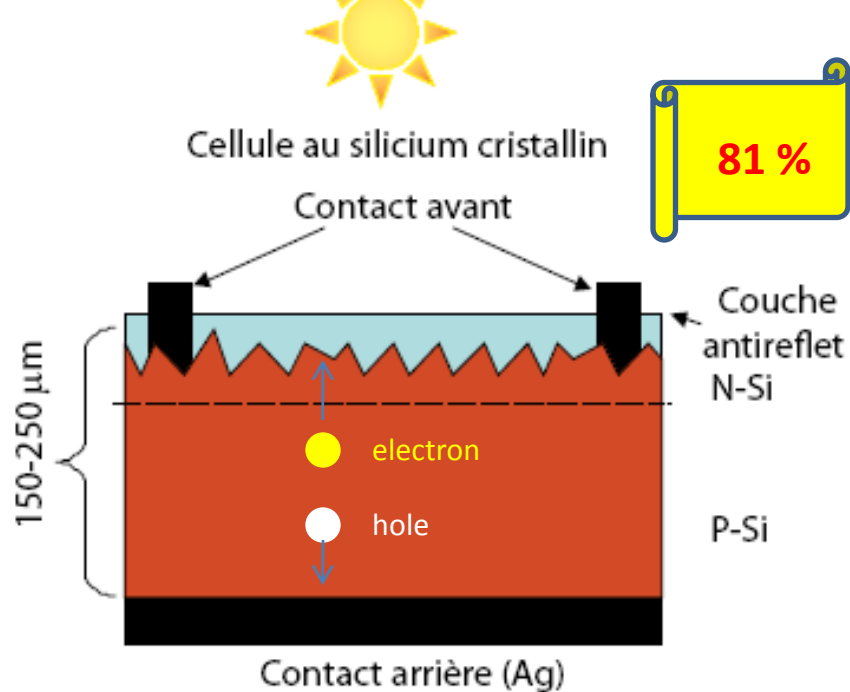
Les filières

Voir l'article qui vient de sortir en kiosque :

« L'électricité , fille du soleil » numéro spécial sur l'énergie

Dossier Pour la science Oct-Dec 2010, page 47-53

D. Lincot, J.F. Guillemoles, P. Roca i Cabarrocas, L. Escoubas, A. Slaoui



Technology	2005	2006	2007	2008	2009	Cumul
sc-Si	614	927	1 646	2 753	3 730	11 051
	33%	37%	39%	36%	33%	35%
mc-Si	986	1 165	1 941	3 647	5 333	15 294
	53%	47%	45%	48%	47%	48%
Ribbon	56	65	94	115	159	651
	3%	3%	2%	2%	1%	2%
c-Si	1 656	2 157	3 682	6 515	9 222	26 995
	89%	86%	86%	85%	81%	84%
a-Si:H	65	118	188	329	597	1 534
	3,5%	4,7%	4,4%	4,3%	5,3%	5%
CdTe	26	68	201	489	1 092	1 943
	1,4%	2,7%	4,7%	6,4%	9,6%	6%
CIS	4	5	21	76	193	317
	0,2%	0,2%	0,5%	1,0%	1,7%	1%
µcSi	4	8	21	61	102	206
	0,2%	0,3%	0,5%	0,8%	0,9%	1%
Thin Films	99	198	432	956	1 984	4 001
	5%	8%	10%	13%	17%	13%
a-Si:H sur CZ	110	151	164	176	225	965
HIT	5,9%	6,0%	3,8%	2,3%	2,0%	3%
Total	1 865	2 506	4 278	7 646	11 432	31 961
Growth	39%	34%	71%	79%	50%	49%

Sources: PV News 1990-2001 / PI Mars 2002 - 2010 / calculs Cythelia

Tableau 2 : Production mondiale de cellules par technologie en MWc (2005-2009) et cumulées (1978-2009).

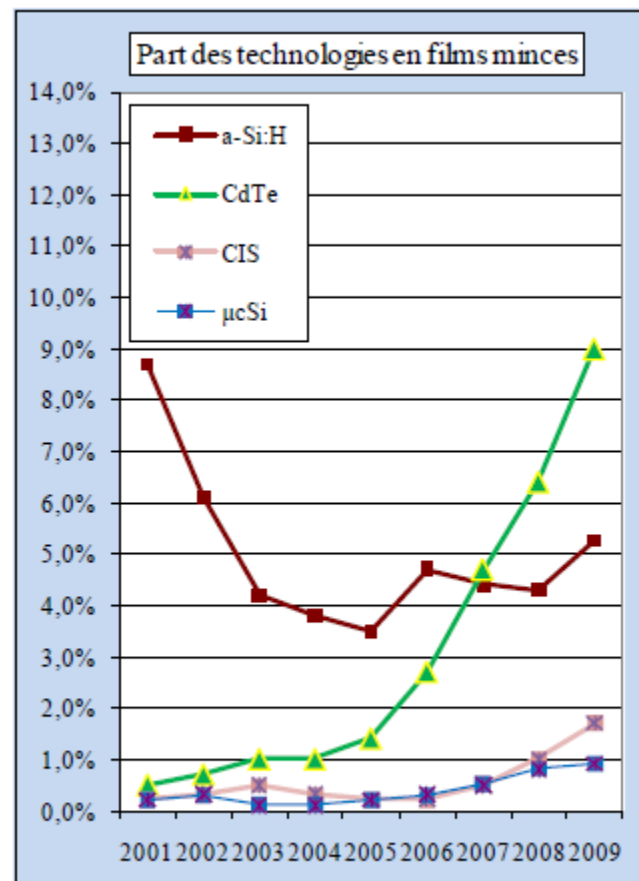
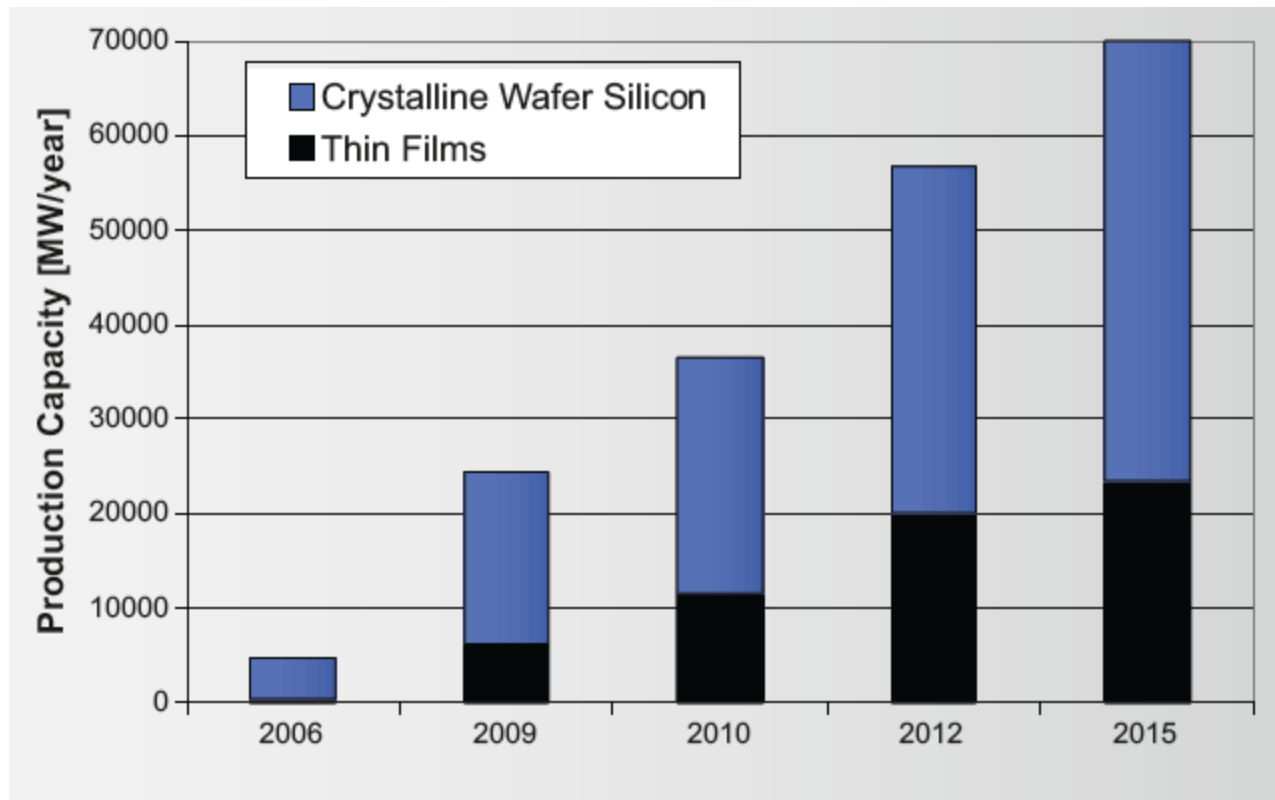


Figure 3 : Evolution de la part des modules PV en films minces par technologie en % (2001-2009)

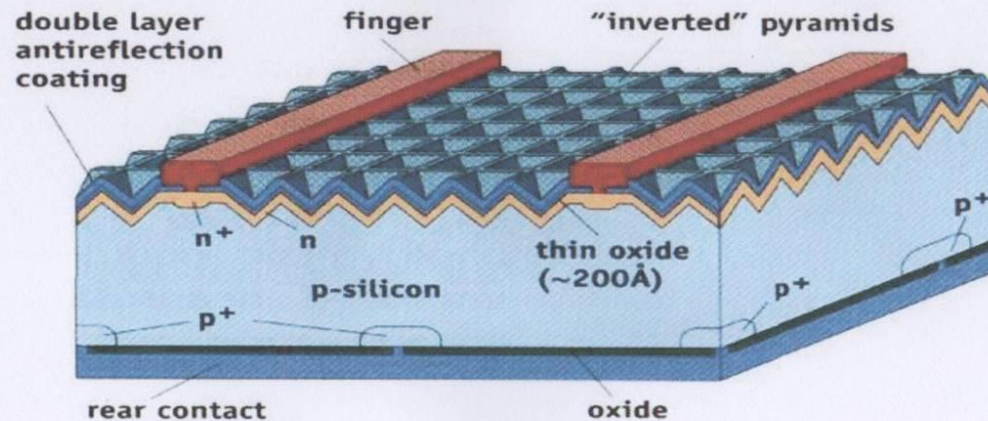


Fig. 7: Annual PV Production capacities of Thin-Film and Crystalline Silicon based solar modules.



