Photovoltaics in the XXIst century: achievements and challenges

JF Guillemoles

IRDEP, Institut de Recherche et Développement sur l'Energie Photovoltaïque

Energy issue

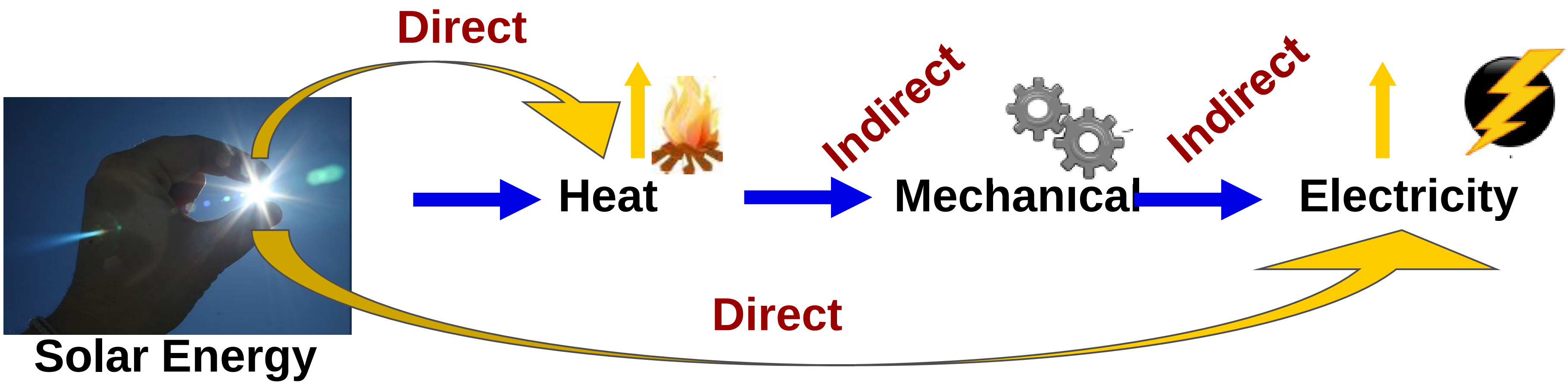
- The world is power hungry
  - 2 kW/pers. average, France: 5 kW, US 11 kW
  - ~15 TW primary energy consumption (AIE 2008)

- There is need for energy that is
  - available, safe, secure, clean …. and affordable

  i.e., sustainable

- Solar energy is
  - Abundant (170 000 TW**, from fusion)**
  - Safe (150 M. km away)
  - Secure (no geopolitics)
  - Clean

Solar Paradox



Harnessing Fusion?

Extremely abundant, safe, secure, but still little used for direct electricity production

Only 0.06% of electricity production yet!

Footprint of Renewables (best cases)

Solar: 100-250 w/m²

PV: 50 w/m² (efficiency 20%)

Biomass : < 0.5 w/m²

Wood < 7 toe/ha/an

sugarcane < 4 toe/ha

Hydro : 11 w/m² (dams)

Wind : 2 –3 w/m²

Best : wind > 5 m/s

Tides : 1-13 w/m²

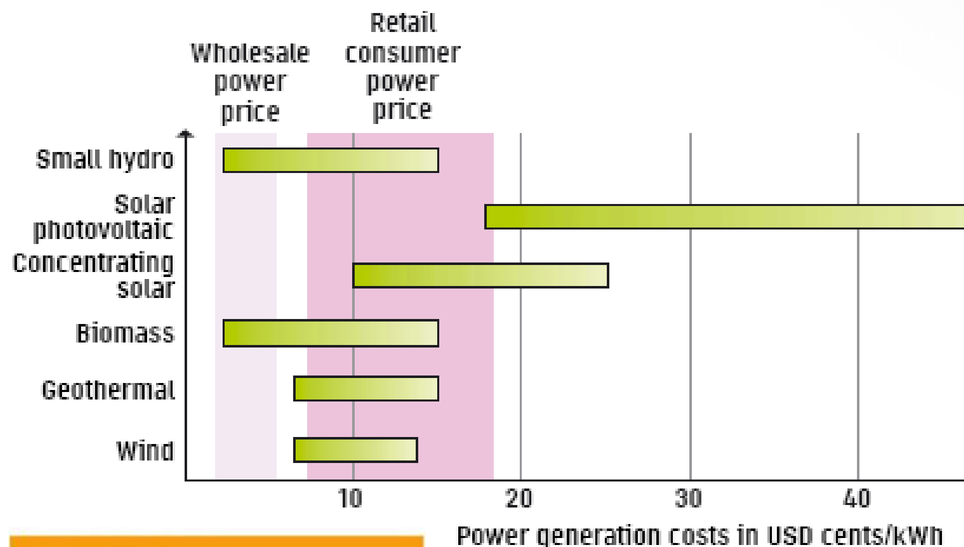
3 w/m² (Dams)

6 w/m² (Marine turbine)

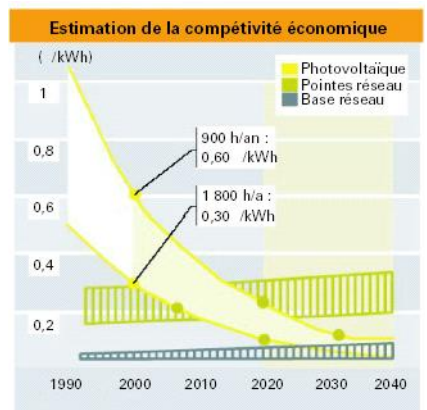
Waves : 40 w/m (Atlantic coast)

Geothermal : 0.05 w/m²

0.015 w/m² if renewable



IEA, 2006

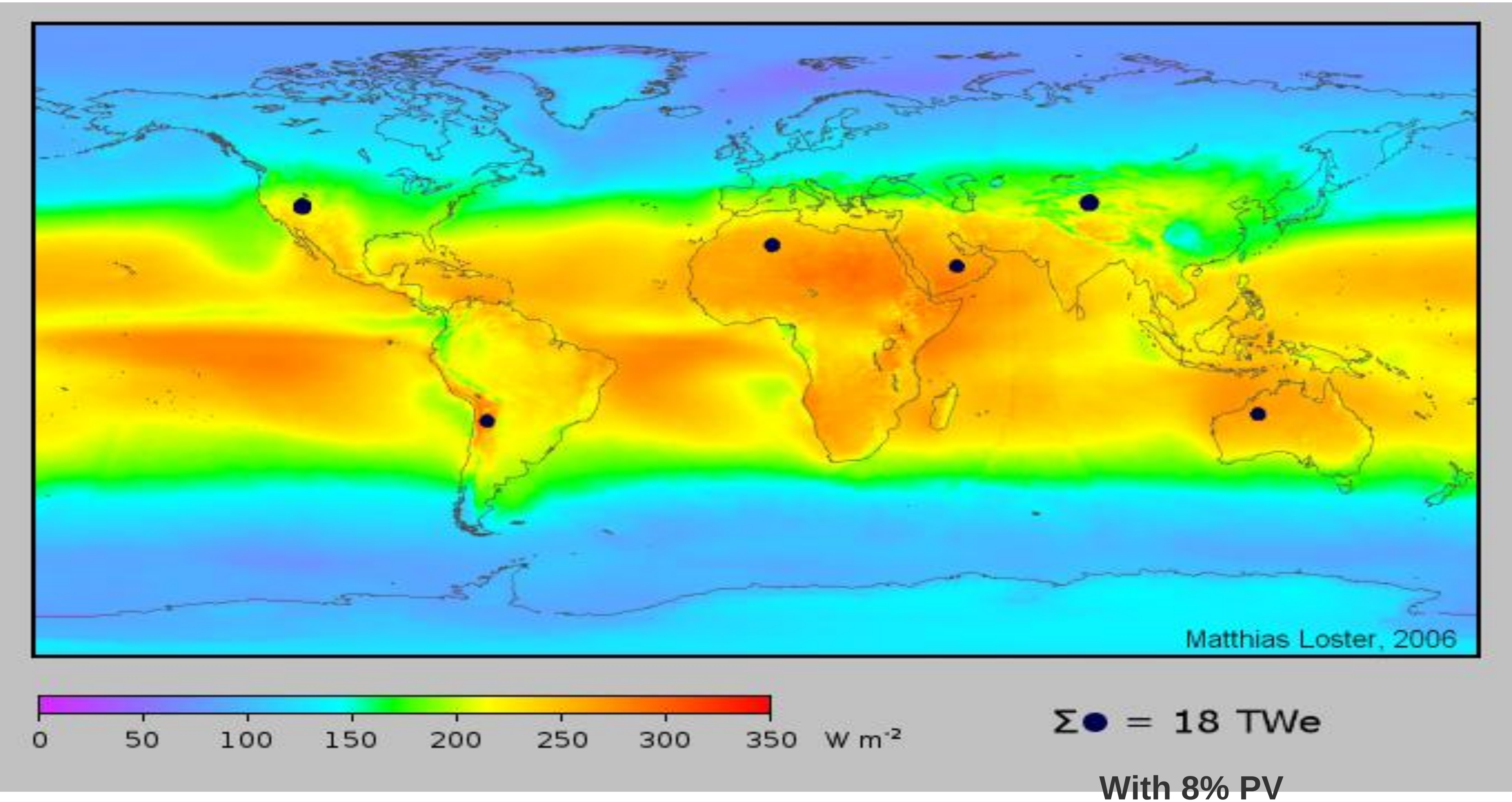


Expensive compared to most renewable energies, but the only resource with decreasing costs

France: Solar > 120 W/m²

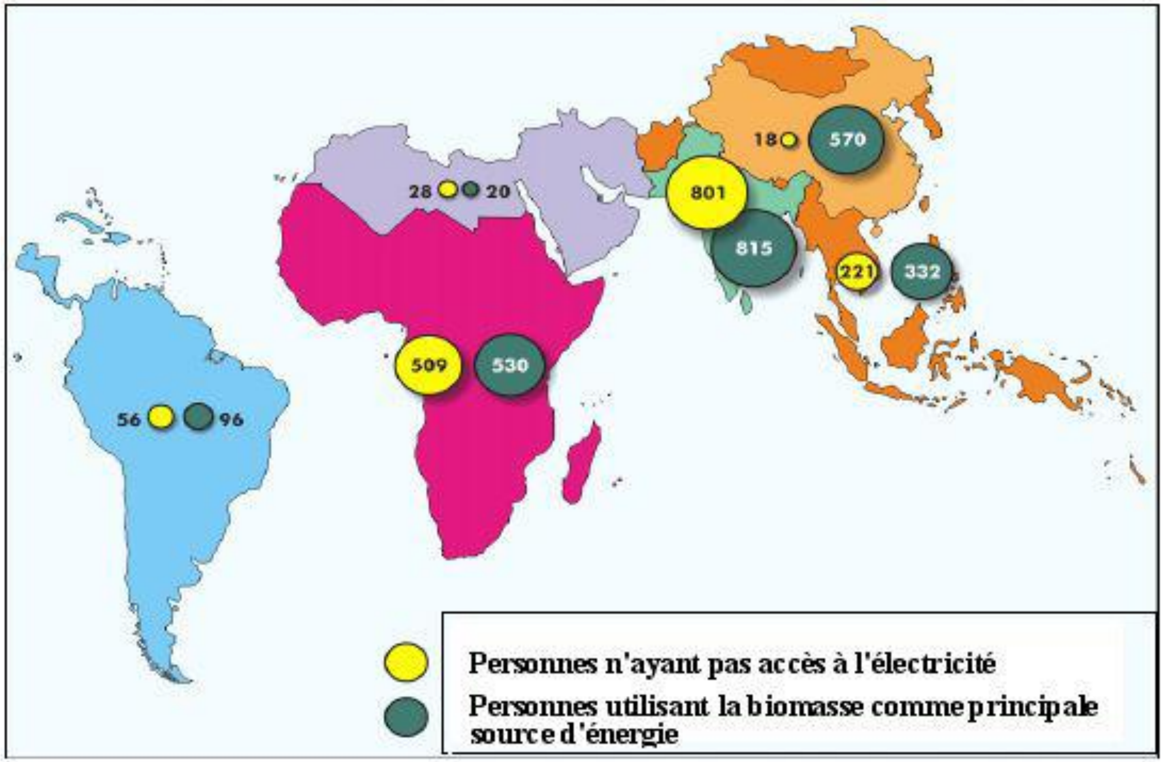
=> Electrical needs from 5000 km² (10 % eff.)

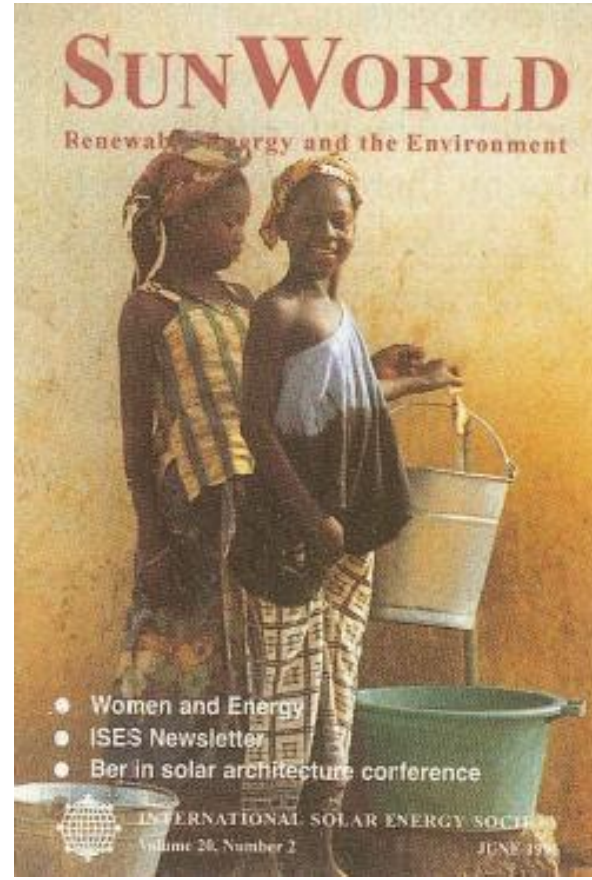
Availability



- Average power > 100 W/m² in populated areas
- Global scale : ~ 10 000 times consumption

Access to electricity





> 1.5 billion people without electricity access

> Global electrification rate : 75% (rural areas : 60% , source AIE)

Outline

- Achievements
  - Short history
  - Principles
  - Technologies
- Challenges
  - Cost
  - Efficiency
  - Environmental
- Summary

1

I- Achievements

E. Becquerel

COMPTE RENDU

DES SÉANCES

DE L'ACADÉMIE DES SCIENCES.

