ECOCLIM 2018

Ecole ECOCLIM2018

Le solaire photovoltaïque

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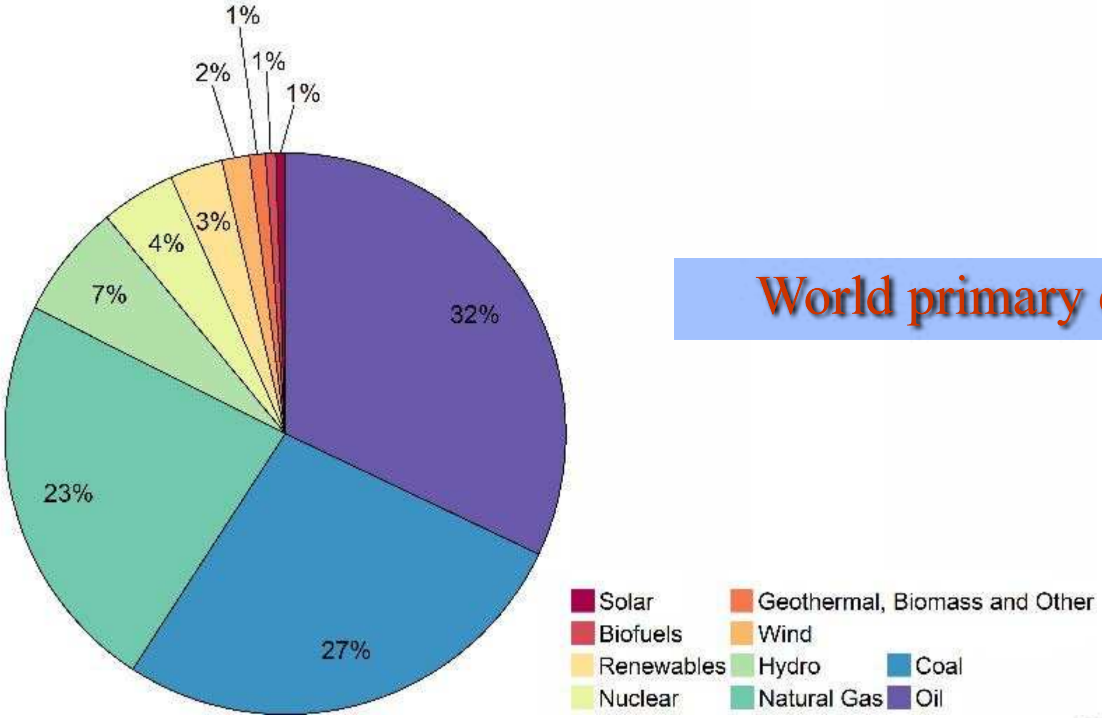
Summary

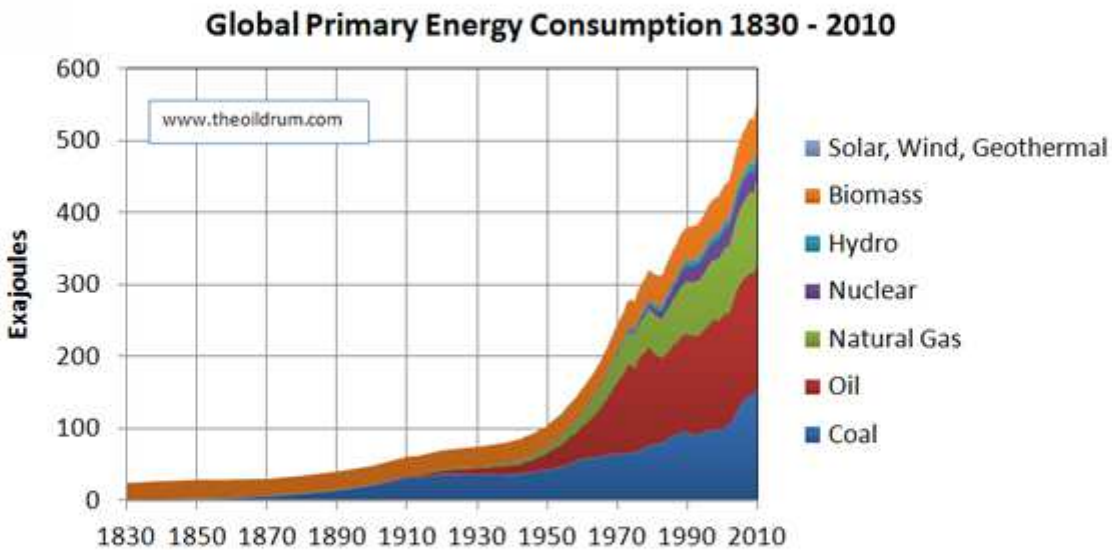
- Energetic context
- Solar cells: Operating principle
- Comparison crystalline/amorphous silicon cells
- Photovoltaic industries

Energetic context

Energetic context (I)