La filière silicium en plaquettes : record 24,7 %
Modules 12-20%, 81% marché

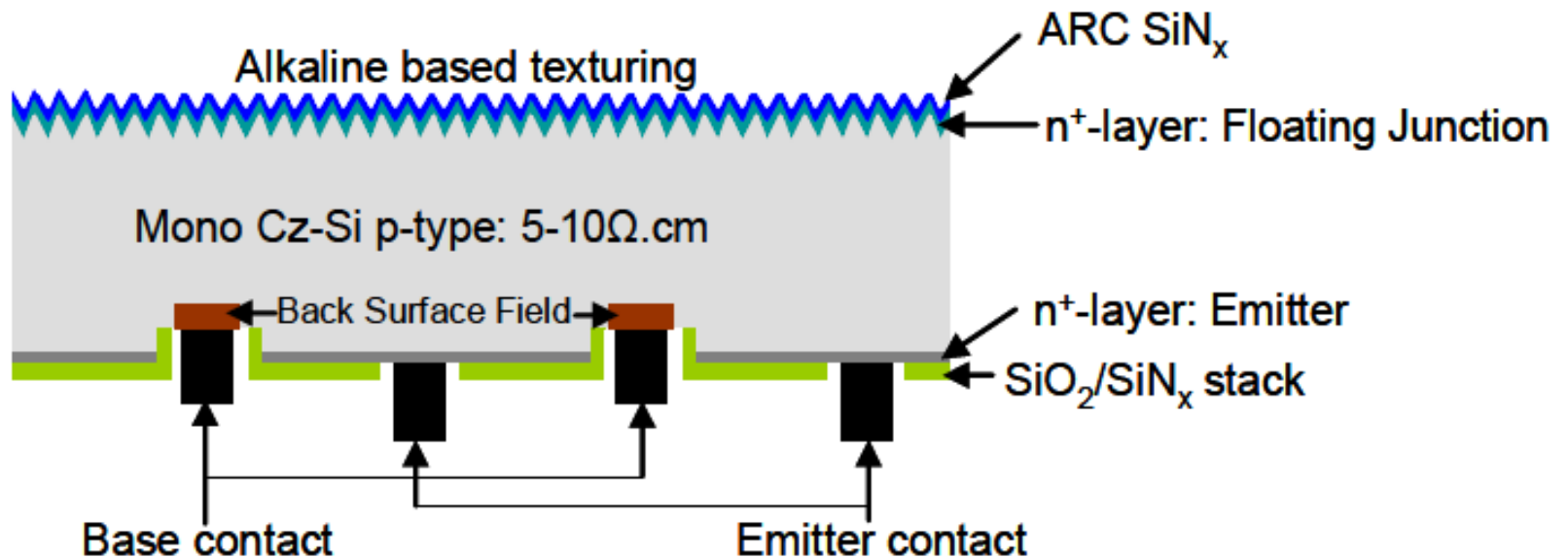
Cellule au silicium de rendement record



$$I_{cc} = 42,2 \text{ mA/cm}^2 \quad ; \quad V_{co} = 0.706 \text{ Volt} \quad ; \quad \eta_p = 24,7 \%$$

Cellule PEARL M. Green et al UNSW (Australie)

Interdigitated Back Junction solar cells

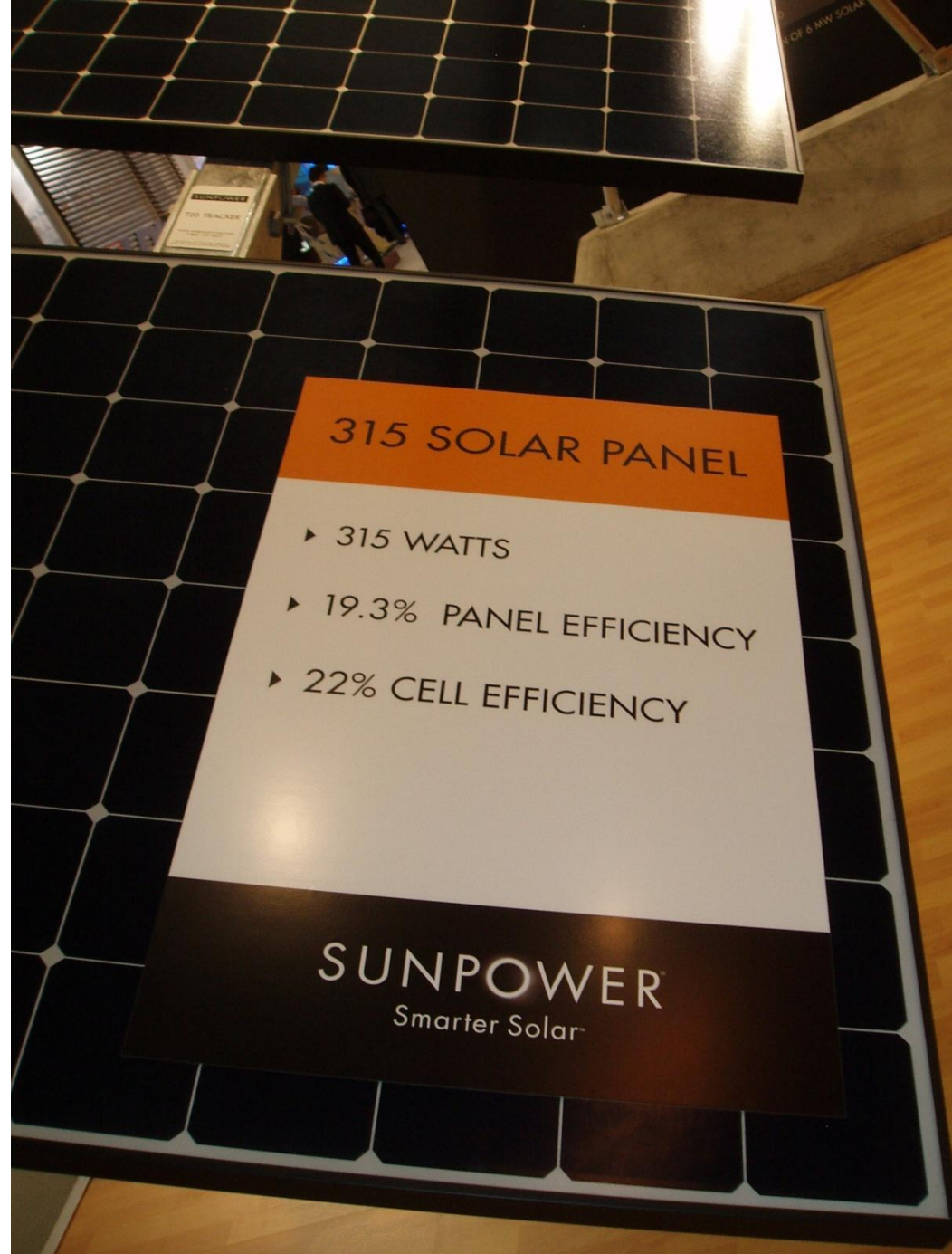


IEEE PVSEC 2009

Autres tendances :

Tranches fines (100 microns)

Découpe Laser

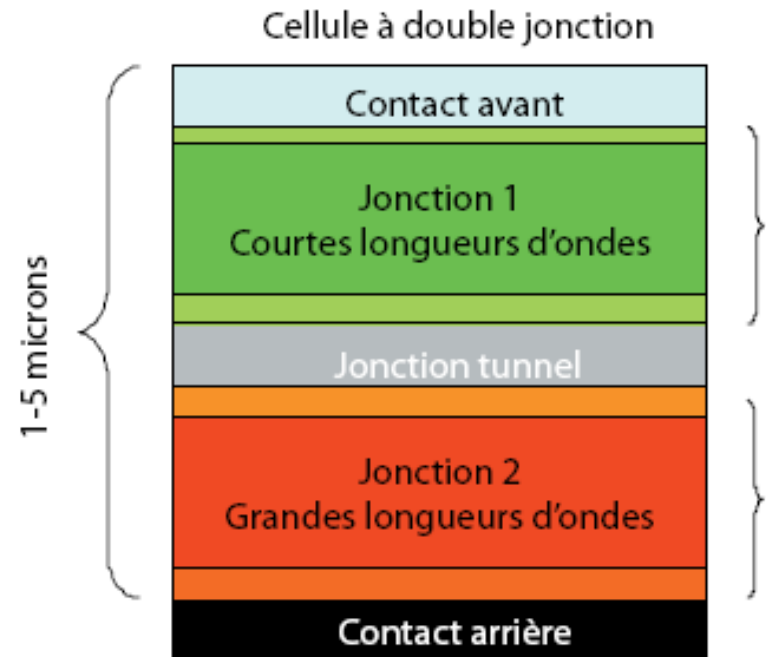
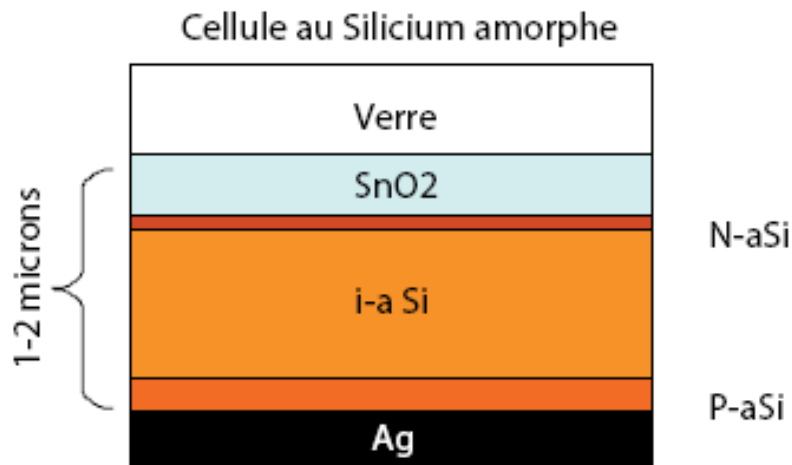


La filière silicium couches minces

Rendement : 6-8 %

Laboratoire : 13 %

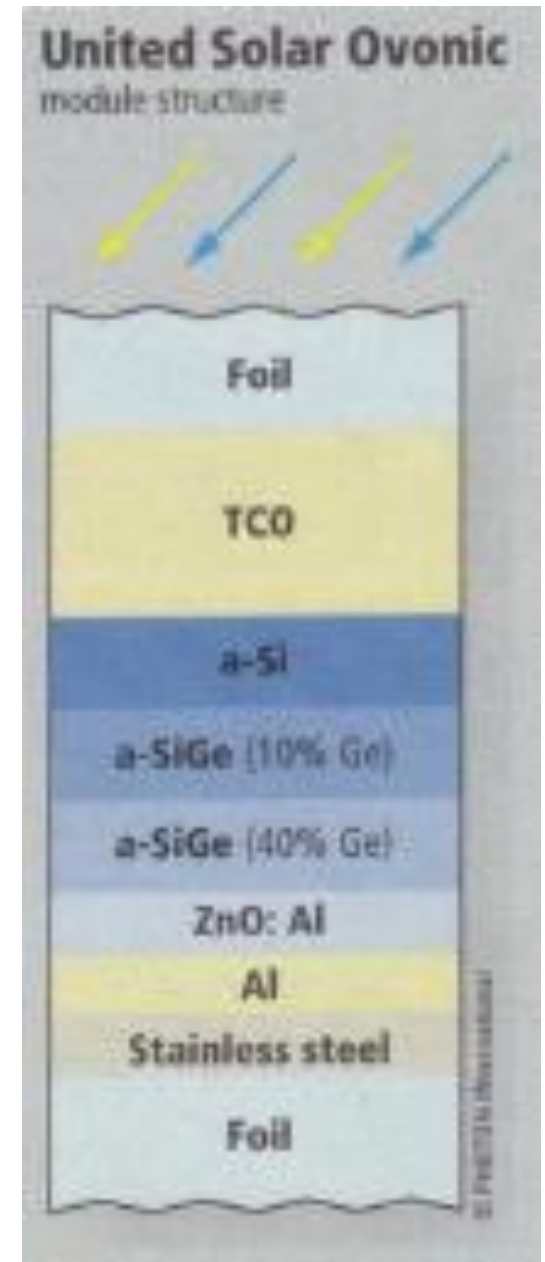
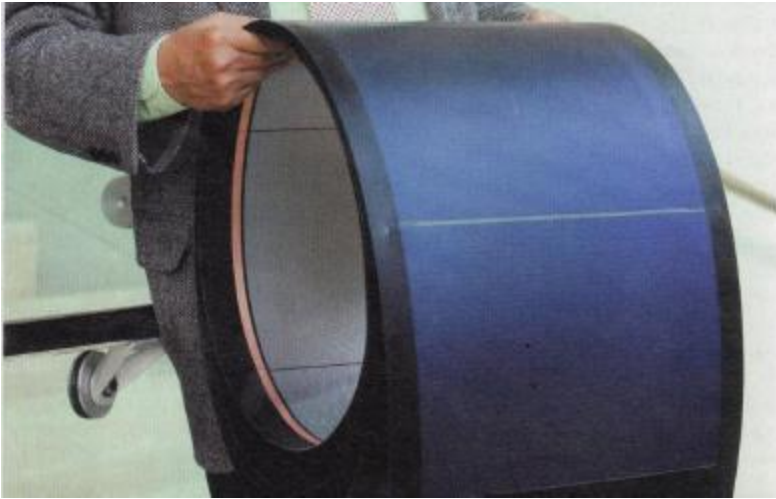
5,6% production



Dépôt des couches par CVD Plasma à partir de silane et hydrogène



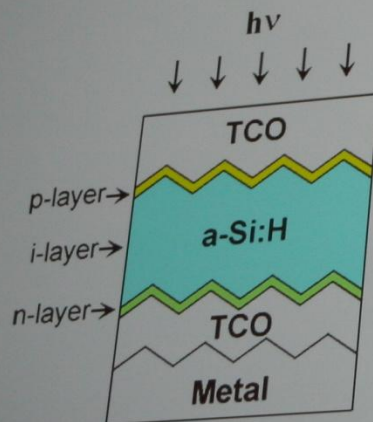
Modules photovoltaïques flexibles et légers



Source Photon Magazine March 2009

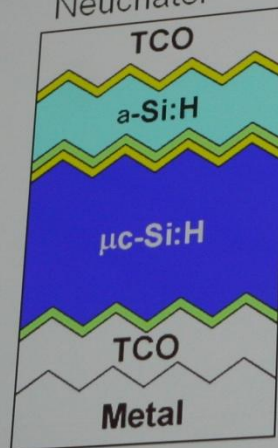
Multi-junction technology

Single junction
~9%(stab.)