SÉANCE DU LUNDI 4 NOVEMBRE 1839.

PRÉSIDENCE DE M. CHEVREUL.

MÉMOIRES LUS.

Mémoire sur les effets électriques produits sous l'influence des rayons solaires; par M. EDMOND BECQUEREL.

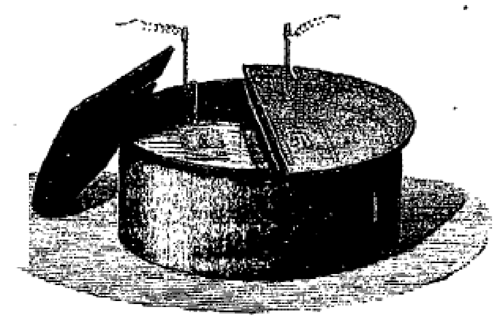


Fig. 50.

Early times

XIXth : the first solid state PV cell 1st cells by R.E. Day (1870), developed by C. Fritts (1883) , with Se wafers (< 1% eff.)

1930: Cu/Cu2O cells by Lange and Schottky

1948: Organic PV with phtalocyanines (Putseiko, URSS)

1912

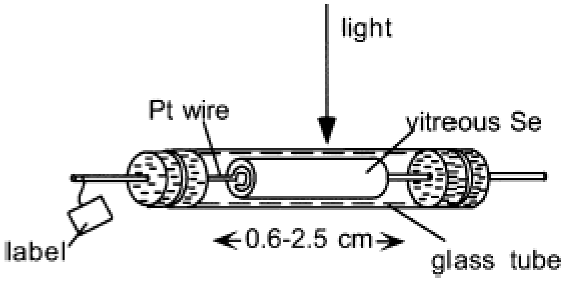
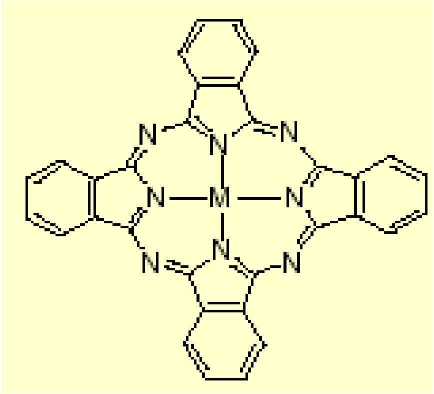


Fig. 2. Sample geometry used by Adams and Day [4] for the investigation of the photovoltaic effect in selenium.



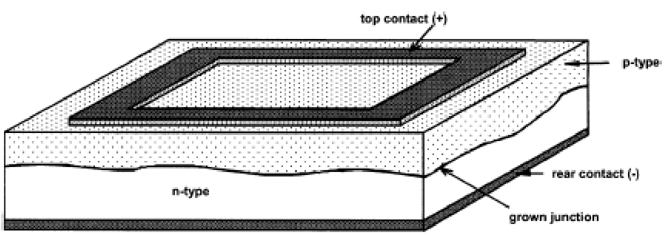
First efficient devices/space applications

1954: 1st cell using Si (5%) by Chapin, Fuller and Pearson at Bell labs

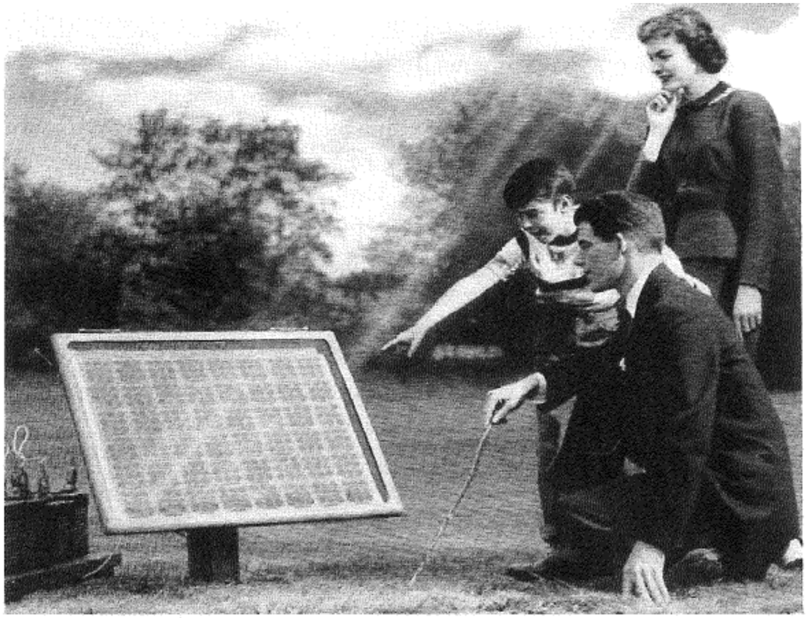
1955: Cu_2S/CdS (US air force)

1956: GaAs 6% (RCA)

60's: Early industrial Production (satellites), Si cell 14%



Joliot Curie (1956): « … we must very seriously and immediately get involved in the utilization of solar energy. »



Something New Under the Sun. It's the Bell Solar Battery, made of thin discs of specially treated silicon, an ingredient of common sand. It converts the sun's rays directly into usable amounts of electricity. Simple and trouble-free. (The storage batteries beside the solar battery store up its electricity for night use.)

Bell System Solar Battery Converts Sun's Rays into Electricity!

Bell Telephone Laboratories invention has great possibilities for telephone service and for all mankind

Ever since Archimedes, men have been searching for the secret of the sun.

For it is known that the same kindly rays that help the flowers and the grains and the fruits to grow also send us almost limitless power. It is nearly as much every three days as in all known reserves of coal, oil and uranium.

If this energy could be put to use — there would be enough to turn every wheel and light every lamp that mankind would ever need.

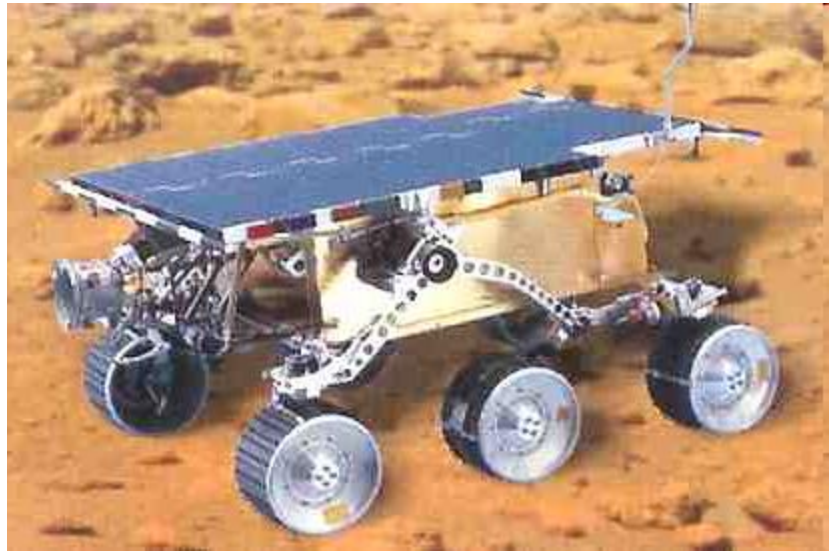
The dream of ages has been brought closer by the Bell System Solar Battery. It was invented at the Bell Telephone Laboratories after long research and first announced in 1954. Since then its efficiency has been doubled and its usefulness extended.

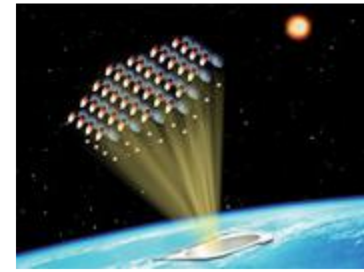
There's still much to be done before the battery's possibilities in telephony and for other uses are fully developed. But a good and pioneering start has been made.

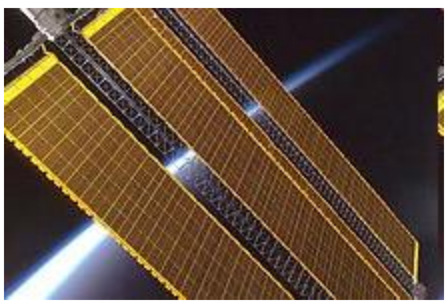
The progress so far is like the opening of a door through which we can glimpse exciting new things for the future. Great benefits for telephone users and for all mankind may come from this forward step in putting the energy of the sun to practical use.

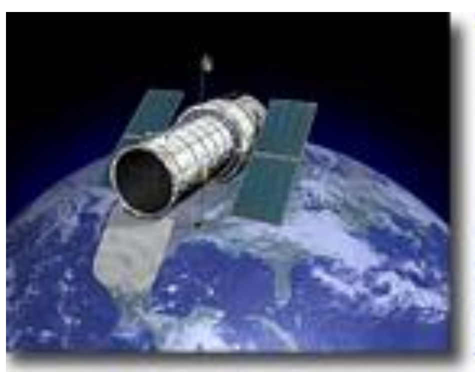
BELL TELEPHONE SYSTEM

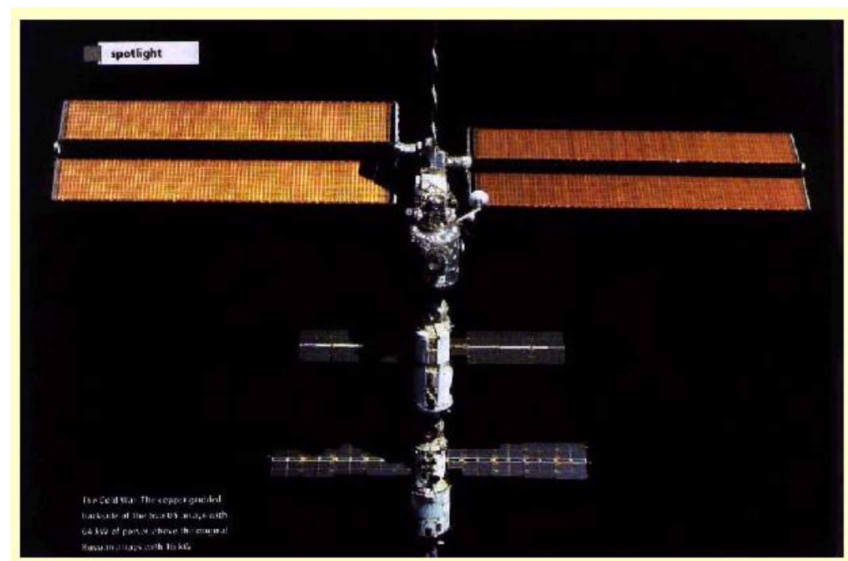
Space





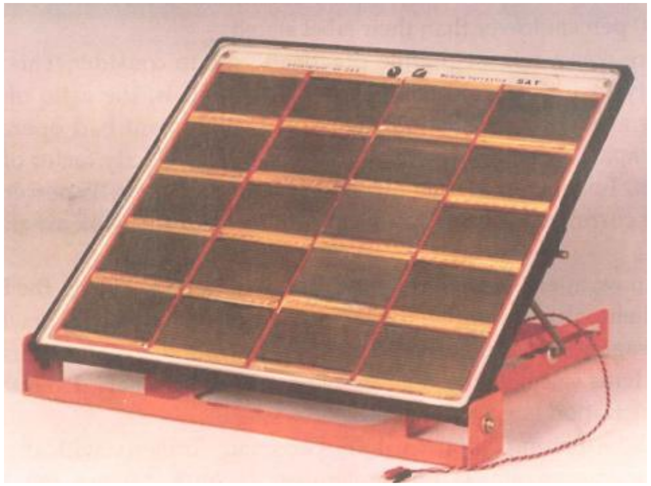


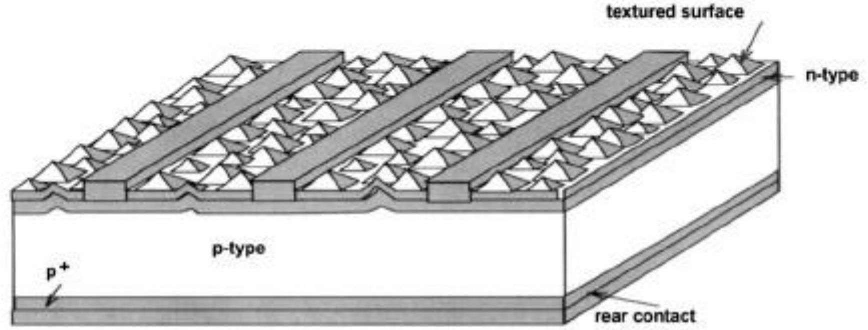




80's: cheaper devices & ground applications

- 70's: successful spatial applications
- 73: renewed interest in solar energy for ground application
- 80's: development of thin film cells (CdTe, CIS, a-Si…)
- Consumer electronic applications
- 82: 1st MWp sized PV power plant
- 85: Si >20% (>25% x200)
- 86: a-Si commercial modules