Double junction
~12% (stab.)

Micromorph
Pioneered by IMT
Neuchatel



Triple junction
~13%(stab.)

Novel material



a-Si:H

a-SiGe:H
or
μc-Si:H

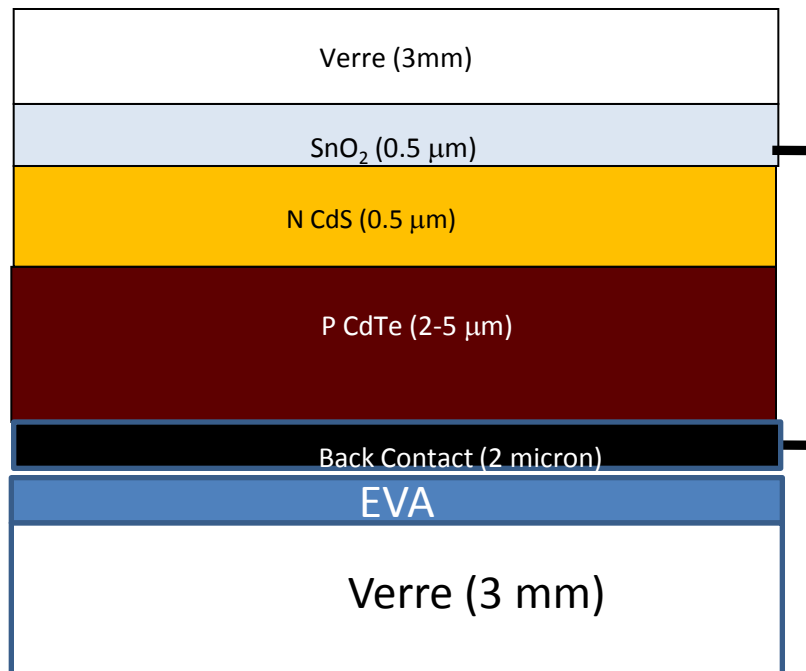
μc-Si:H

?

J. Meier 9.5% on LPCVD ZnO
Sonobe 9.3% on Asahi-U

Les cellules solaires CdTe

Laboratoire : 16,5 %
Modules : 11%
Production 10%



10.8 % Module efficiencies in 2009



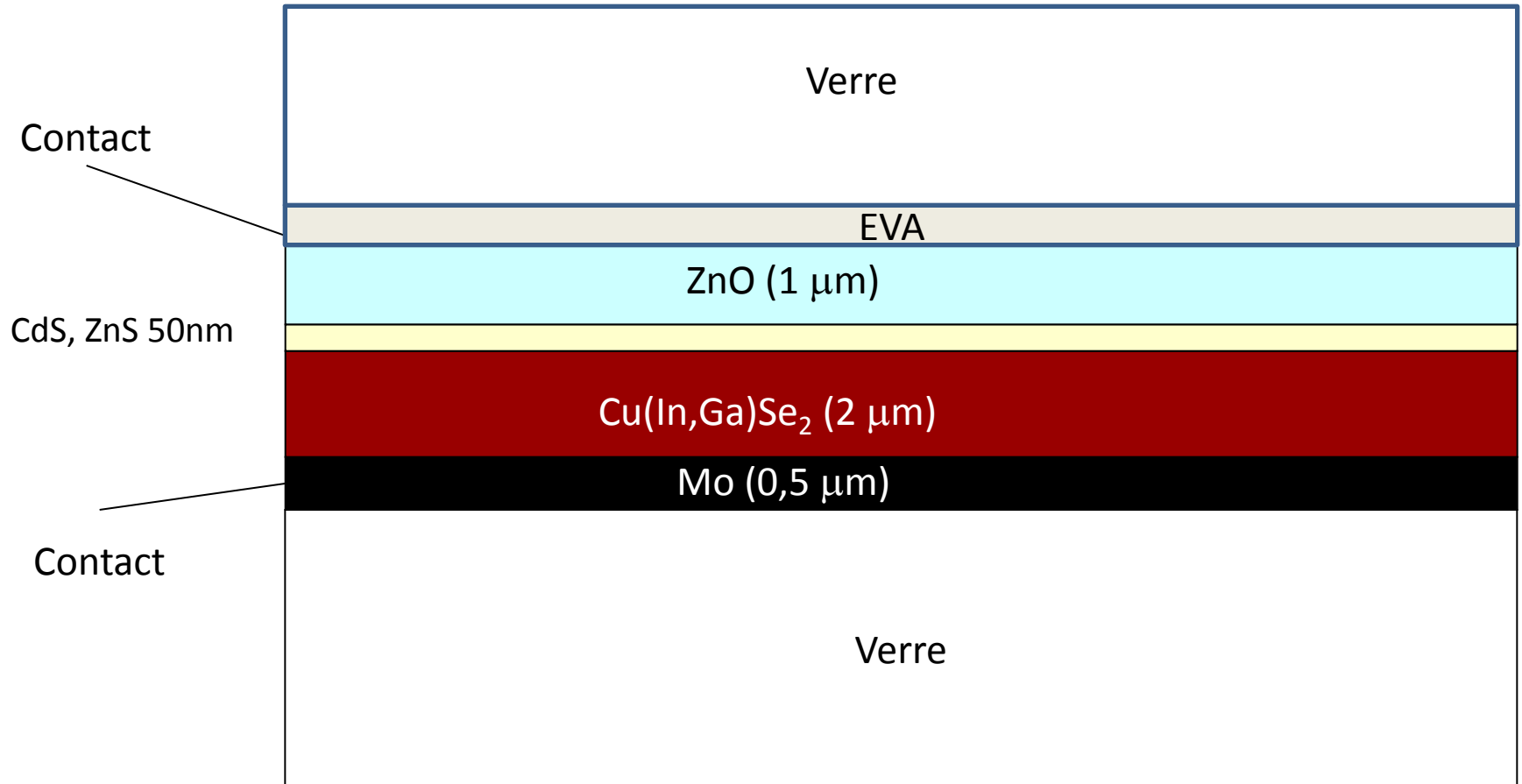
[http://www.firstsolar.com/pdf/FS_brochure_F
R.pdf](http://www.firstsolar.com/pdf/FS_brochure_FR.pdf)

La filière CIS (Cuivre Indium Sélénium)

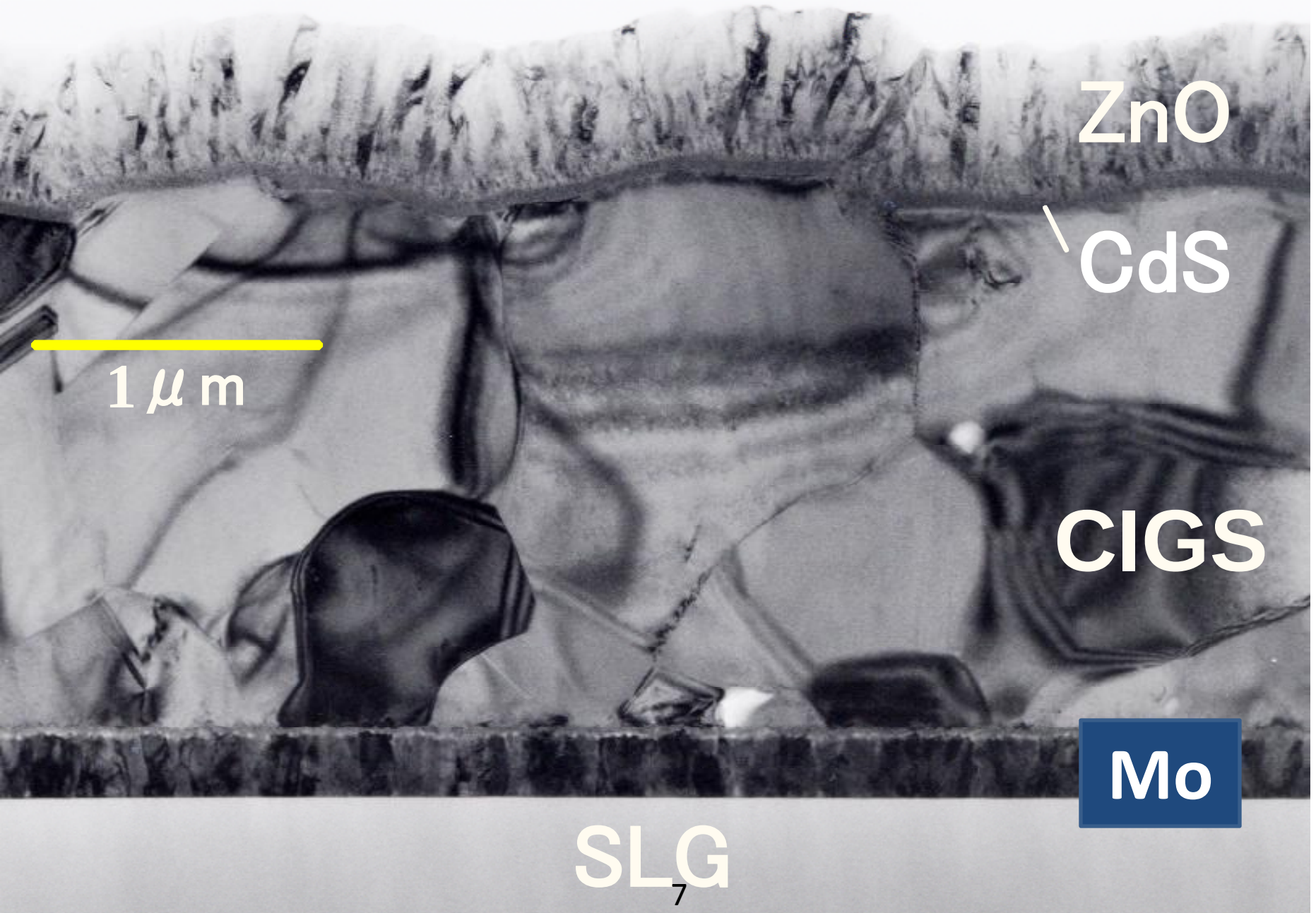
Laboratoire : 20,3 %

Modules : 8-13%

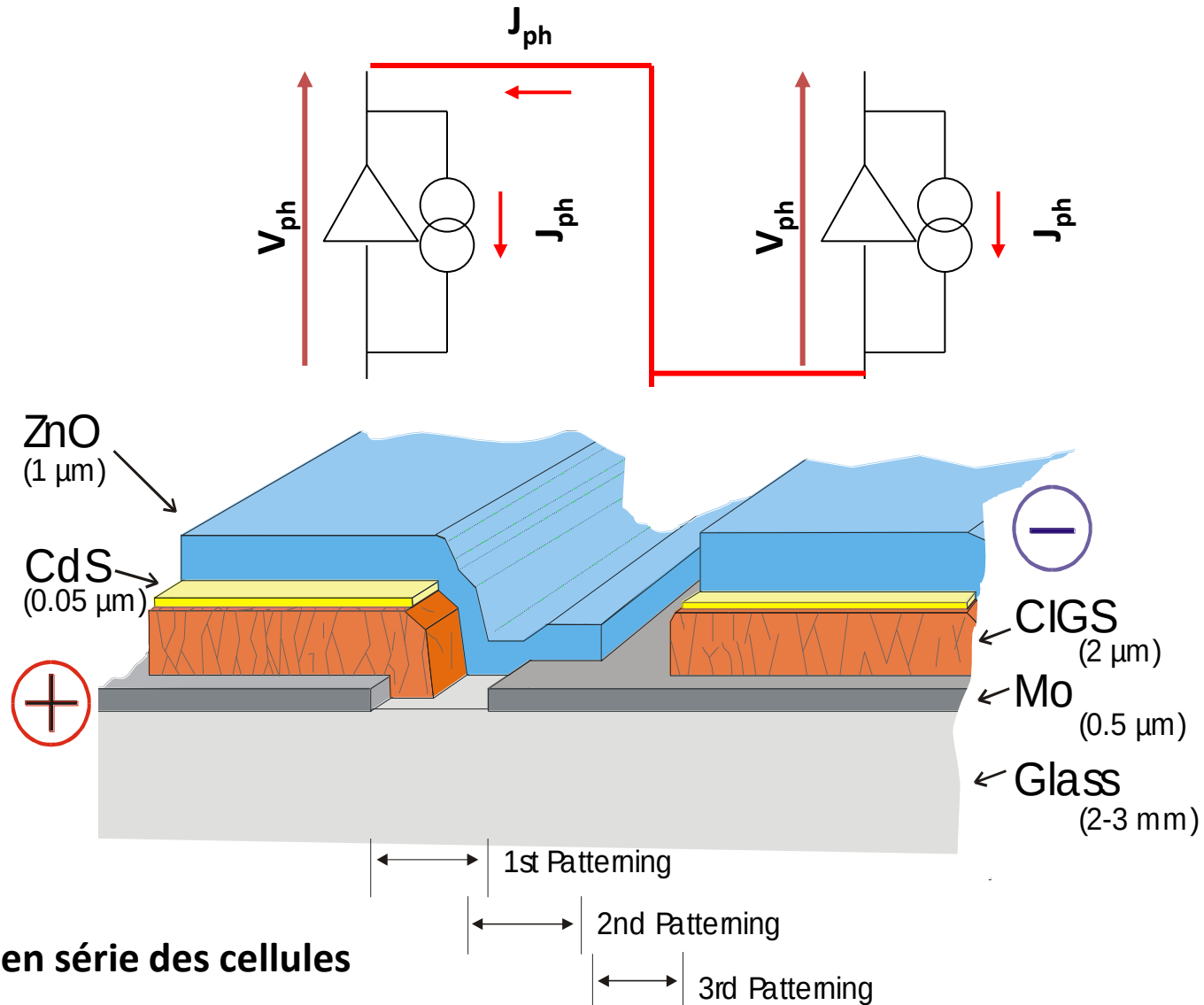
Production : 1,7 %



Source : Prof Nakada



La connectique « monolytique » des panneaux en couches minces



Mise en série des cellules

Par Courtoisie : Dr. Hans W. Schock (IPE)

La maison Zen (Zero Energy Net) in Chambéry of Alain Ricaud

Positive energy house in France

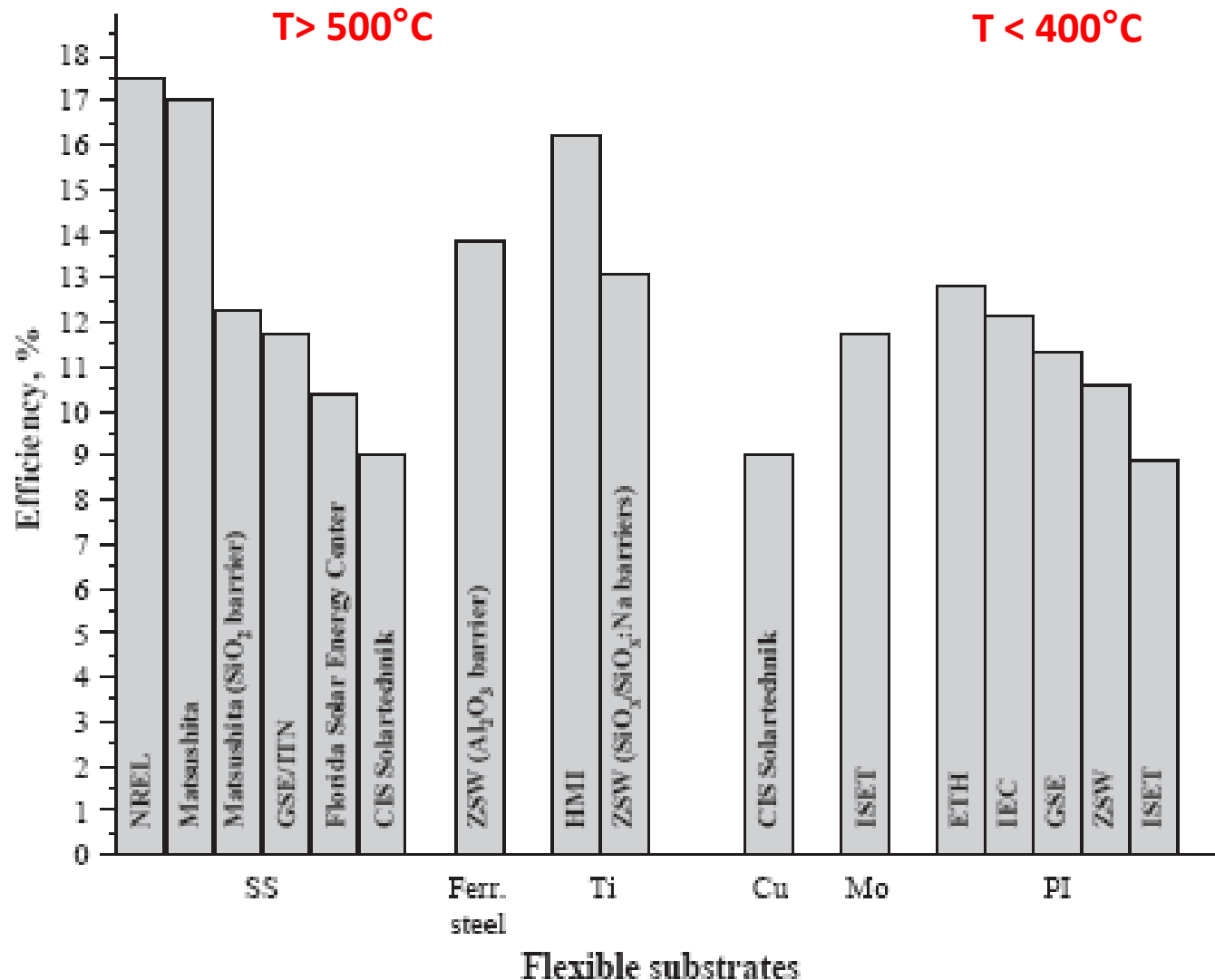
<http://www.cythelia.fr>



PV System CIS (Sulfurcell) 13.5 kWp 12 000 kWh/year
for 9000 kWh/year consumption

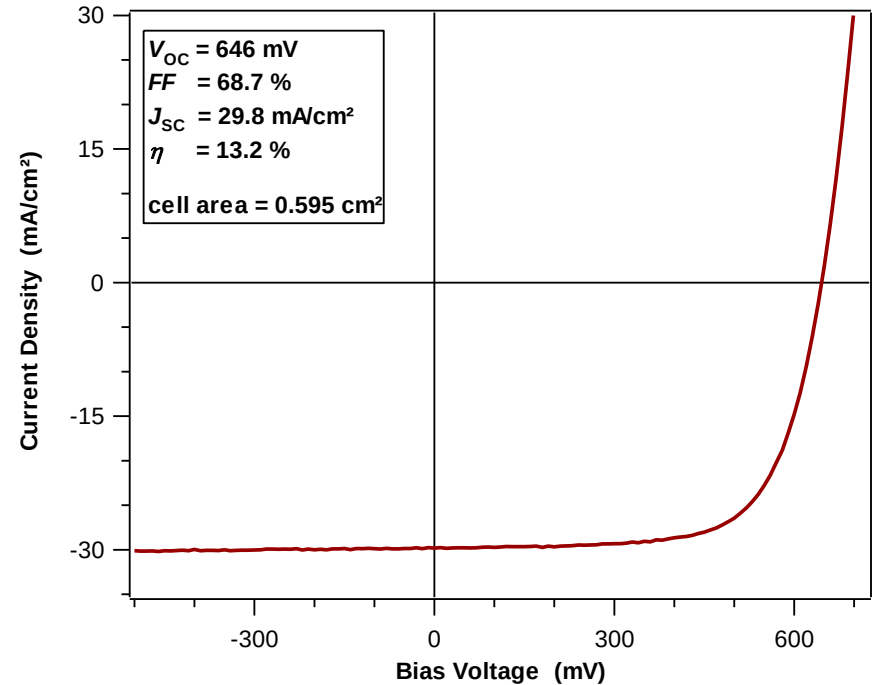
Cellules CIGS sur des substrats flexibles

K. Otte et al. Thin Solid Films 511(2006)613



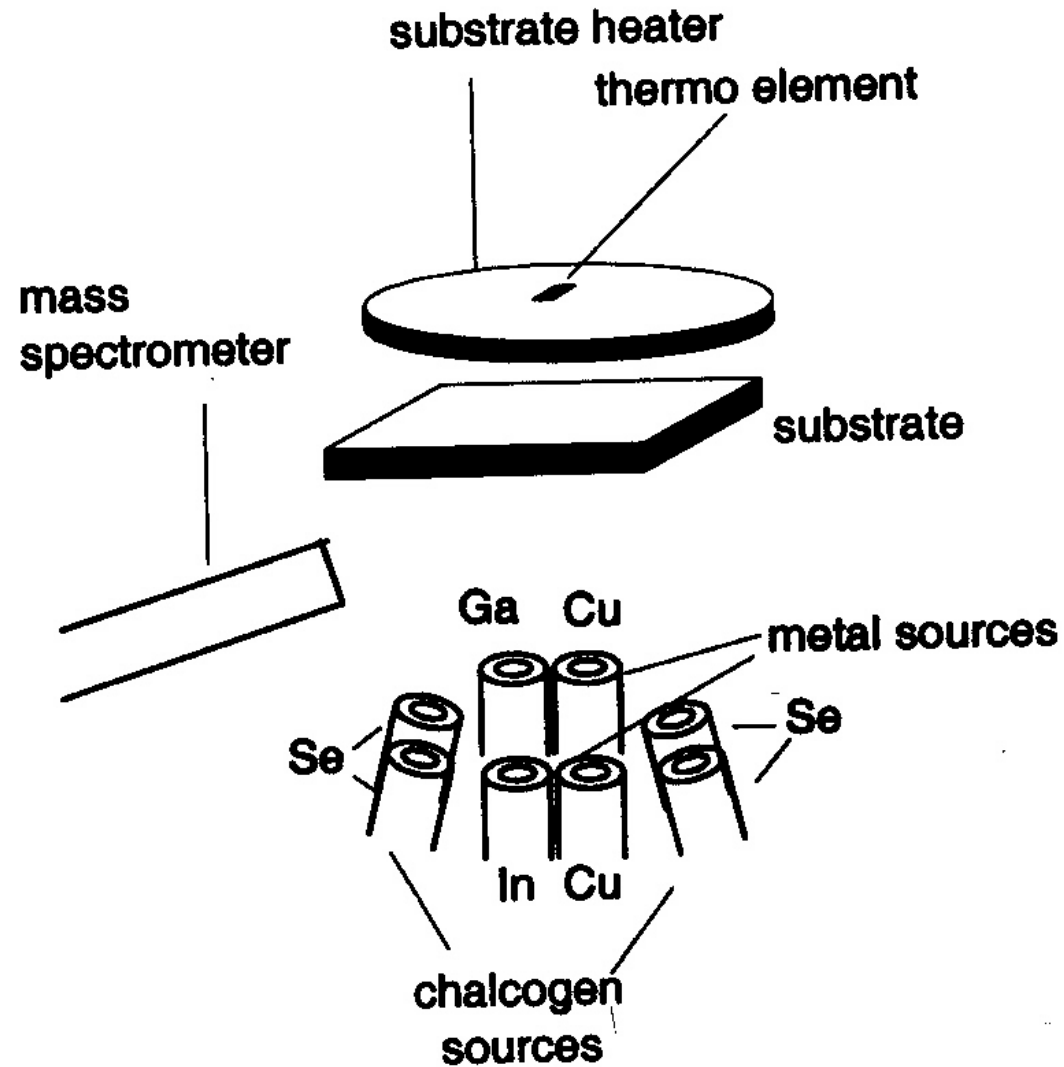
Flexible & lightweight CIGS solar cells on polymer films