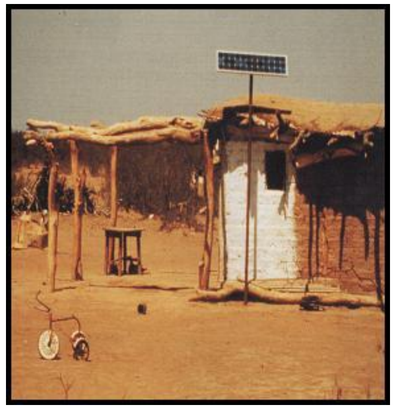


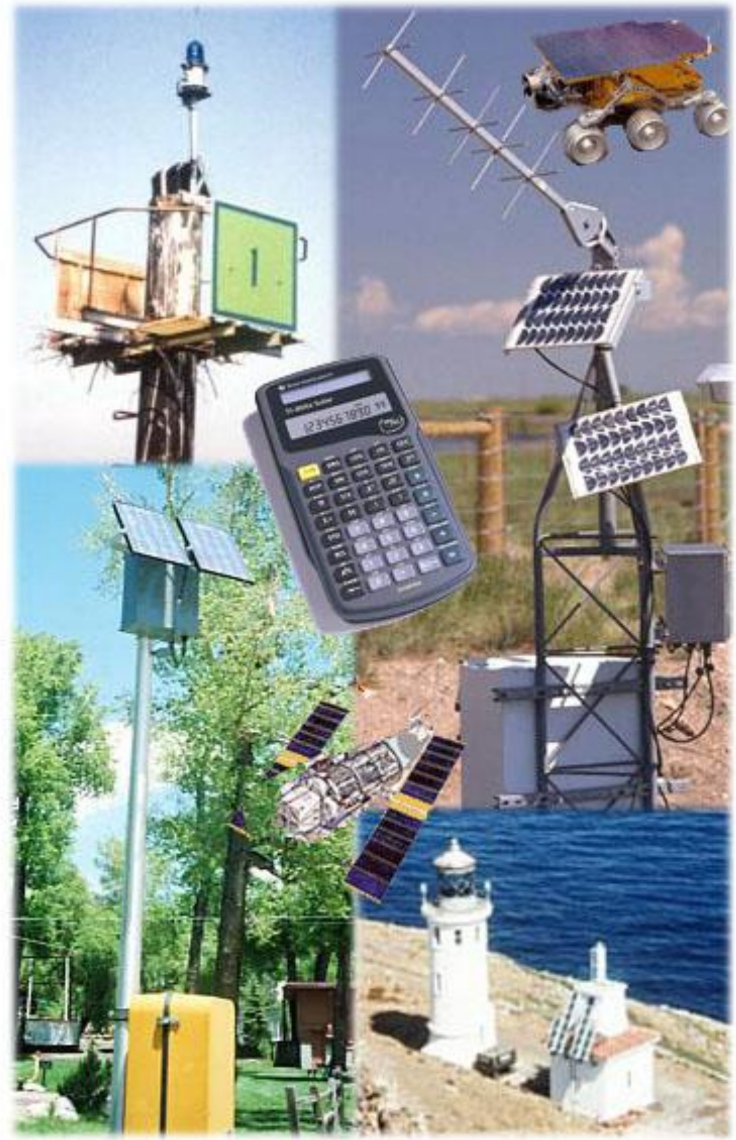


Autonomous systems

- **Cheaper than batteries for consumer electronics**

- **With batteries for remote systems**





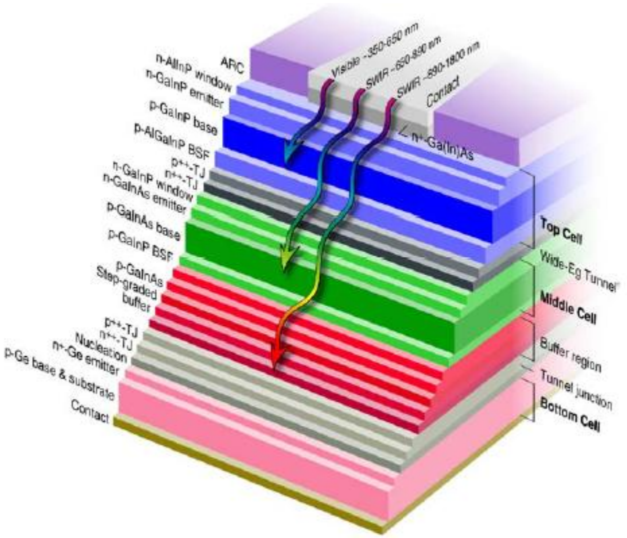
> 90's: Maturing technology & Grid connected plants

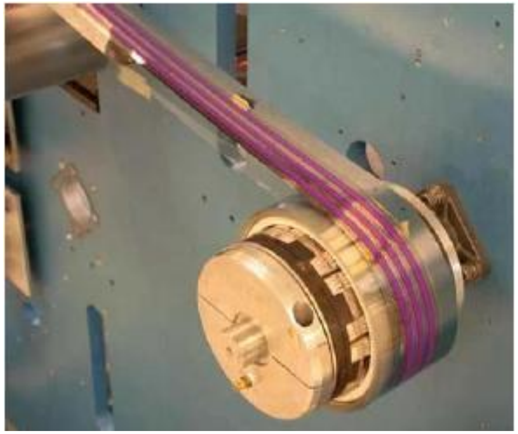
- **90's: Hybrid and organic cells**

  90: Dye cells >10%
- **94: Tandem cells under concentration >30%**
- **98: Thin films ~ 20 %**
- **99: PV cumulated prod. > 1 GWp worldwide**

  & first organic cell > 1%
- **2007: PV cumulated prod. > 10 GWp worldwid**

  & Tandem cells under concentration> 40%
- **2010: organic cells > 8%**





Building integration

Otha experiment 550 houses

with 4 kWp each

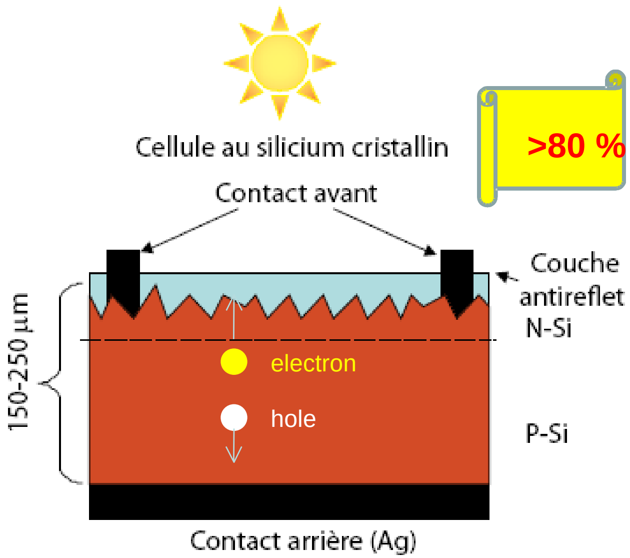
Solar farms

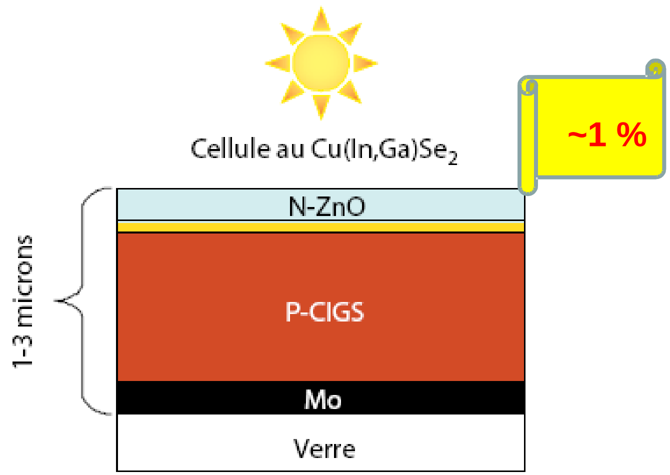
Sacramento (Californie) Parking de 1000 places, 540 kW.

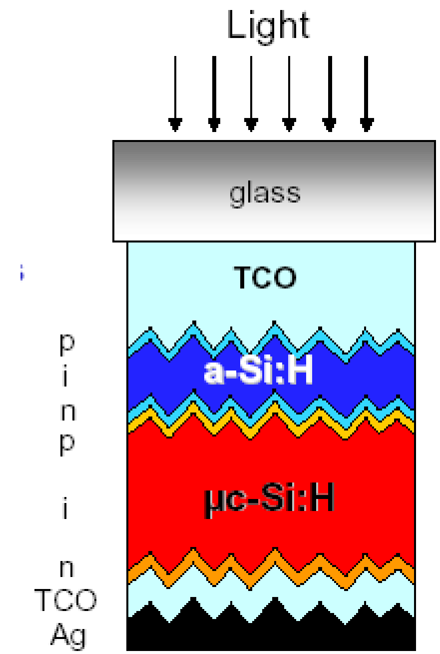
Transportation

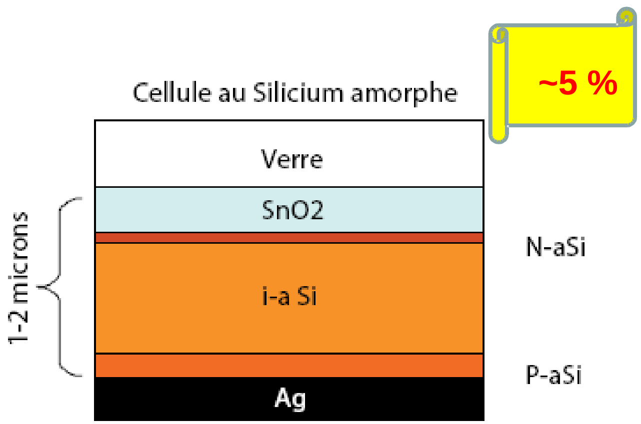
Future developments?

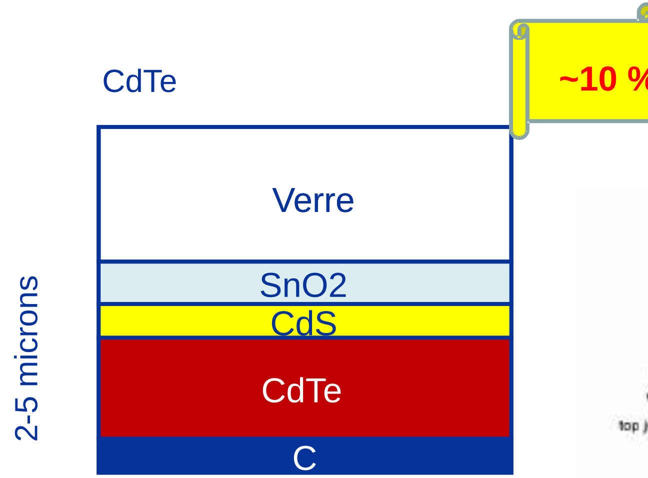
Many industrial technologies today

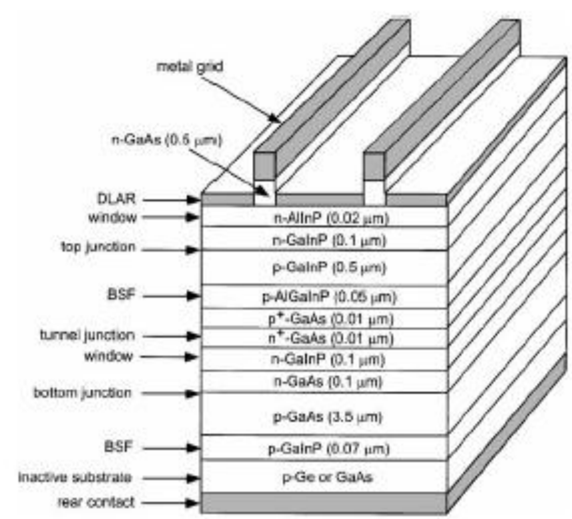




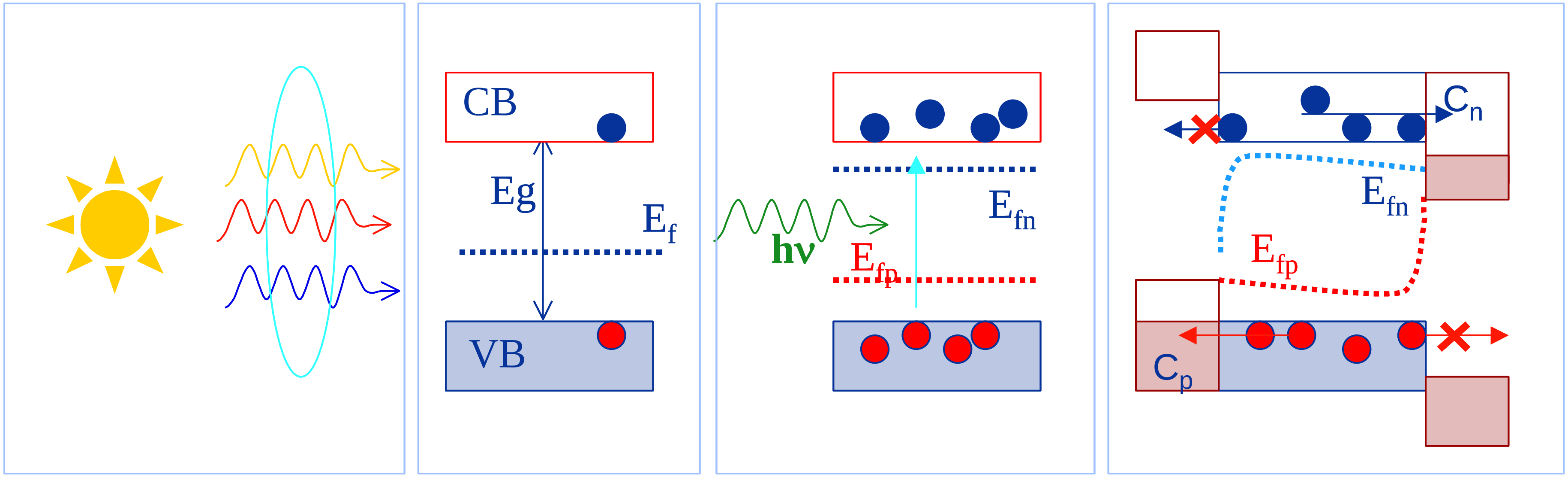








What they have in common: principles



Photon harvesting	Absorption hv (driving force)	Quasi equilibrium (lifetime >> Thermalisation)	Preferential collection at contacts (transit time << lifetime)

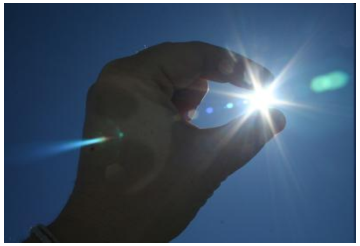
Work/photon : $qV = \Delta E_f$

$h\nu > Eg > \Delta E_f$ (Radiative Limit : $\Delta E_f \approx$ **Eg**)

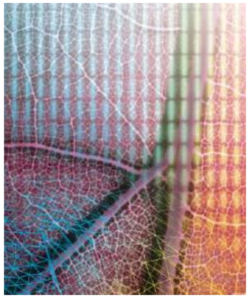
=> Fundamental limit to conversion

Direct conversion?