World Record Efficiency of 13.2% (No AR coating, total area)



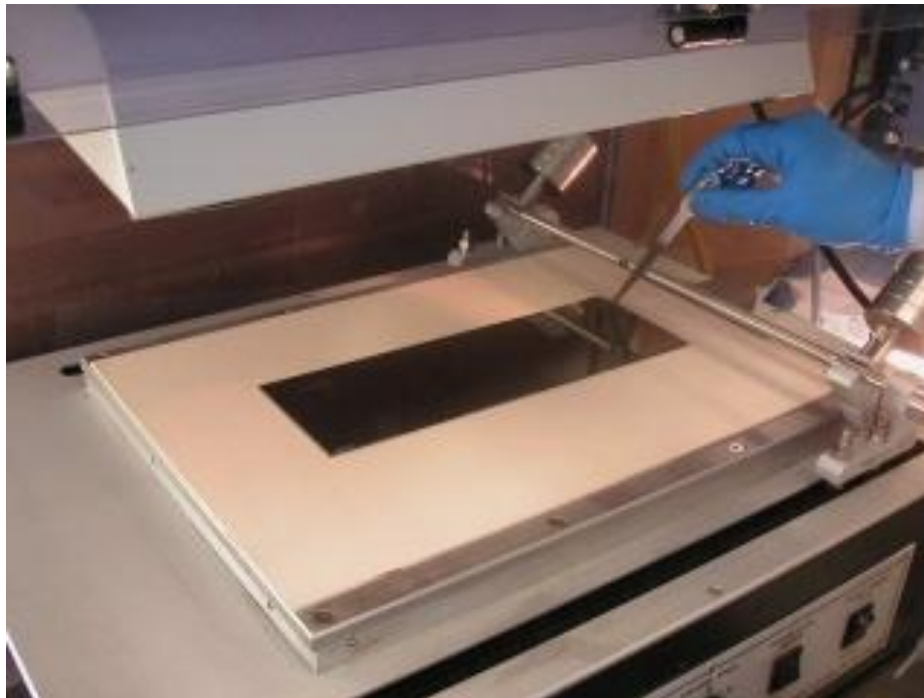
Recent development: 14.1% efficiency measured at ISE-FhG

Meilleurs rendements : Coévaporation sous ultravide
Coûts élevés



Méthodes bas coûts : Sérigraphie , électrolyse
Rendement plus faibles mais coûts faibles

Substrate	Efficiency	Air Mass Index
Soda Lime Glass	13.6%	AM1.5 ^a
Molybdenum Foil	13.0%	AM1.5
Titanium Foil	9.5%	AM1.5
Polyimide Film	9.3%	AM0 ^b

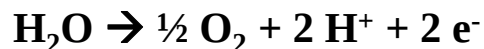


Dépôt électrolytique (IRDEP → Nexcis)