Fusion



Electromagnetic



Chemical

Electricity

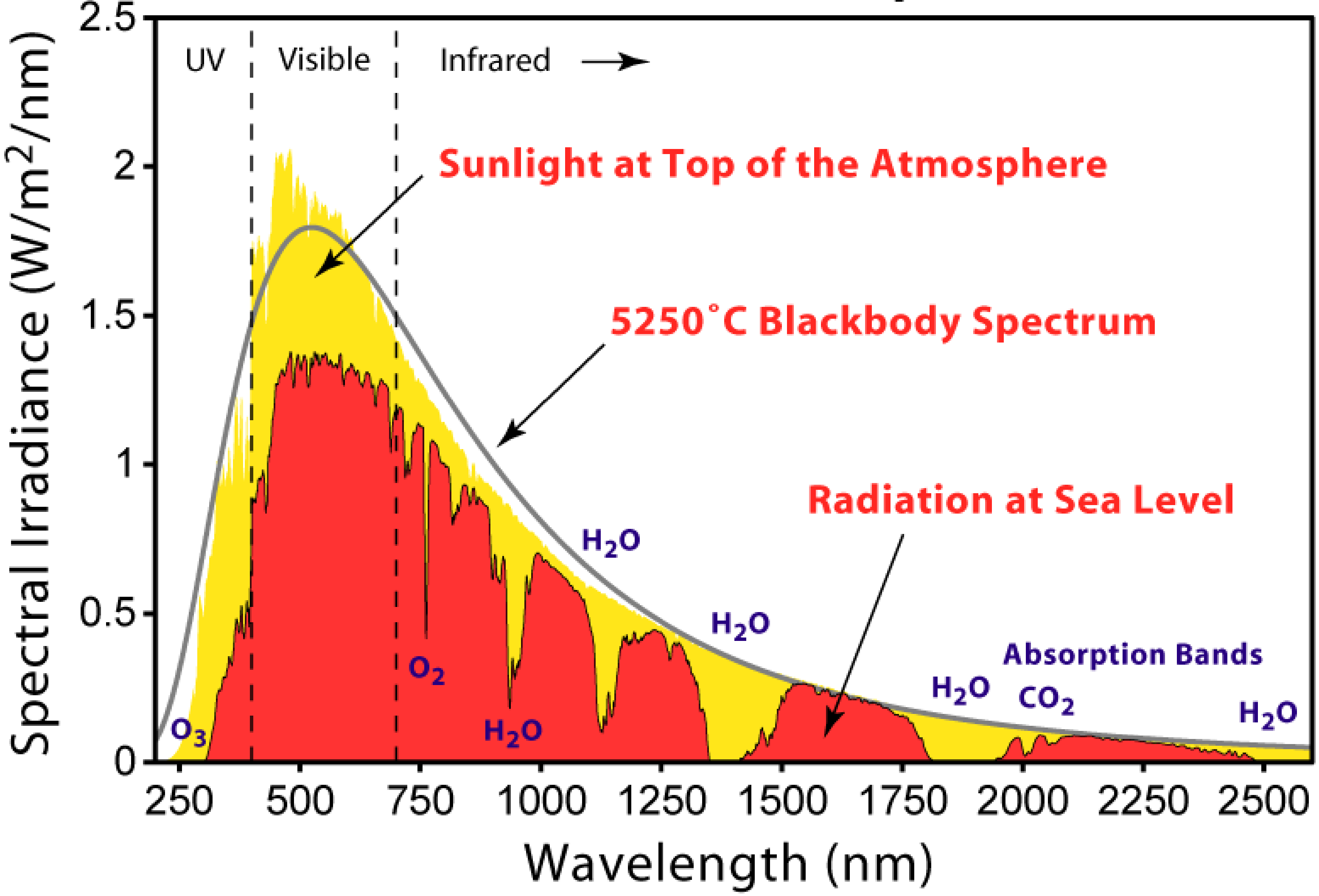
Entropy production at each step

Can be minimized if

- good absorptivity of active material
- little parasitic recombination
- good charge transport

=> semiconductors

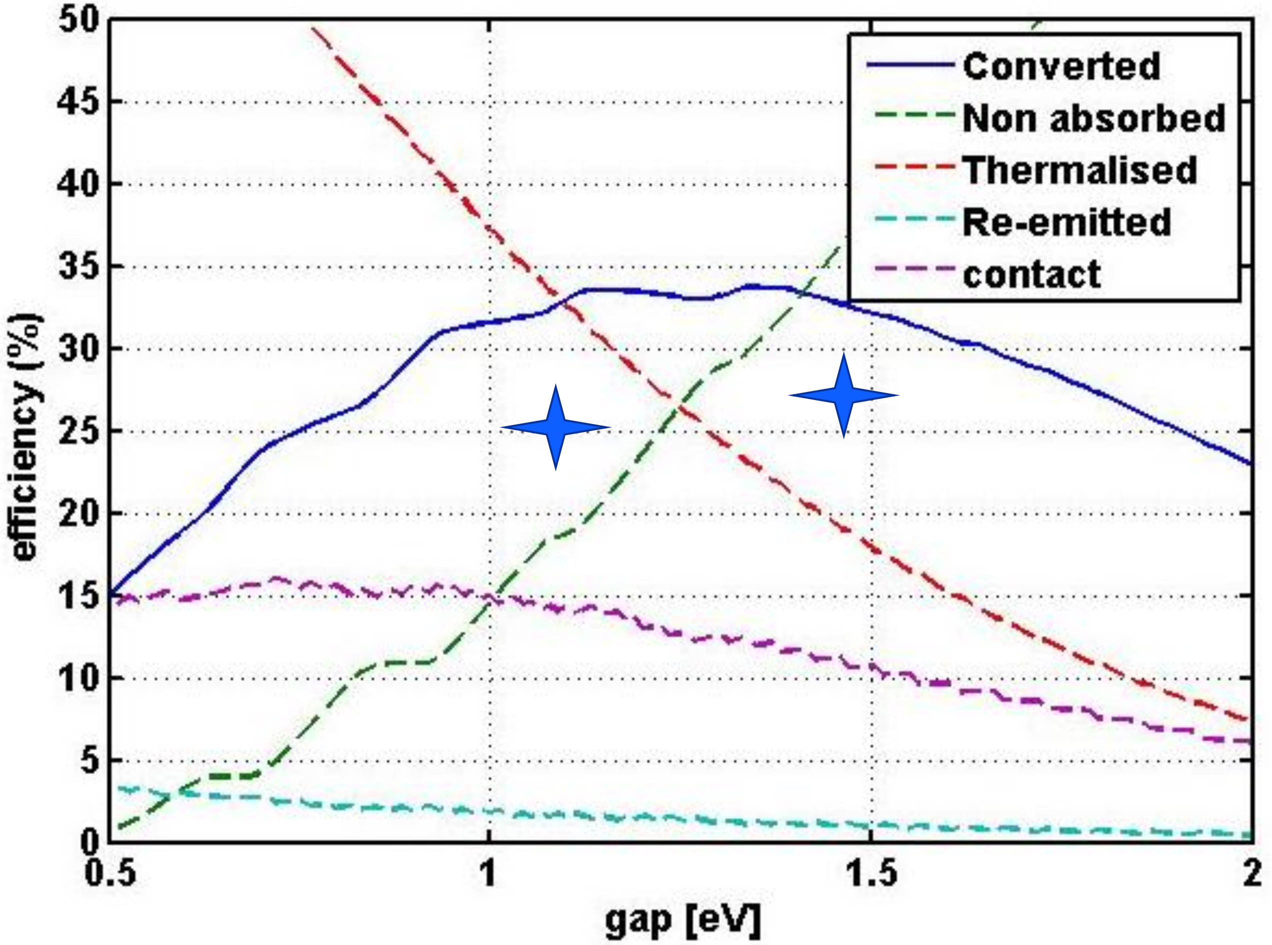
Solar Radiation Spectrum



1 to > 2 MWh/m²/year

AM = $(\sin\alpha)^{-1}$

Limits of semiconductor devices



Optimal gap: 1 to 1.6 eV

J-V Characteristic

Current balance

$I=q(n_{abs}-n_{rec})$
$n_{rec} \sim n.p \sim \exp(qV/kT)$

=> Schockley eqn.

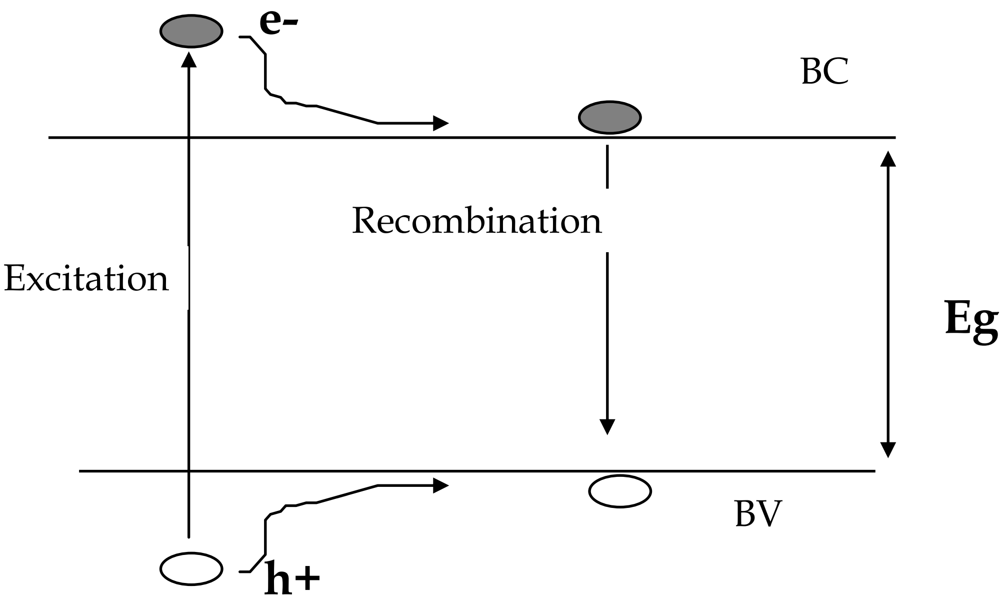
Law of mass action

$qV = Ef_n - Ef_p$

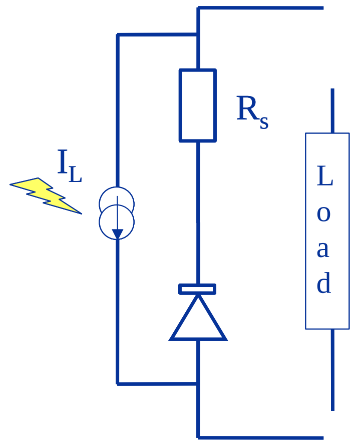
$Ef_n \sim E_c + kT.\ln(n/N_c)$

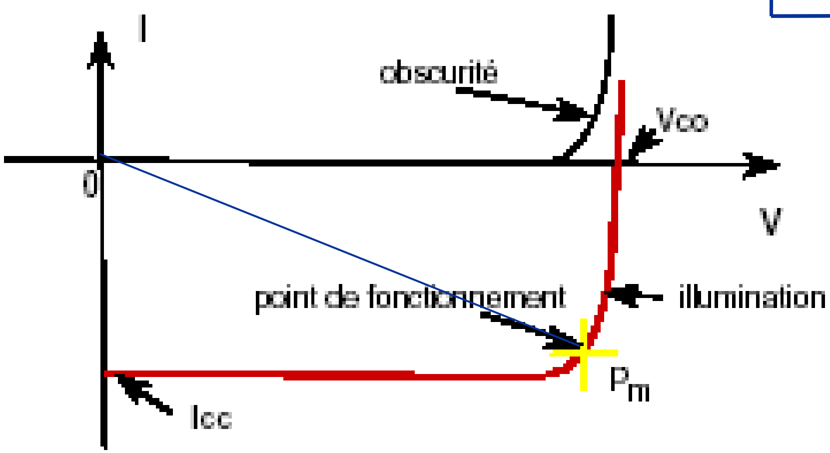
$Ef_p \sim E_v - kT.\ln(p/N_v)$

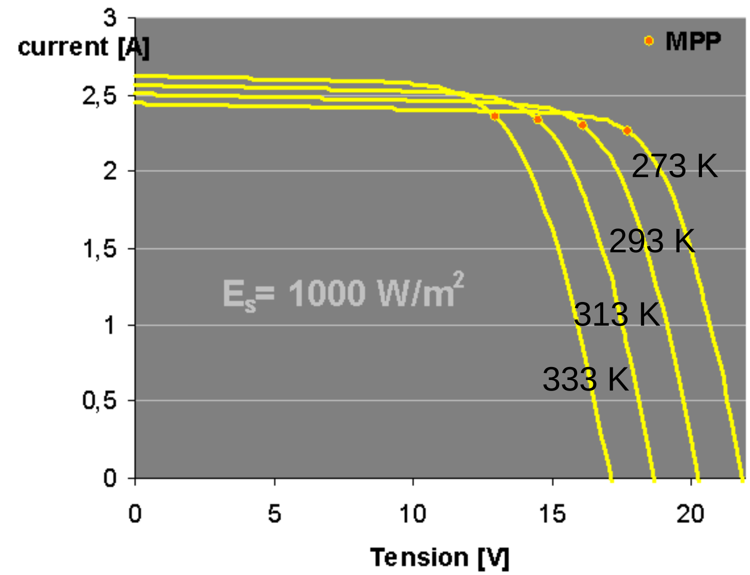
$n.p \sim \exp(qV/kT)$

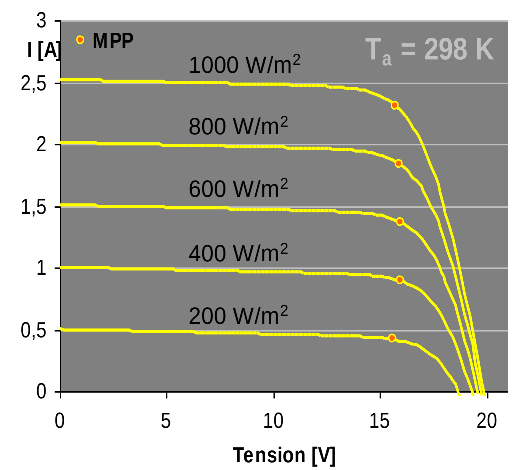


Electric power









Power extracted is a function of operating point : P=V.I

Typical load: 25 Ω.cm²

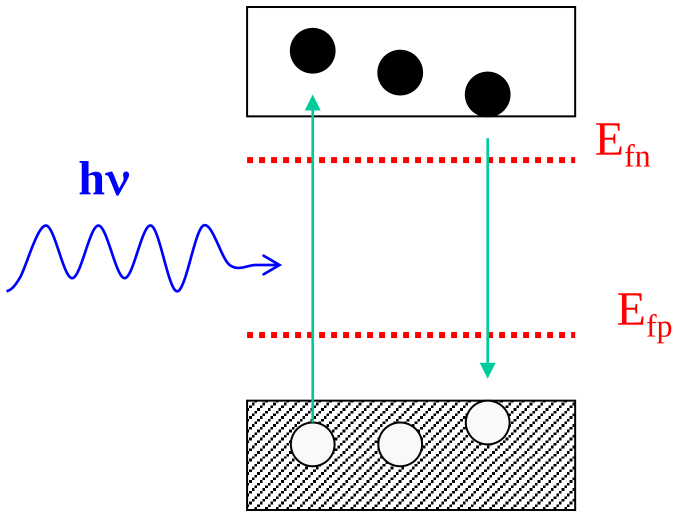
Also depends on temperature and illumination level