Réaction globale à la cathode



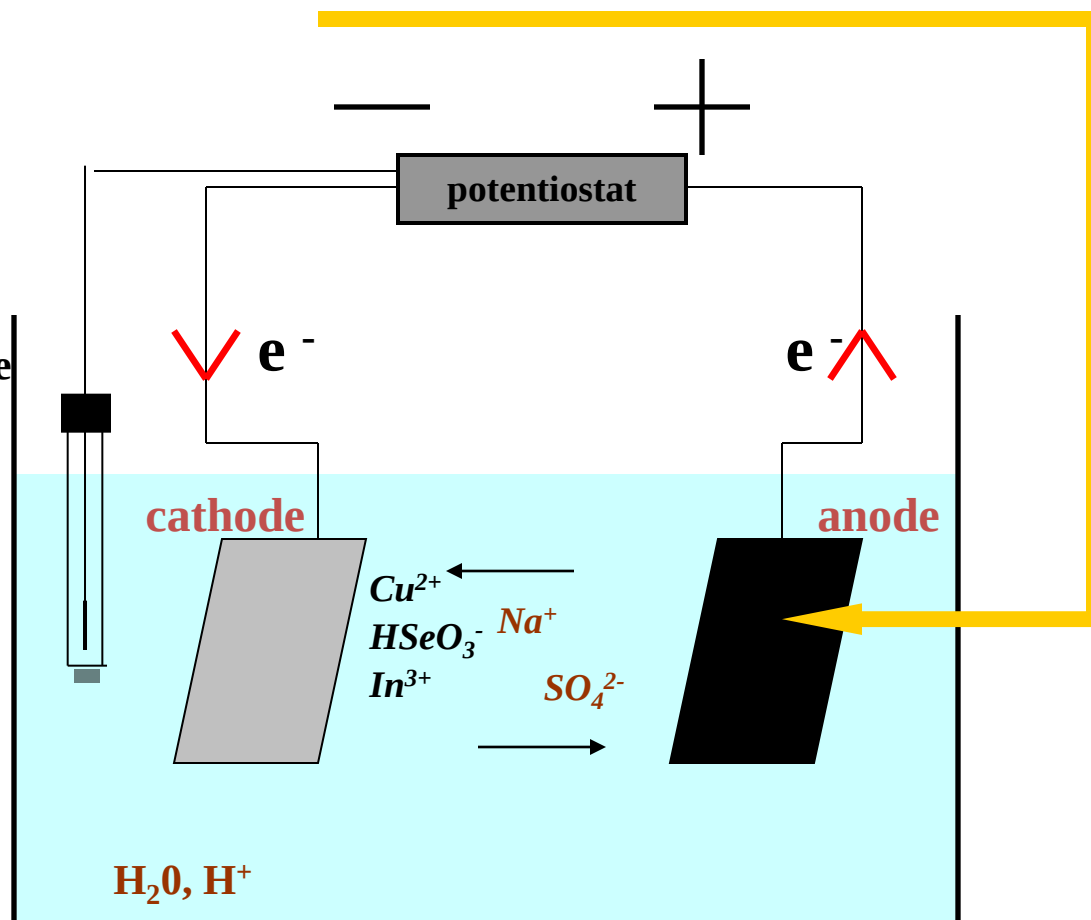
Réaction à l'anode



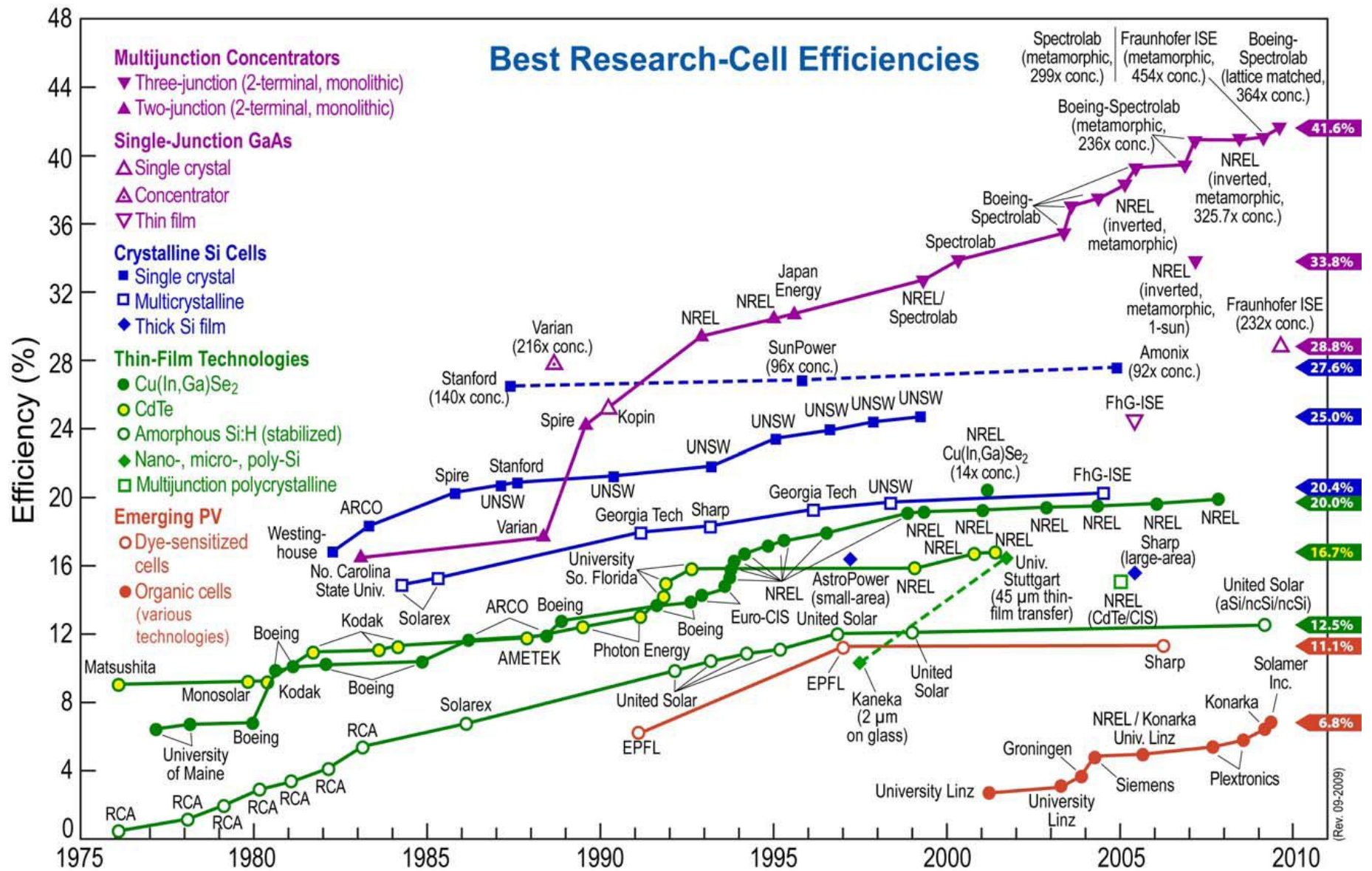
Puis recuit

Record : 11,5 %
Modules proto : 8-9 %
Industrialisation en cours

électrode de
référence



Les autres filières



Source NREL

Les cellules nanocristallines à colorants

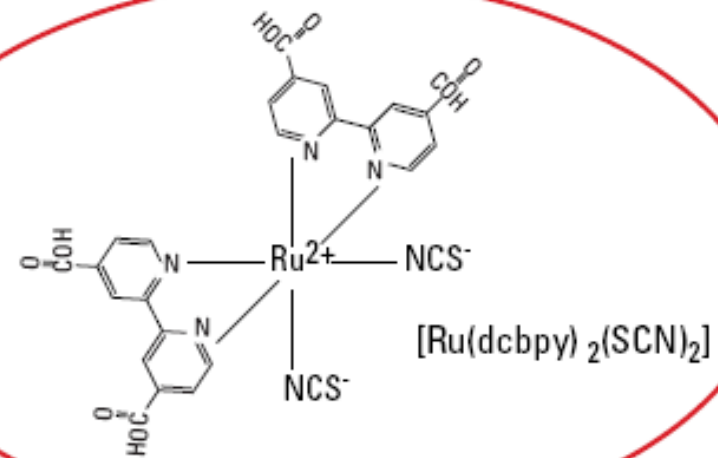
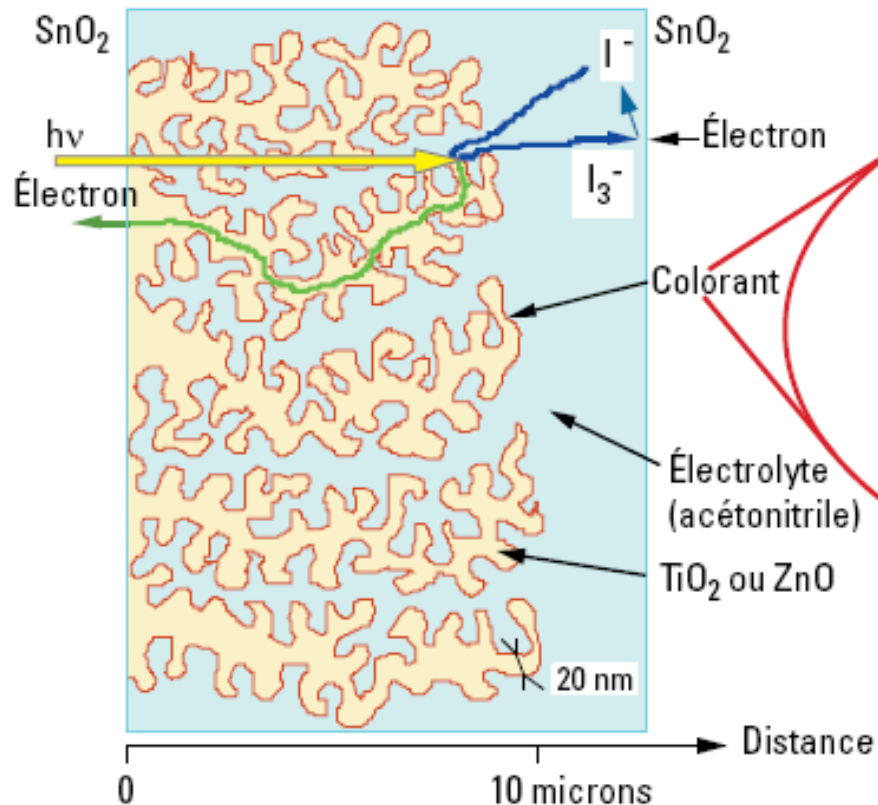
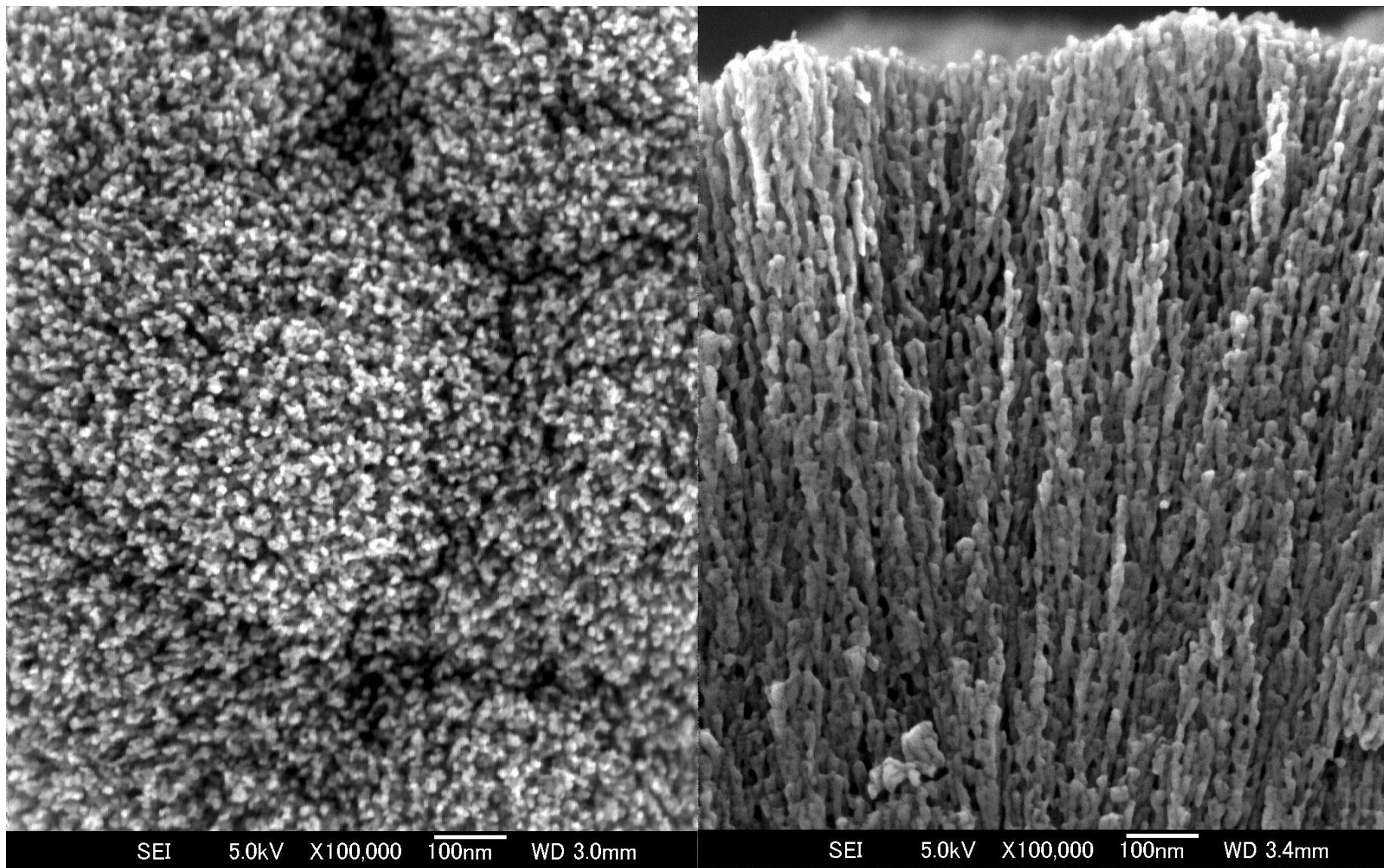
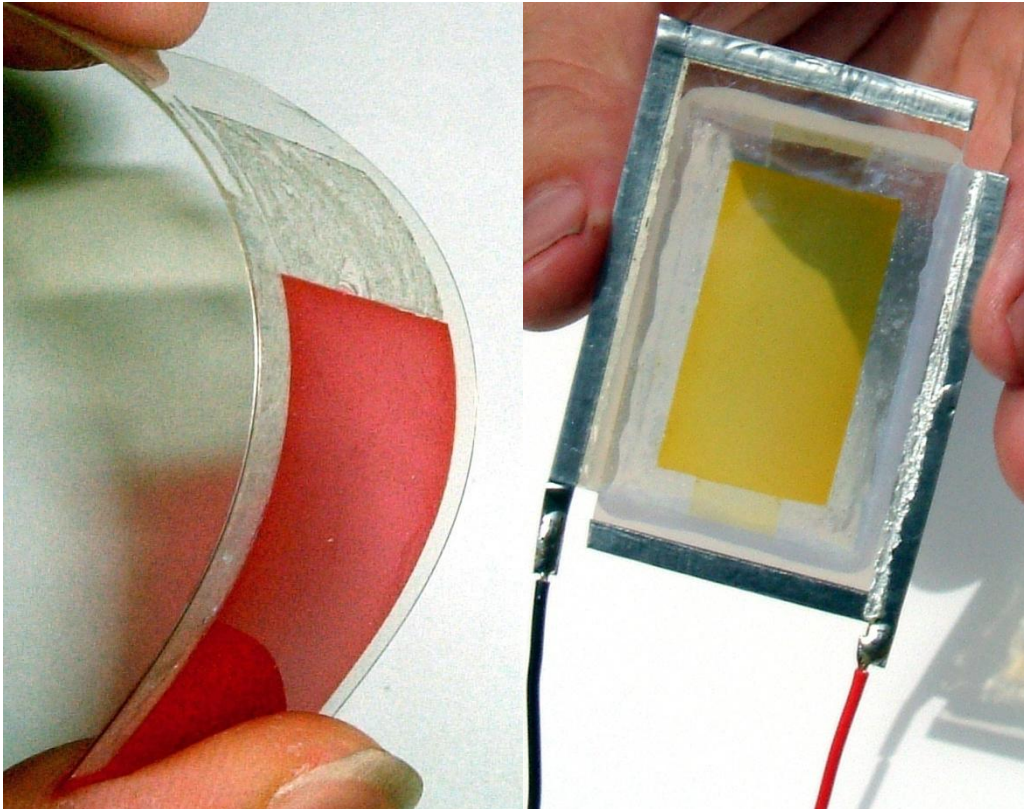
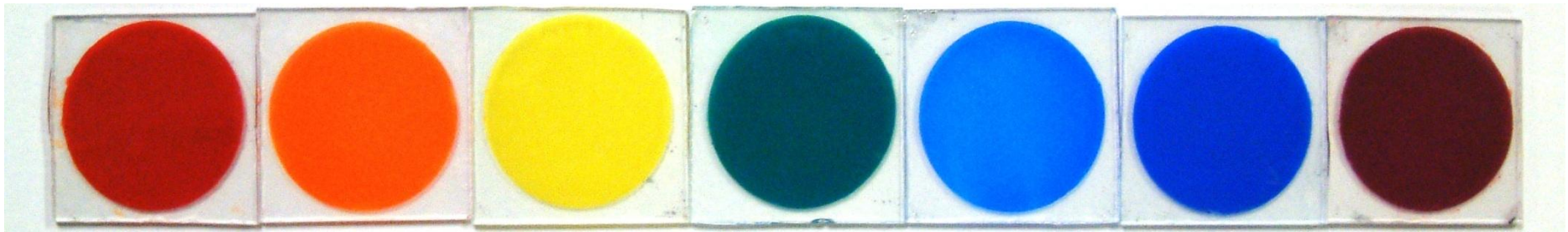


FIGURE 18
Principe de fonctionnement
d'une cellule à colorants.