Concentration

$V = \Delta E_f \sim \log(p.n)$

=> Solar Concentration helps

=> Small generation volume also



Triple transport problem :

- ✓ **Photons**
- ✓ **Electrons**
- ✓ **Heat**

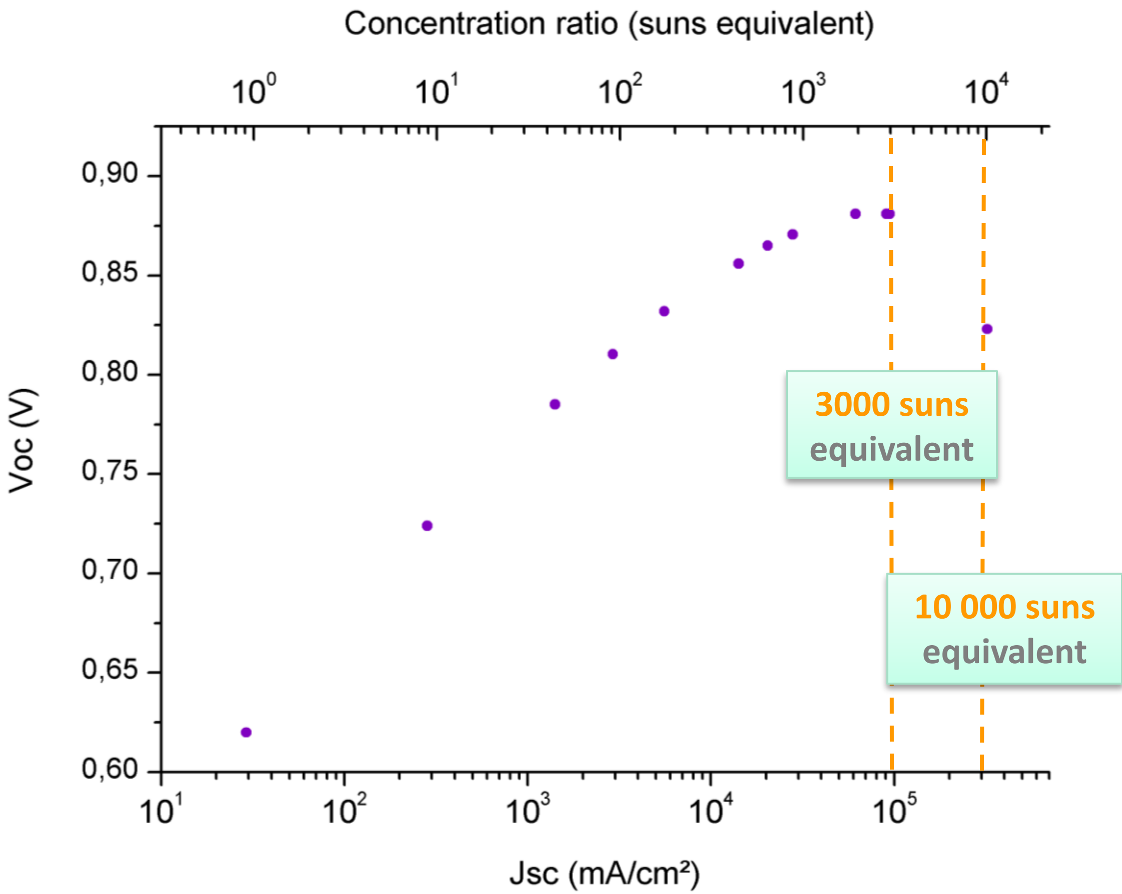
Microcells for very high concentration

Microcell down to 7 µm diameter

Maximum **Voc = 881mV** corresponding to a **Jsc = 61.6 A/cm²**

Voc increases up to
3 000 suns equivalent

Microcell tested up to
40 000 suns equivalent



(IRDEP & LPN)

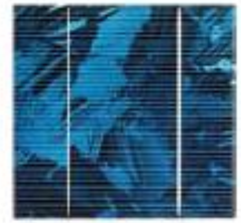
Increasing efficiency, low CIGS utilisation

Paire et al. JAP 2010, EUPVSEC 2010, APL 2011,

Crystalline Silicon

Silicon

Wafer



Solar Cell

Solar Module

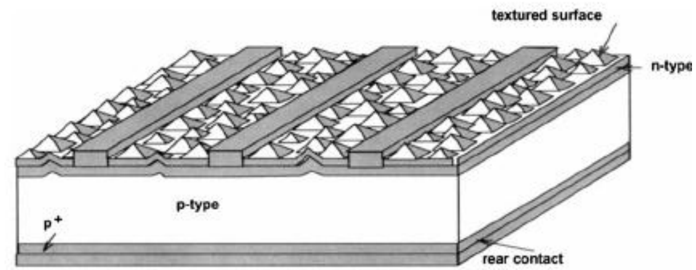
Sate of the art:

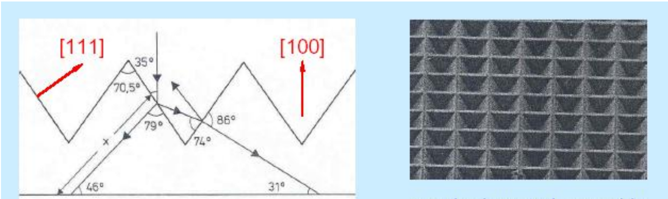
25% lab efficiency

> 20% at module level,

Stable > 30 years

Needs ~ 7g/Wp (Si indirect absorber)



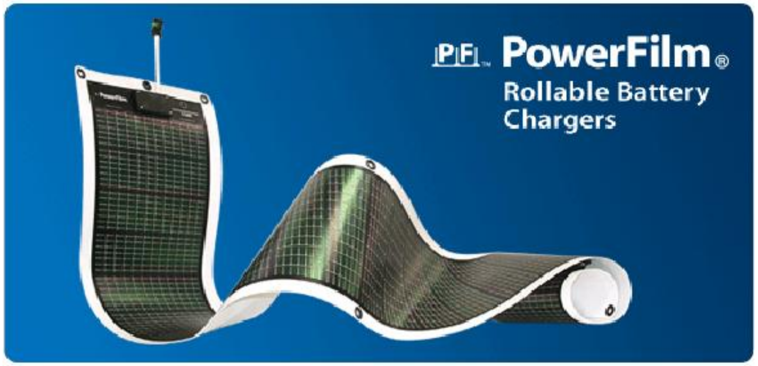


regular inverted pyramids

Silicon consumption: 200 000 t for solar (>> microelectronics)

Mature technology

Thin Films



Only µm thick layers needed

Fast deposition processes, automation

Flexible large areas (a-Si:H)

Good efficiencies (CIGS):

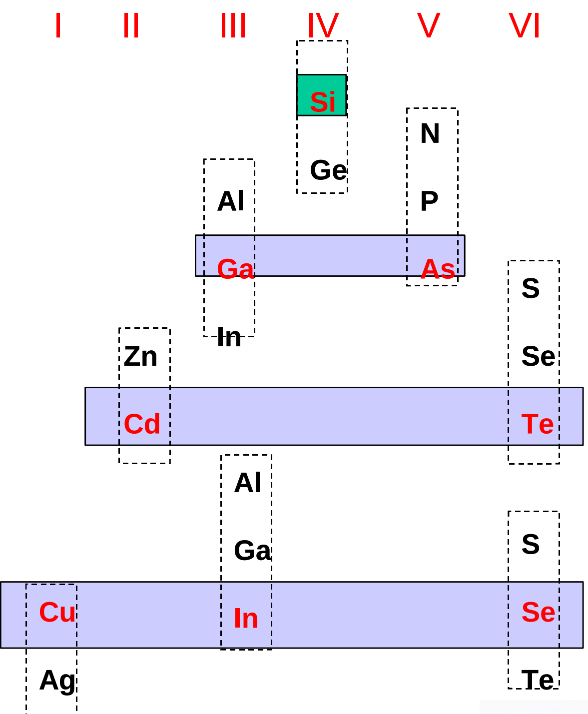
>20% lab. scale

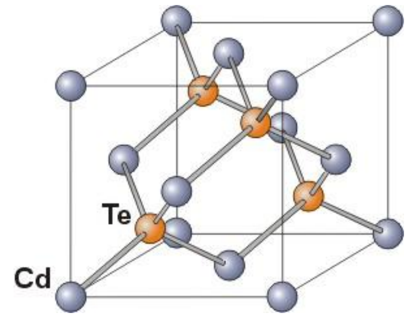
13% industrial scale

Lowest cost : 0.75 $/Wp (CdTe)

Getting industrially mature

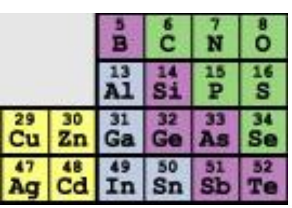
New materials

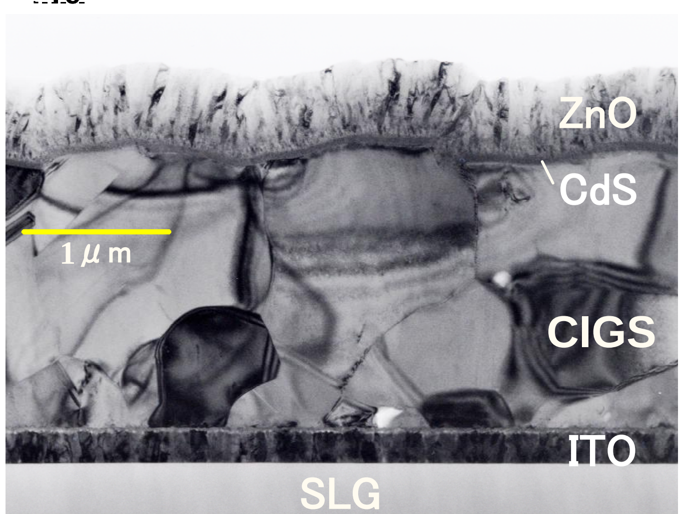




4 e-/atom rule

- All semiconductors for optoelectronics have the same structure
- In more ionics ones, native disorder/defects can be accommodated more easily
- Self-healing sometimes observed
- Chemically challenging device structures but property tailoring abilities!



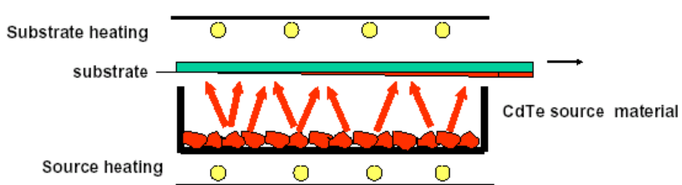


New processes for optoelectronic grade semiconductors

- From metallurgy to vacuum processes to soft chemistry routes
- Moderate to low temperatures (new substrates)
- **But still functionnal materials!**

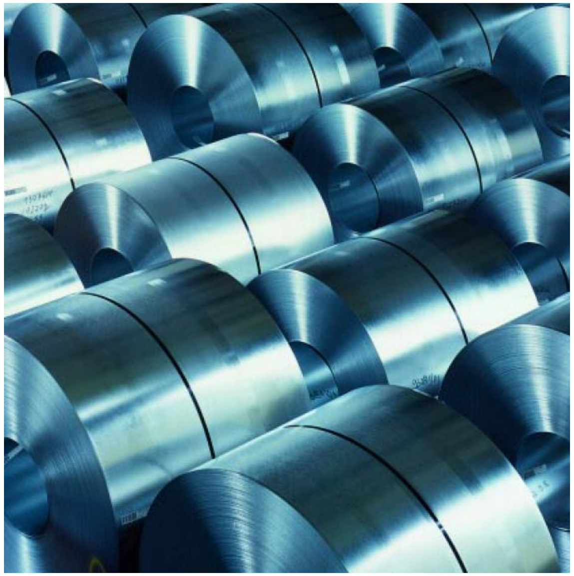
Cluster tool
for plate glass substrates

Plasma processes



Evaporation (CSVT) processes

Electrodeposition, inkjet



Deployment

Growth : 40% / year sustained

2008: 12 TWh produced

Capacity additions:

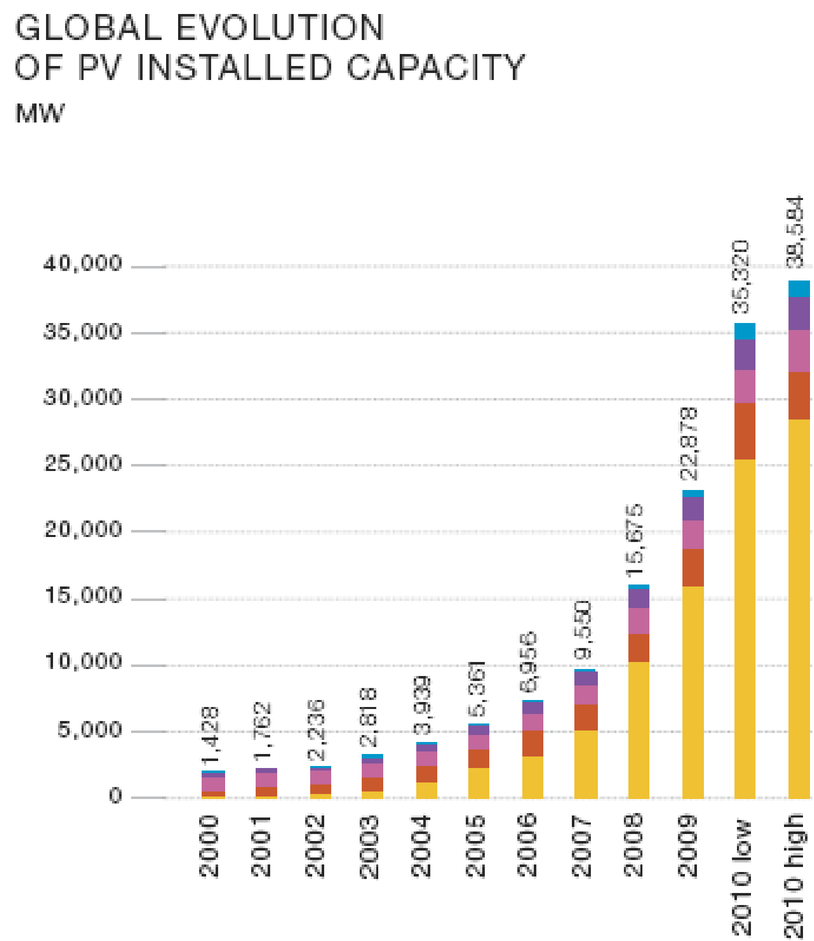
+ Combustible Fuels	17	GWh
+ Nuclear	- 76	GWh
+ Hydro	25	GWh
+ Other renewables	166	GWh