ZnO nanoporeux préparé par électrolyse (IRDEP)



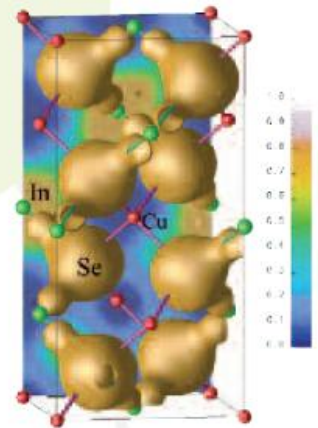
Rendement IRDEP avec ZnO : 4,5%

Les recherches menées à l'IRDEP

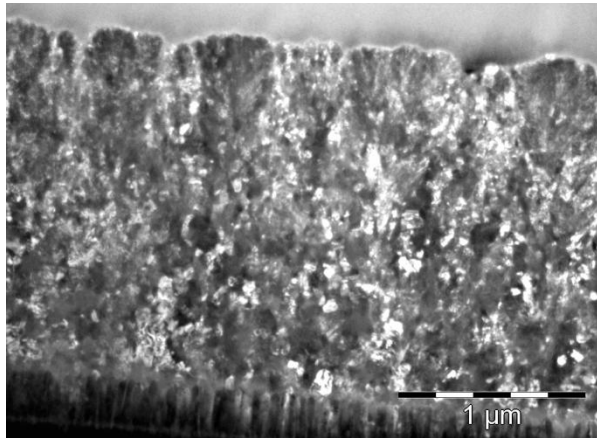
IRDEP is developing both targeted projects to address specific issues and exploratory research projects on innovative and fundamental issues.

Research Programs of IRDEP

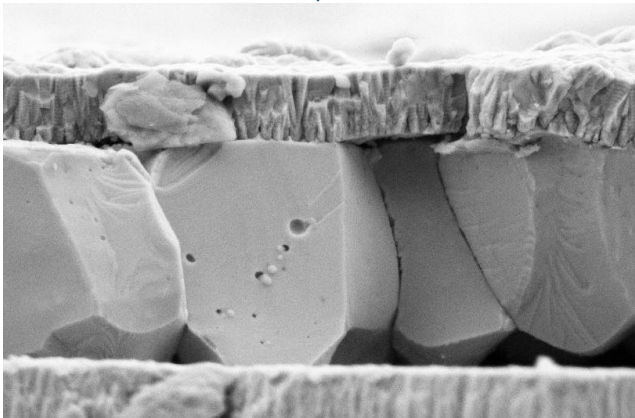
- **CIGS technologies**
 - Low cost electrodeposited CIGS Solar cells
 - High efficiency CIGS Solar cells
 - Ultrathin CIGS Solar Cells
- **Very High PV Efficiencies (→50%) and new concepts**
 - Photonics, photon conversion, hot carriers, intermediate band gap, multijunctions
 - Theory and Modelling
- **Exploratory thin film research**
 - Nanostructured hybrid solar cells
 - Transparent conducting oxides for high efficiency solar cells
 - Deposition processes (Electrodeposition, Chemical Bath deposition, Sputtering, ALCVD...)



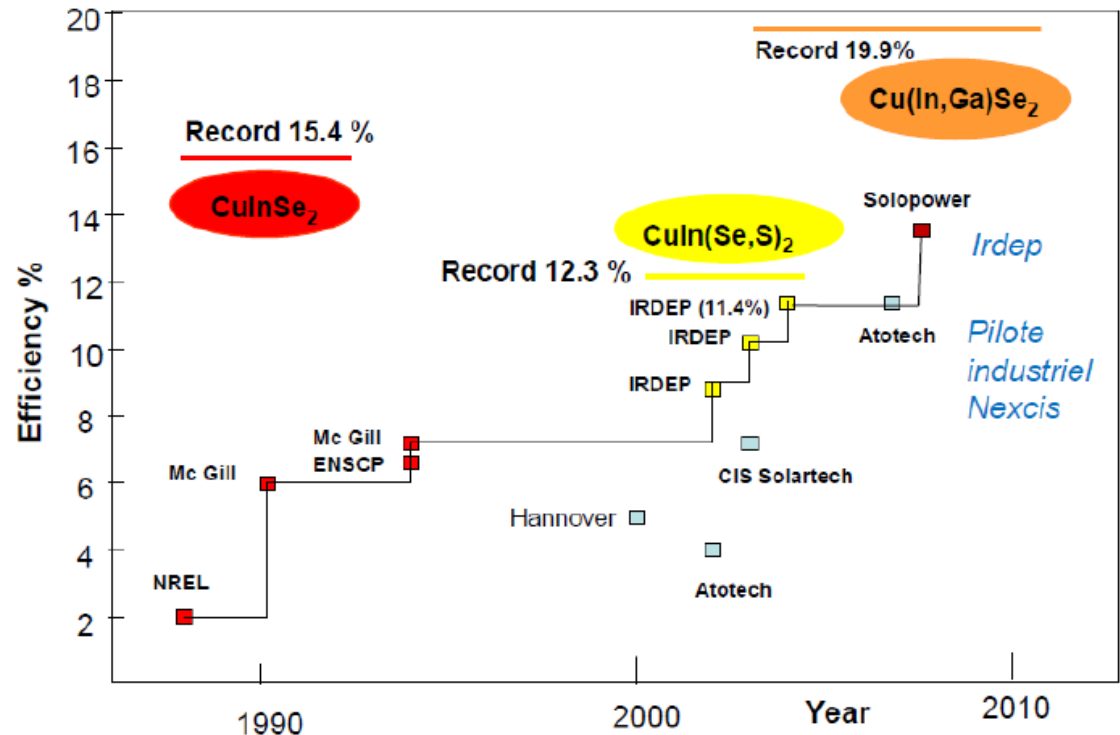
Cellules CIGS par électrodépôt: Objectif coût de production



CIGS after electrodeposition



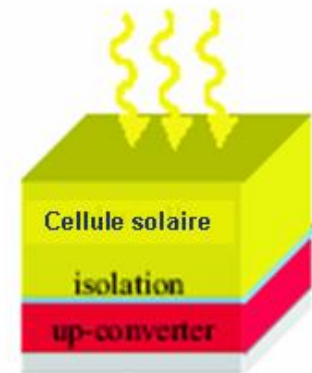
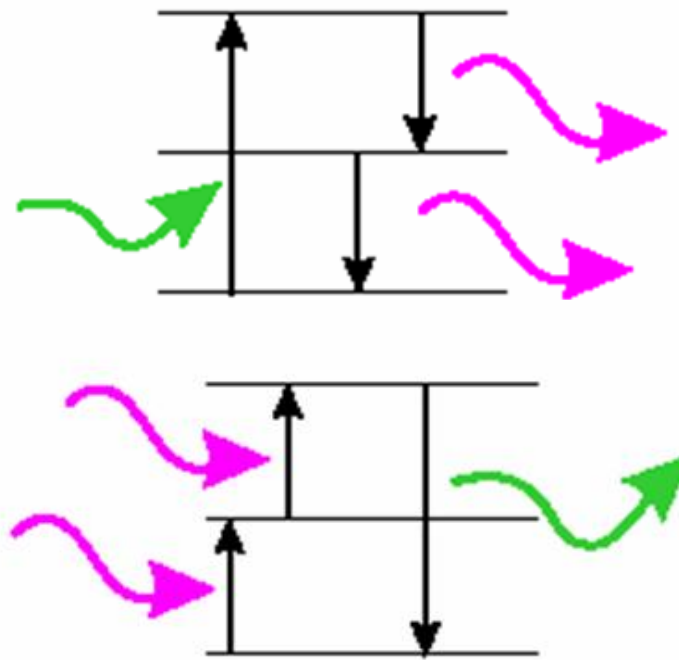
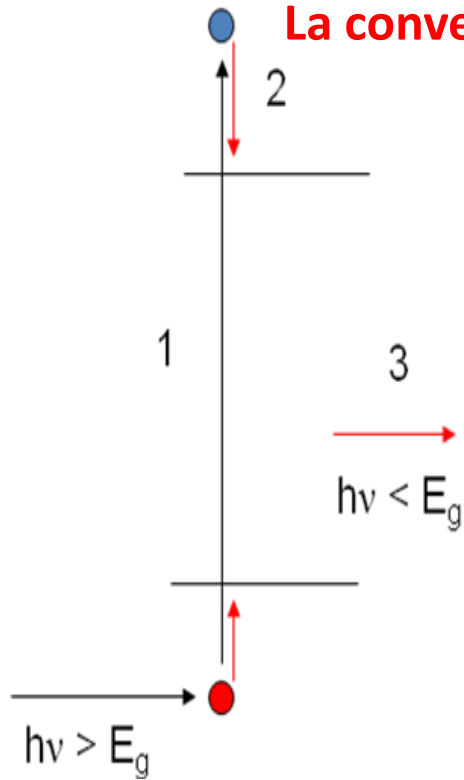
CIGS after rapid thermal annealing
In complete cell



Industrial developments : Spin Off Nexcis
IRDEP priority: High efficiency with Ga

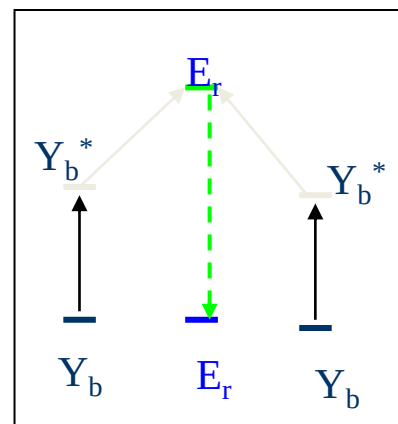
Nouveaux concepts photovoltaïques très hauts rendements

La conversion de photons

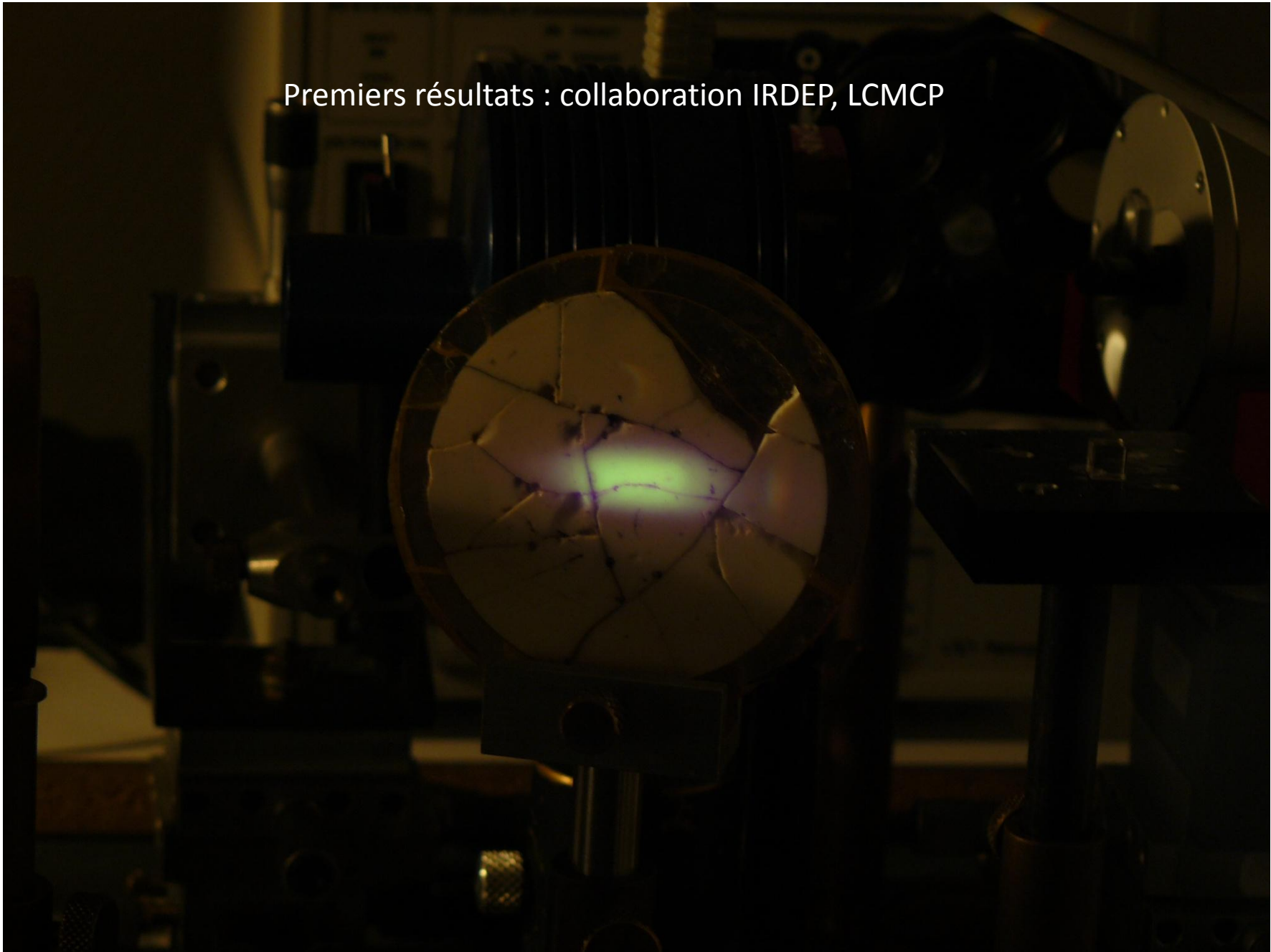


oxides, fluorides
Rare earth doping

(ex: NaYF_4)