2006-2010

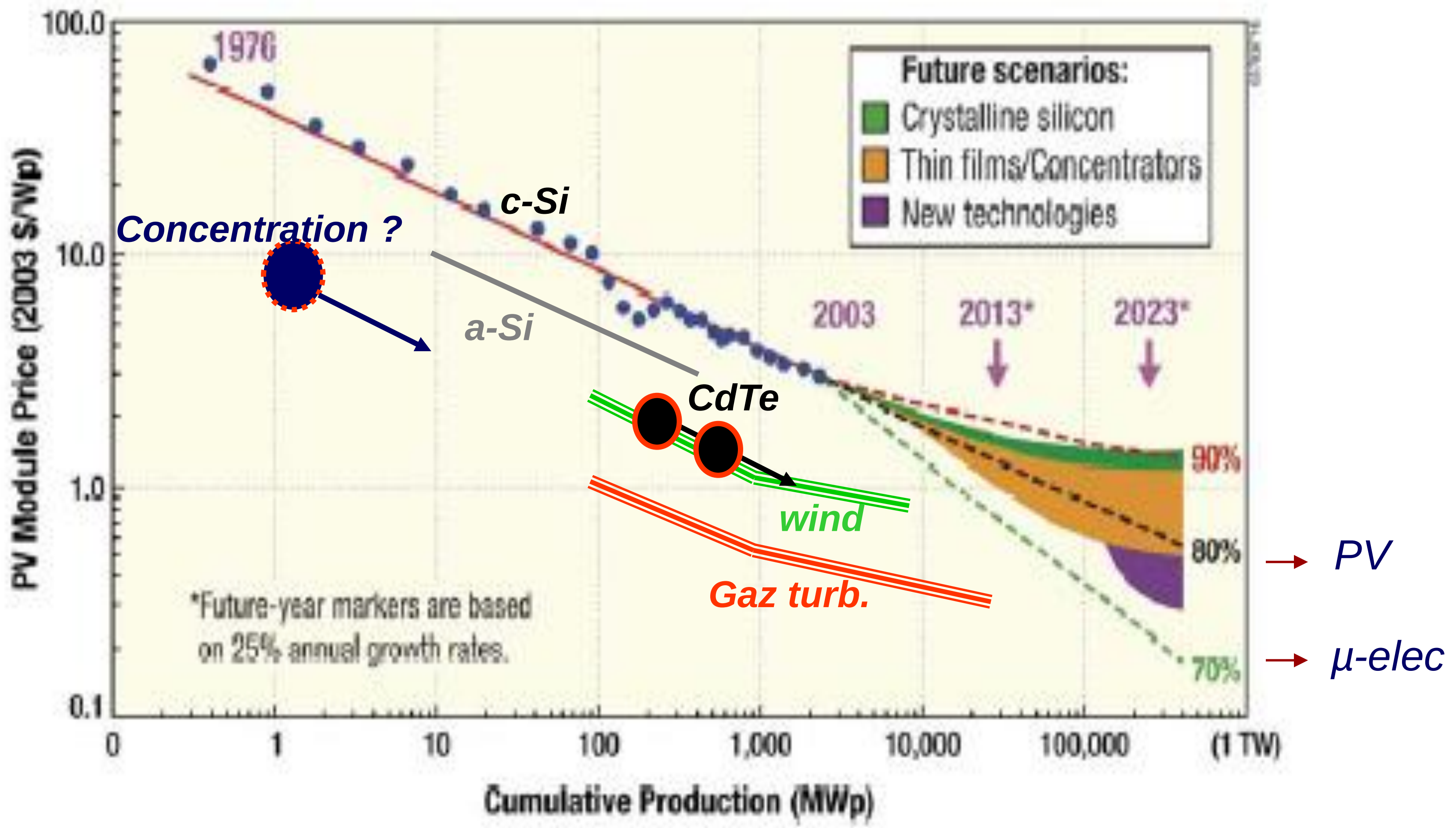
In OECD, mainly renewables

2010: > 2 large power plant/year

NB: capacity factor 10-25%



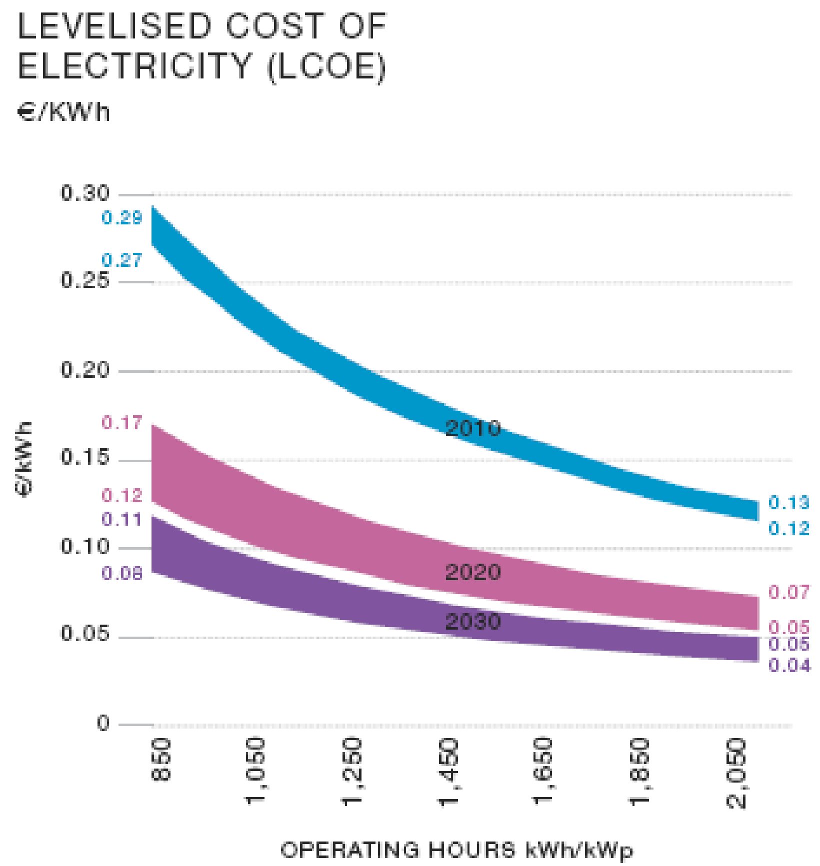
Learning curves (modules)



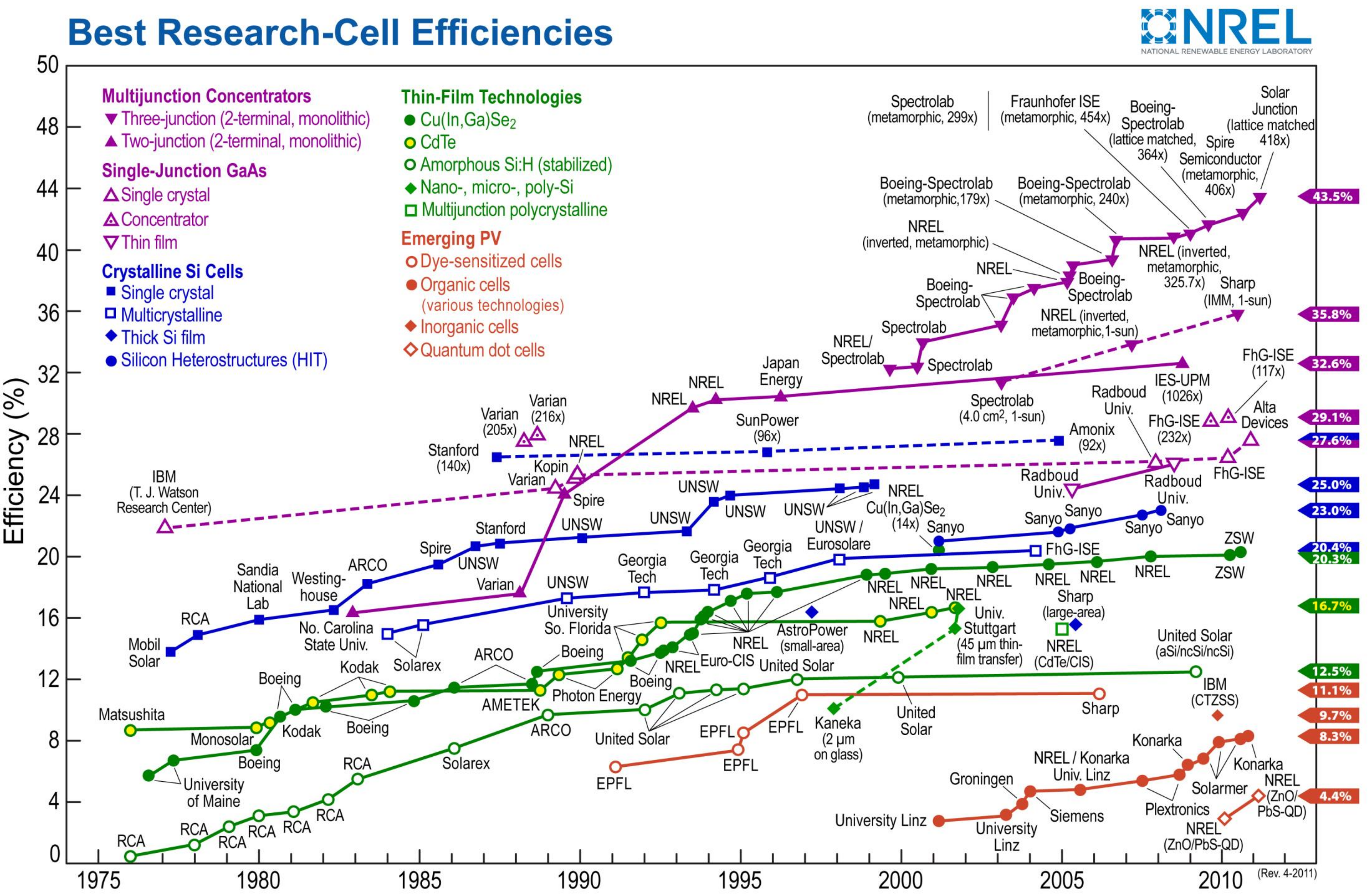
Learning curve on full systems?

Quick facts

- ***Performance***
  - *> 20 % commercially*
- ***Stability***
  - *> 25 yrs*
  - *energy payback < 2 yrs*
- ***Cost***
  - *2.5 €/Wp installed ,*
  - *15 cts/kWh (best practice)*
- ***Growth of PV***
  - *30-40%/yr, > 5 GW/yr since 2008*
  - *40 GWp installed*
- ***Storage for grid application >10-20% of the energy mix***