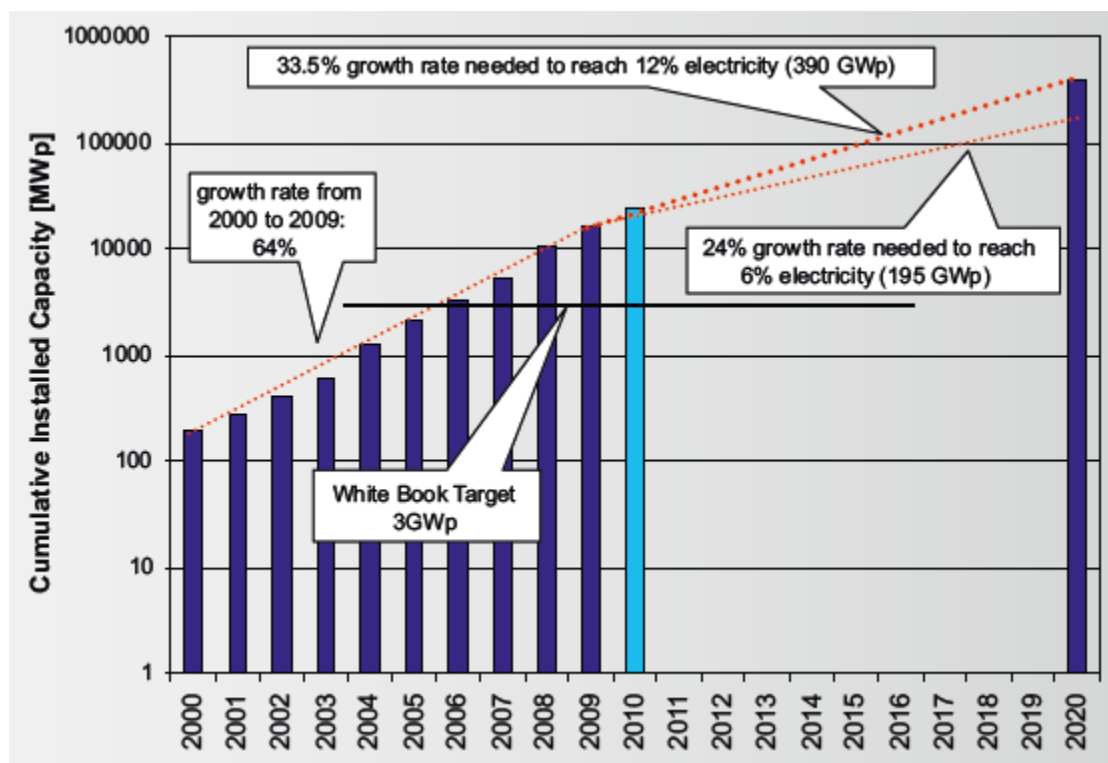


Premiers résultats : collaboration IRDEP, LCMCP



Perspectives

Fig. 12: PV growth in the European Union and estimate for 2010.

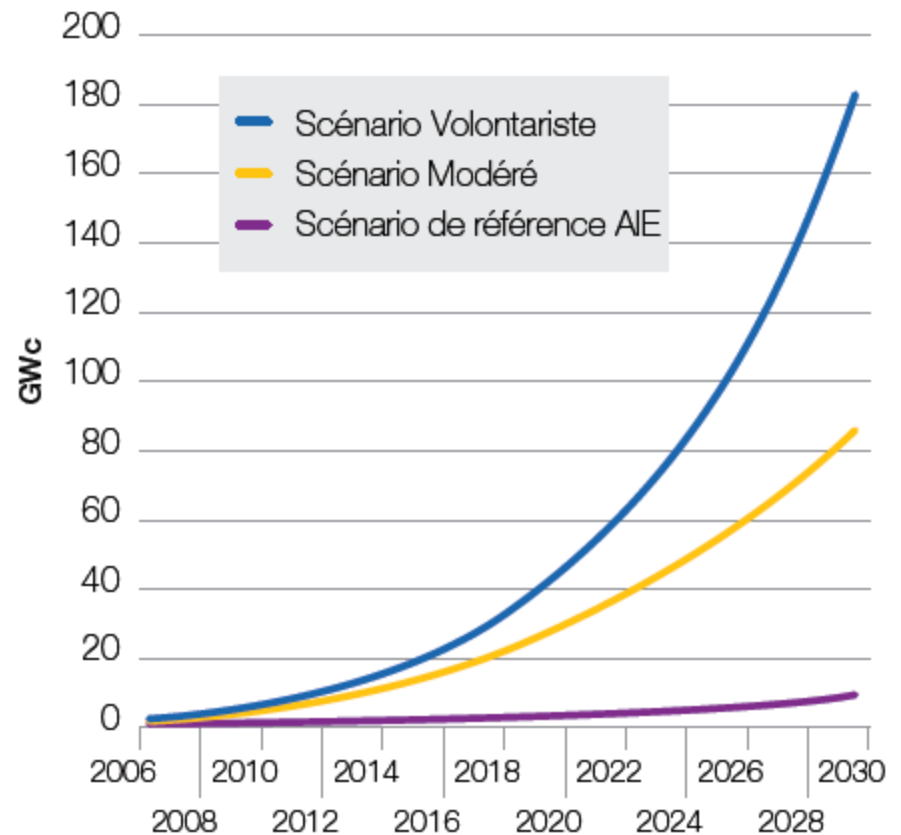




Accelerated growth scenario for Europe
(2009) :
12% of PV electricity in 2020

This sets the scene

Figure 3.2 : Capacité installée annuelle du PV mondiale jusqu'en 2030



PV technology development

Achievements, challenges and opportunities

The Implementation Plan for the Strategic Research Agenda

Wim Sinke

on behalf of Working Group 3: Science, Technology & Applications

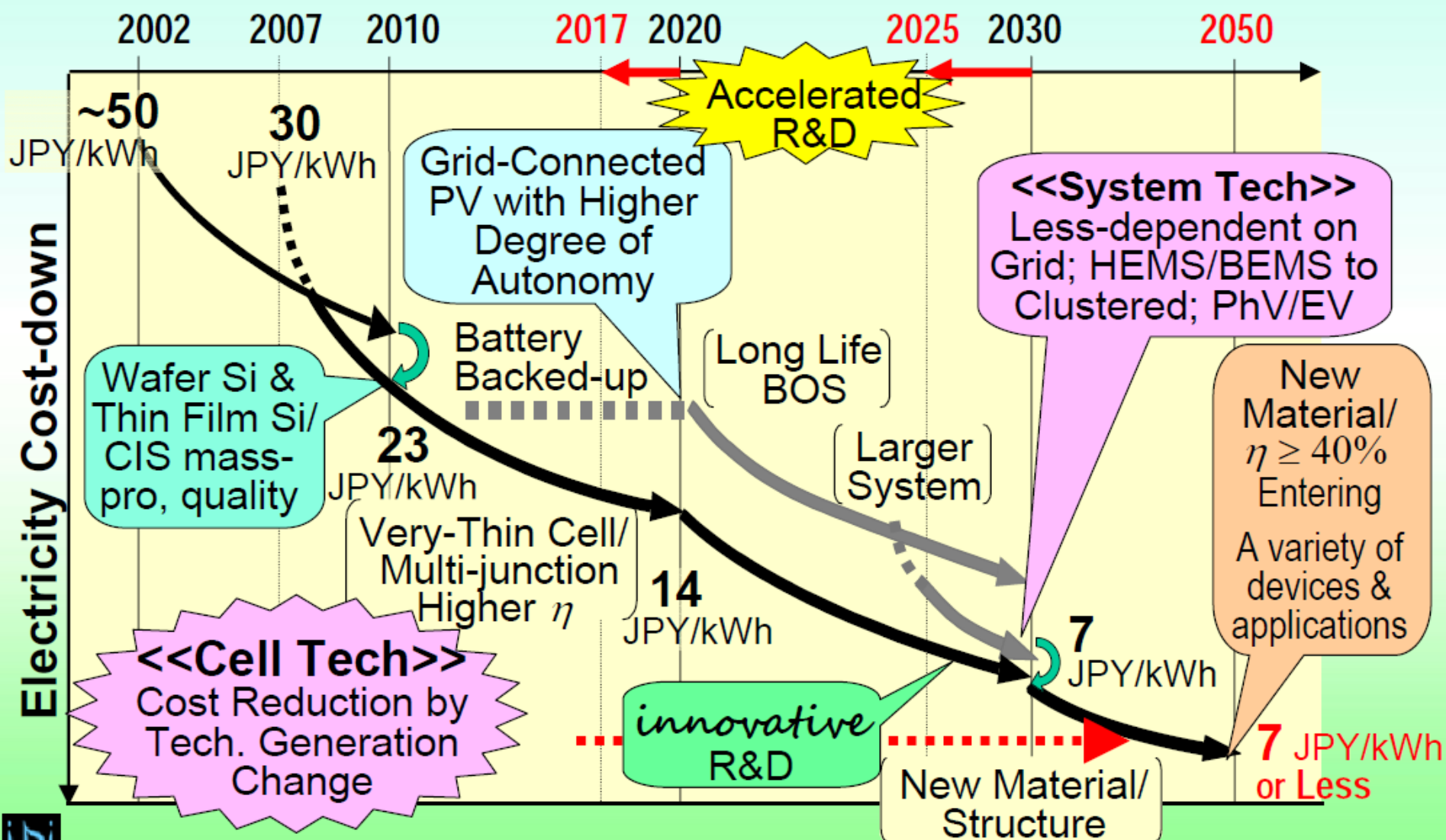
**4th General Assembly
Vienna, 19 June 2009**

● Industrial sector objective (SET Plan):

Establish photovoltaics (PV) as a clean, competitive and sustainable energy technology providing up to 12% of European electricity demand by 2020.

<i>Rounded, indicative figures</i>	1980	2009	2020	2030	Long term potential
Typical turn-key system price (2009 €/Wp)	>30	4 (range 3 ~ 7)	2 (range <1.5 ~ 3)	<1	0.5
Typical electricity generation costs Southern Europe (2009 €/kWh)	>2	0.25	0.12 (<0.10 ~ 0.18)	<0.06	0.03
Typical commercial <i>flat-plate</i> module efficiencies	up to 8%	up to 15%	Up to 20%	up to 25%	up to 40%
Typical commercial <i>concentrator</i> module efficiencies	(~10%)	up to 25%	Up to 30%	up to 40%	up to 60%
Typical system energy pay-back time Southern Europe (yrs)	>10	2	1	0.5	0.25

Accelerated, Extended "PV2030 +" Roadmap



<http://www.desertec.org/en/concept/>