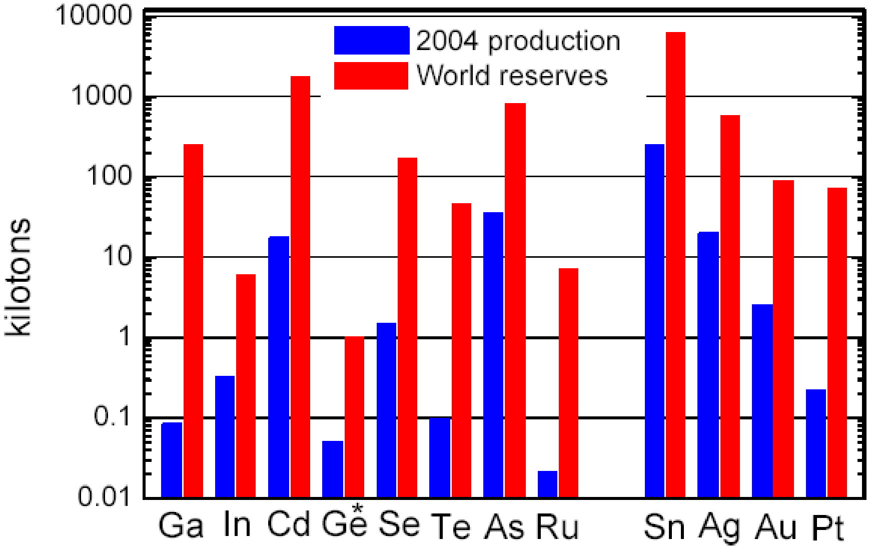


Best Research-Cell Efficiencies



Availability of materials

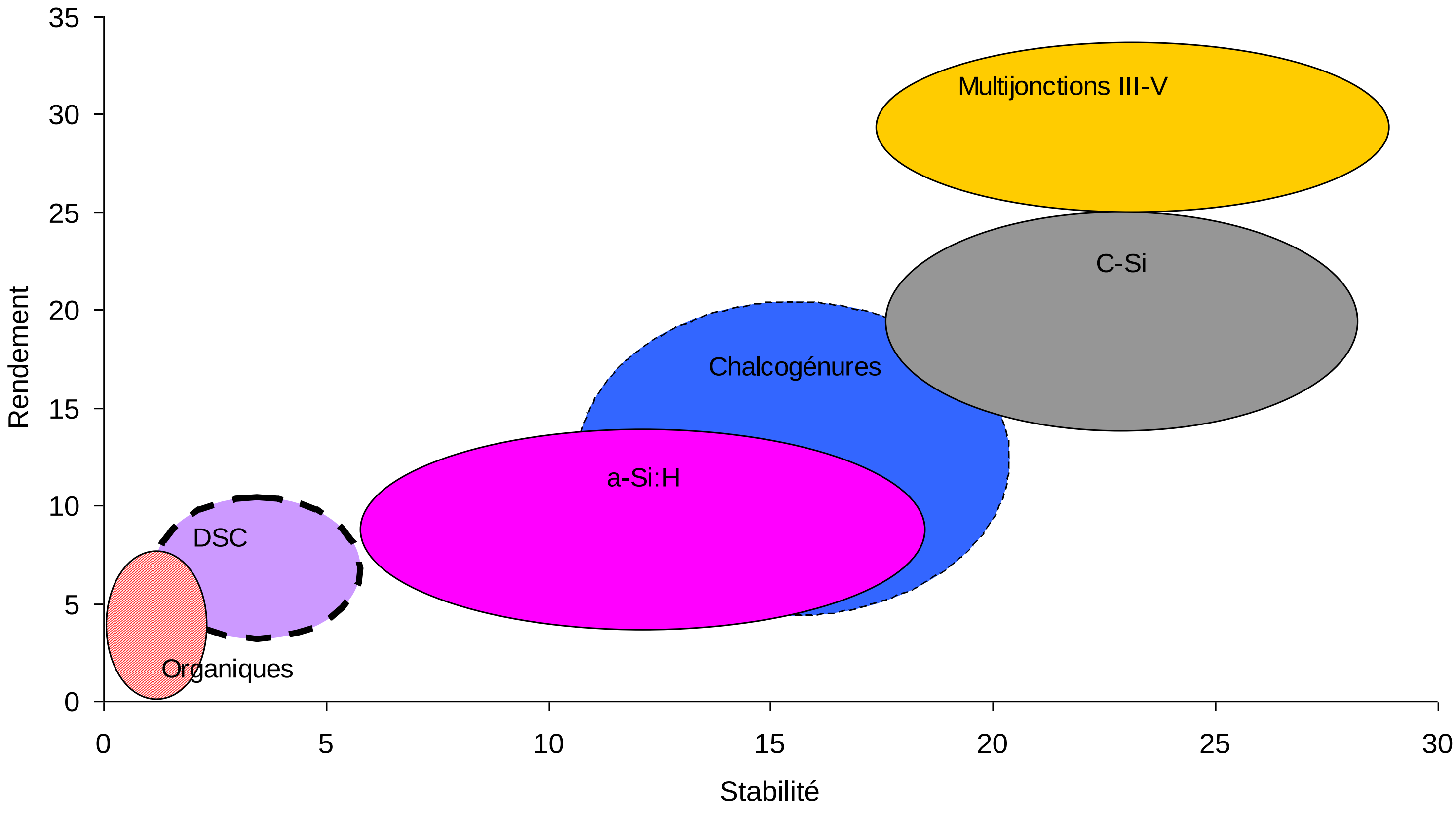
- **Si**
  - Electronic grade: capacity issue
  - also Ag => < 1-2 TWp
- **Thin films**
  - In, Te, Ru: < 300 t/yr
  - Limit now: 5-10 GWp/yr
  - Limit (foreseeable): **50-100** GWp/yr for CdTe, CIGS
- **Tandem**
  - Ge substrate ! => 15 GWp unless lift-off



US geol. survey

From Freundlich 06

PV Materials



Materials: optical ➚, size ➘, chemistry ➚

Processes: metallurgy ➔ thin film ➔ soft chemistry

Concepts : planar junction, interpenetrated junction, … ?

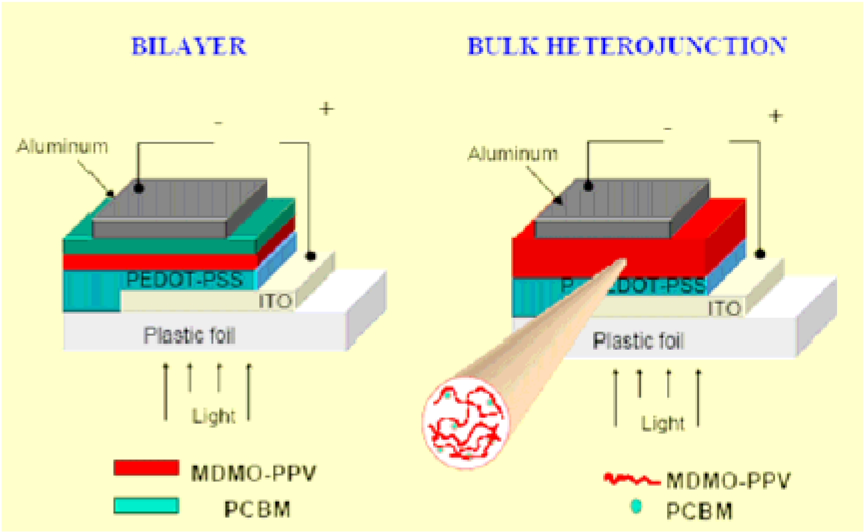
2

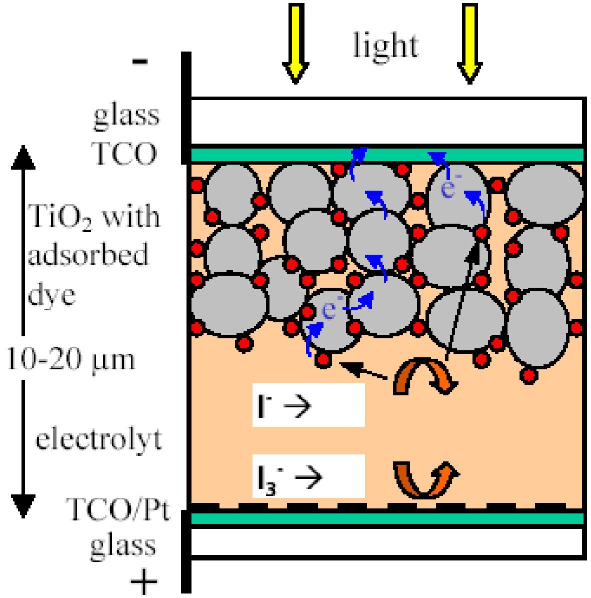
II- Challenges

Challenges

- Photovoltaic solar energy should
  - be more affordable
    - towards very cheap materials and processes
  - be more efficient
    - also to reduce full system cost and footprint
  - take into account the full life cycle
    - toxicity, abundance of materials, …
  - blend itself well in the grid (storage?), in the city (design?), …

Very low cost approach





Organics: absorption +, mobility -, processing ++

Concept: interpenetrated systems

Materials:

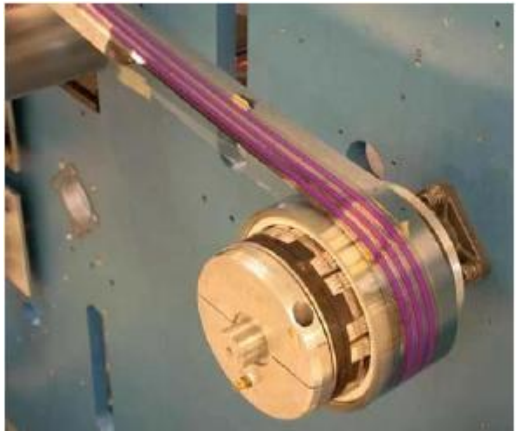
Organics OLED type (8%)

Hybrid Systems (12%)

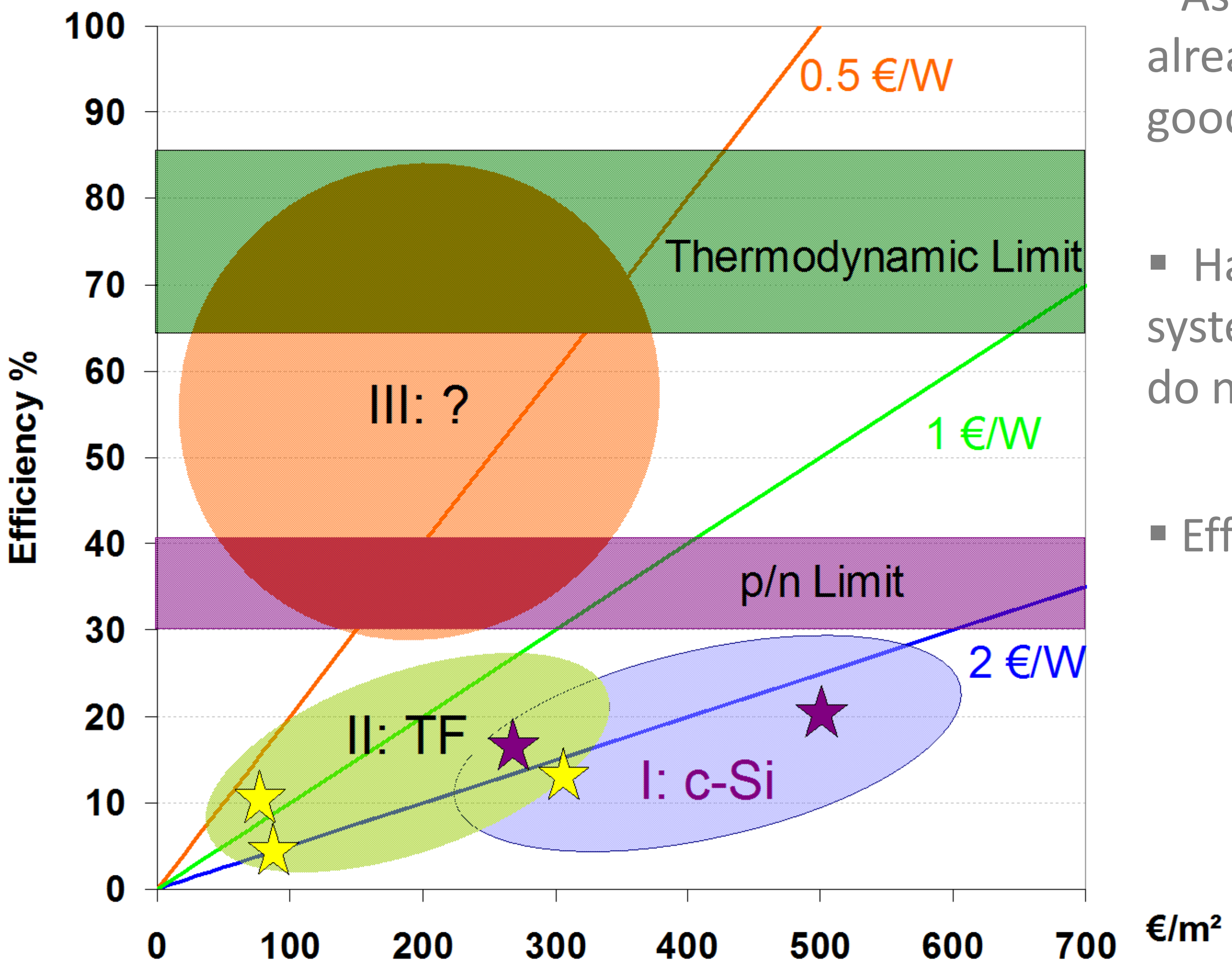
Nouveaux procédés possibles (self assembly, to a point)

Stability ??

Still at R&D stage, with early attempts at commercialization

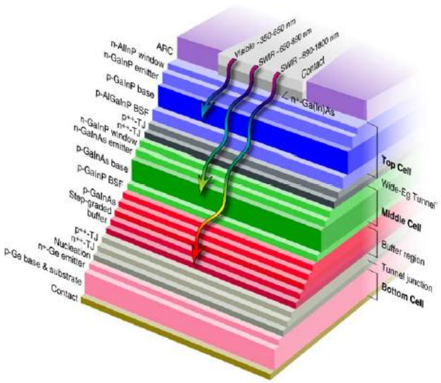


Very High efficiency approach



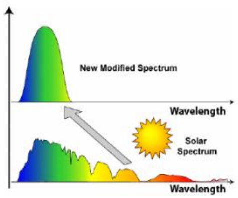
- As surface costs are already low, efficiency is a good driver
- Has also an impact on full system cost (free modules do not yield free electricity!)
- Efficiency limit:
  - Carnot : 95 %
  - Multicolor: 87 %
  - Depends on concentration level!

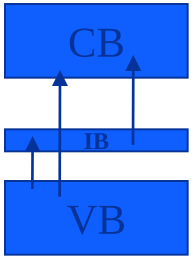
Pathways

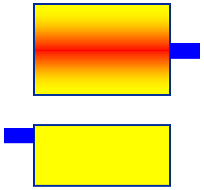


Through better use of solar spectrum

- Concentration (classical+near field optics)
- Multi-jonctions
- Up/down conversion
- Intermediate Bands
- Multiple exciton generation
- Hot carriers
- …



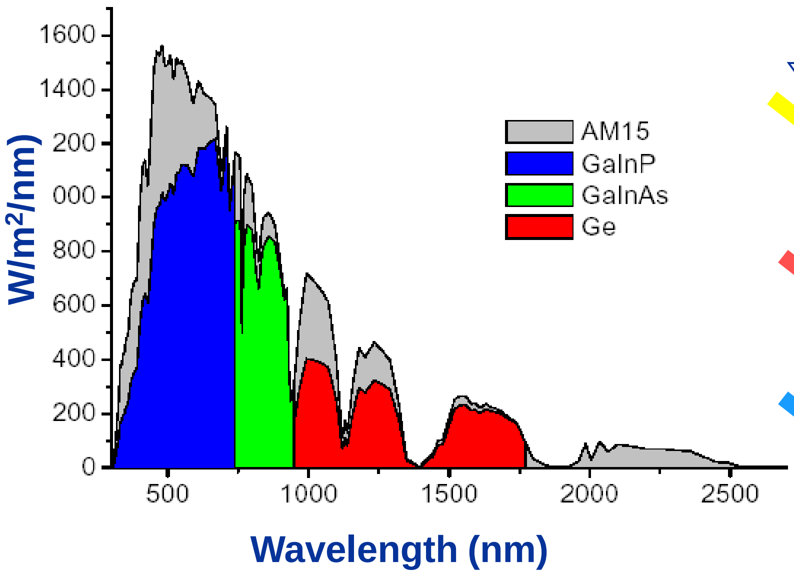


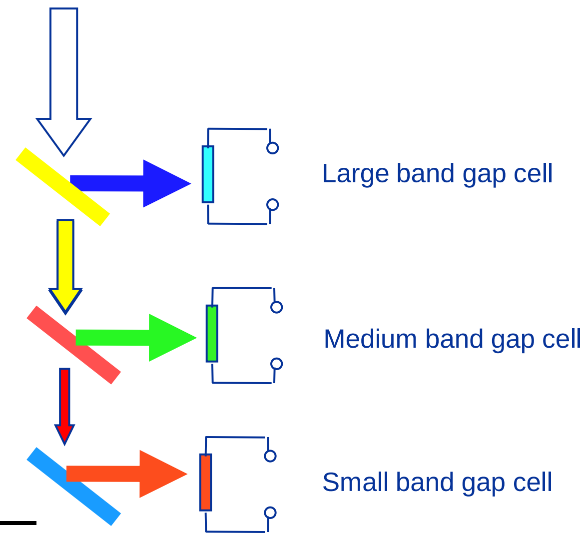


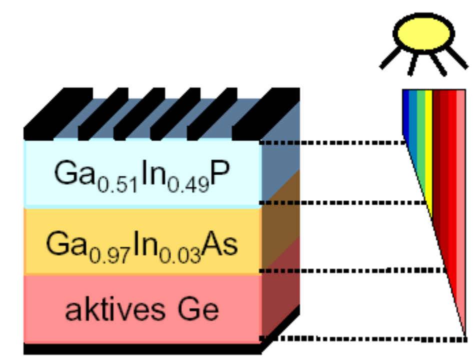
Concentration > 500x

Triple junctions > 40%

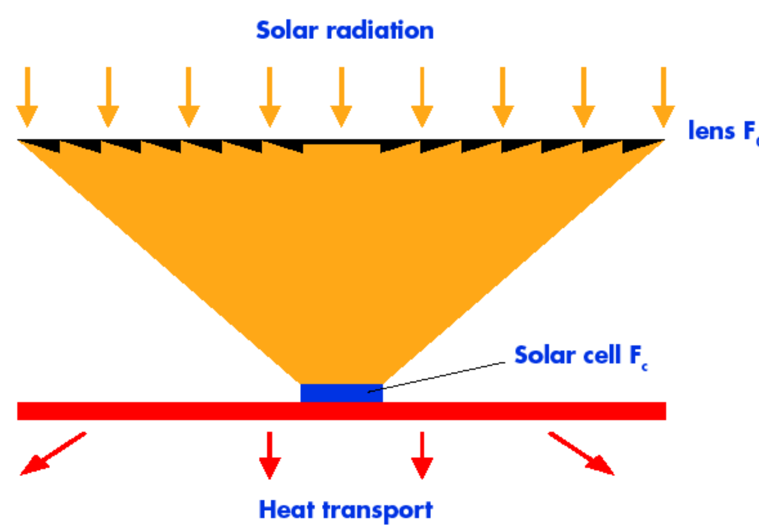
Multijunction principle



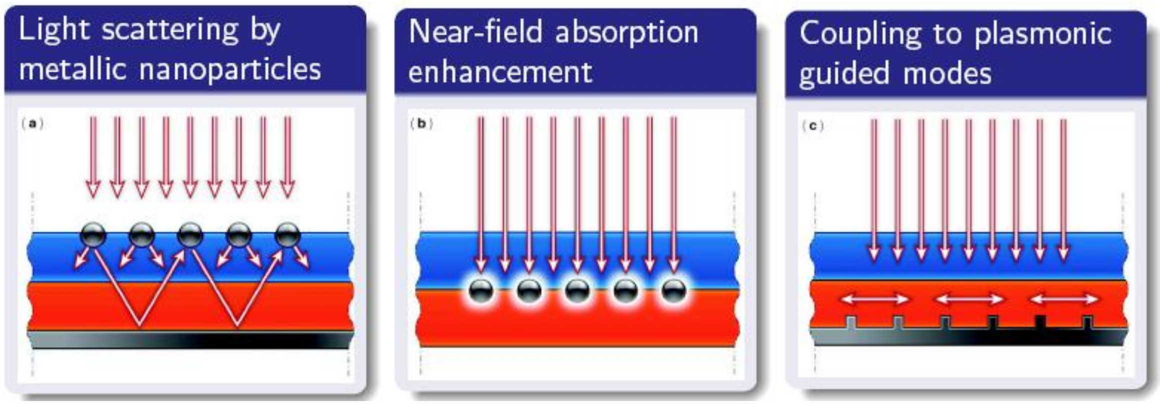




- From unoptimal broadband converters to spectrum range specific devices
- Several designs possible
- Now: 43.5 % (400-1000 suns)



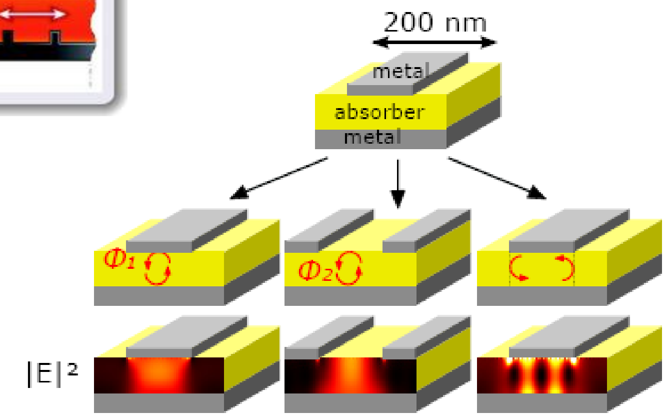
Concentration

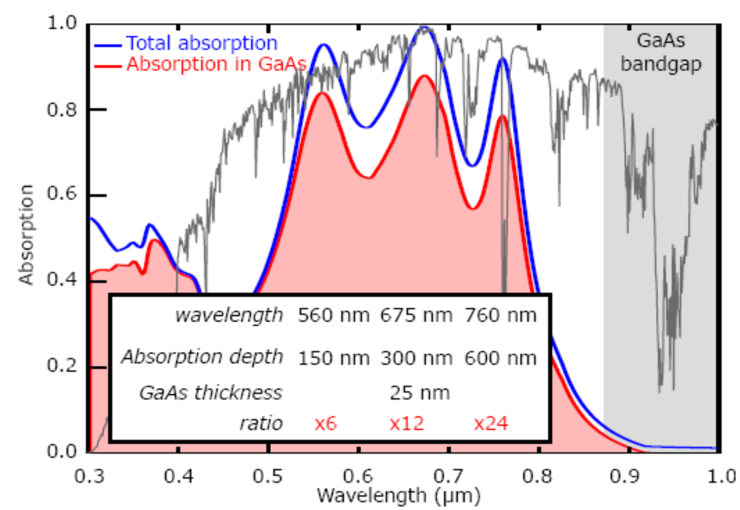


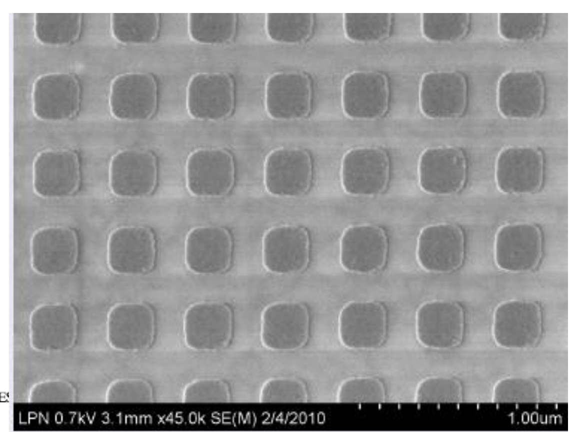
Attwater & Polman 2010

- Plasmons, photonic cystals help enhance absorption by thin layers

- > 70 % absorption possible in ultra thin layers (25 nm, 100x thinner than standard)

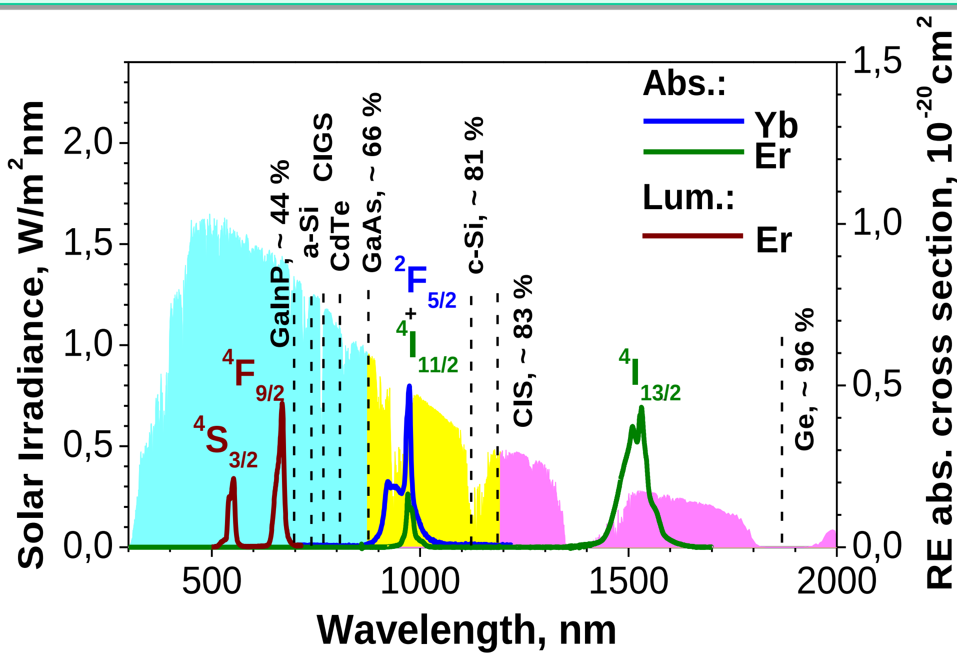


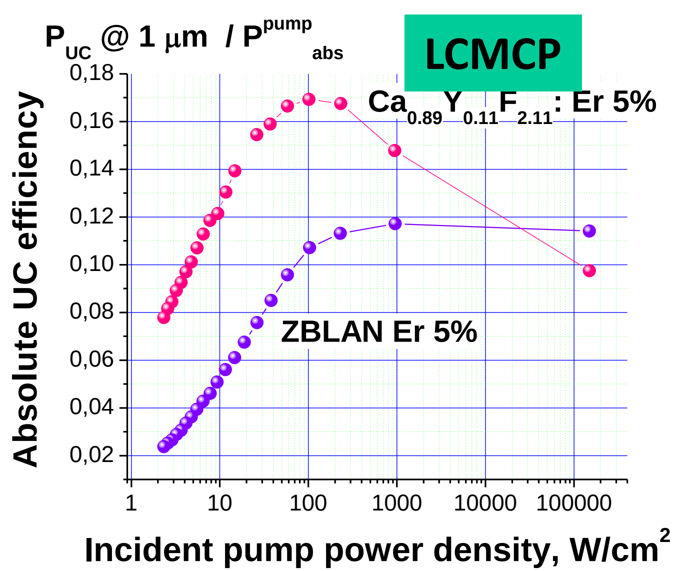




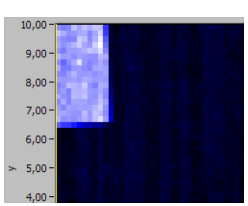
LABORATOIRE
DE PHOTONIQUE
ET DE NANOSTRUCTURES

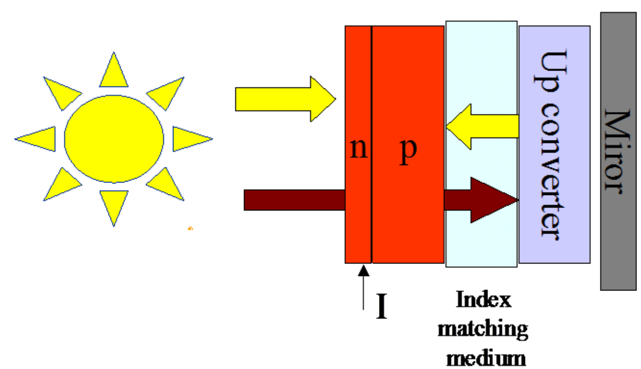
Photons Conversion





- Large gain (200-400 W/m² unadressed)
- Ease of implementation
- Up conversion requires high concentration (2 photons)
- Benefits from nanophotonic approaches (E⁴ factor) demonstrated

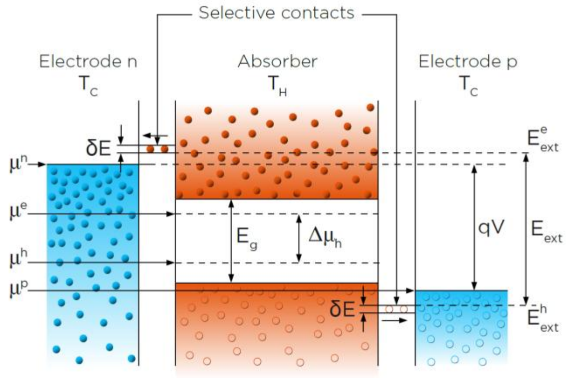




Hot carriers: the ultimate PV device?

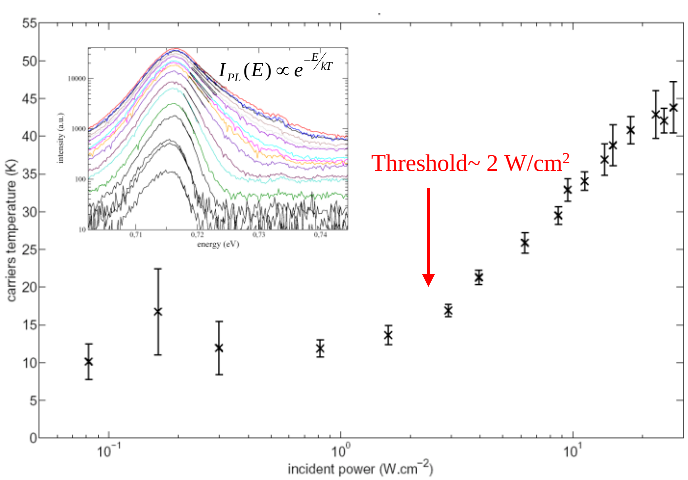
- Tapping into the fraction turned into heat

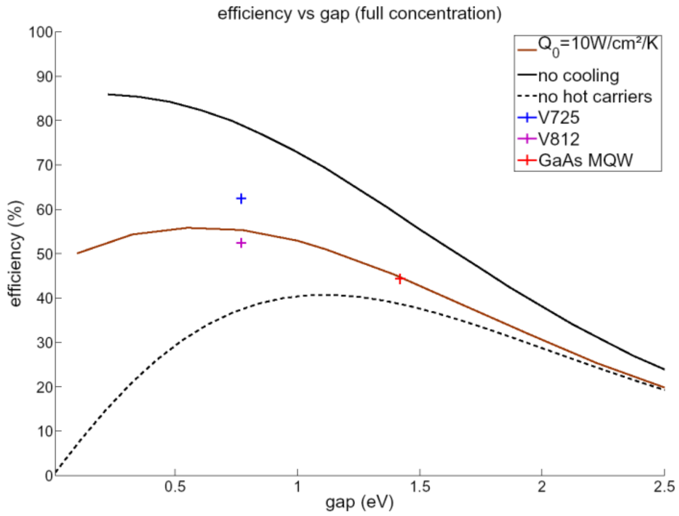
  $\Rightarrow$ thermoelectric conversion of hot carriers



- Theoretical efficiency close to the thermodynamic limit (85%)

- First observations promising, 50% eff. possible





3

III- Summary

Take home message

- Solar energy is sustainable
- PV is technologically mature
- Yet it has still room to improve and develop further

Fusion Harnessed!

Acknowledgements

IRDEP & colleagues