World primary energy consumption 2016

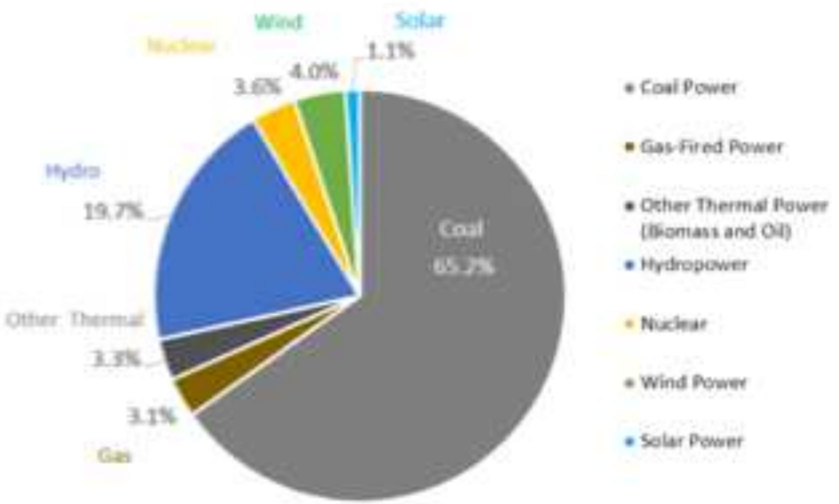


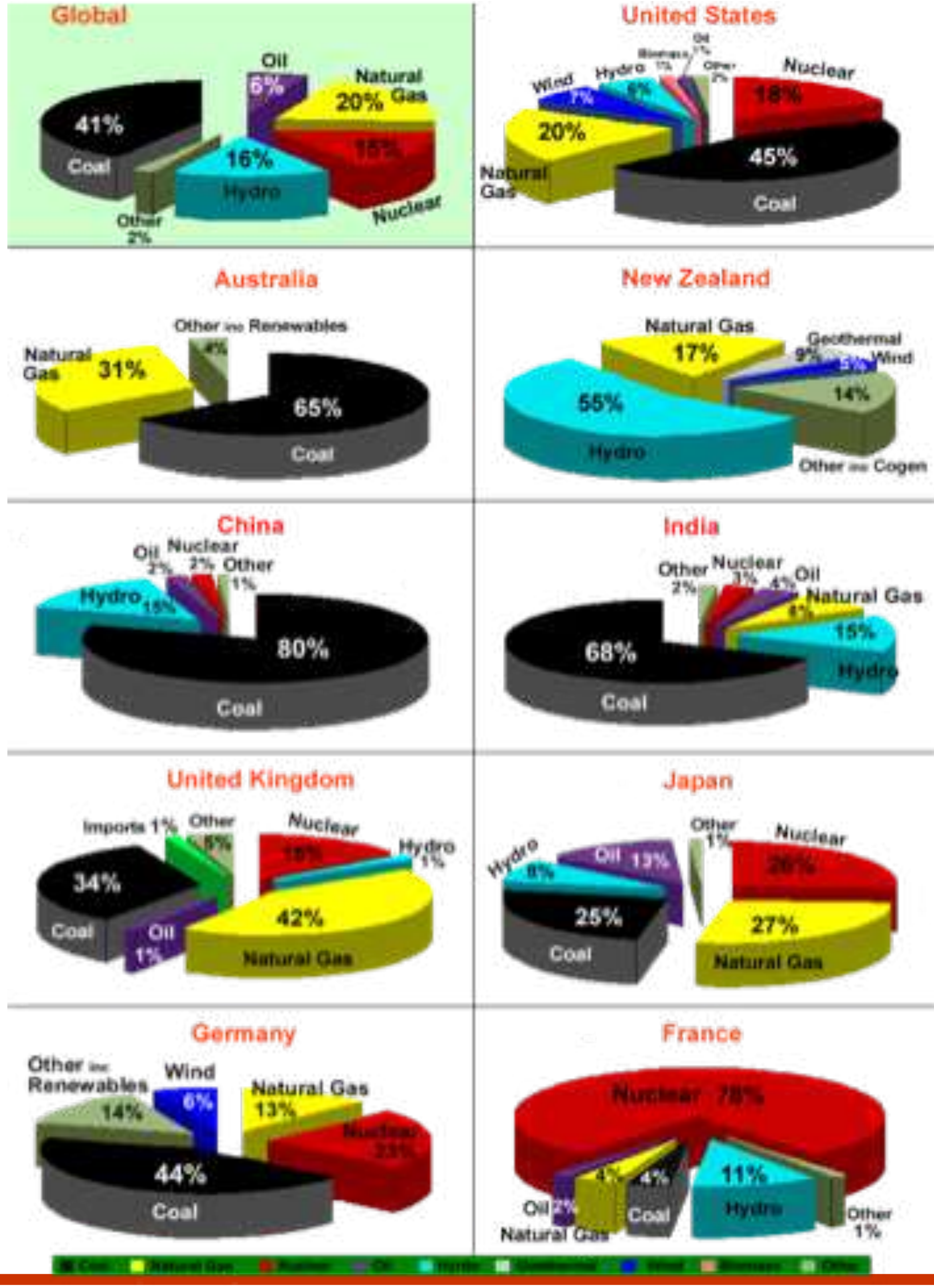
World energy consumption Dominated by fossil energies Strong increase still 1950

Energetic context (II)

Electricity production strongly influenced by national policies (2010)

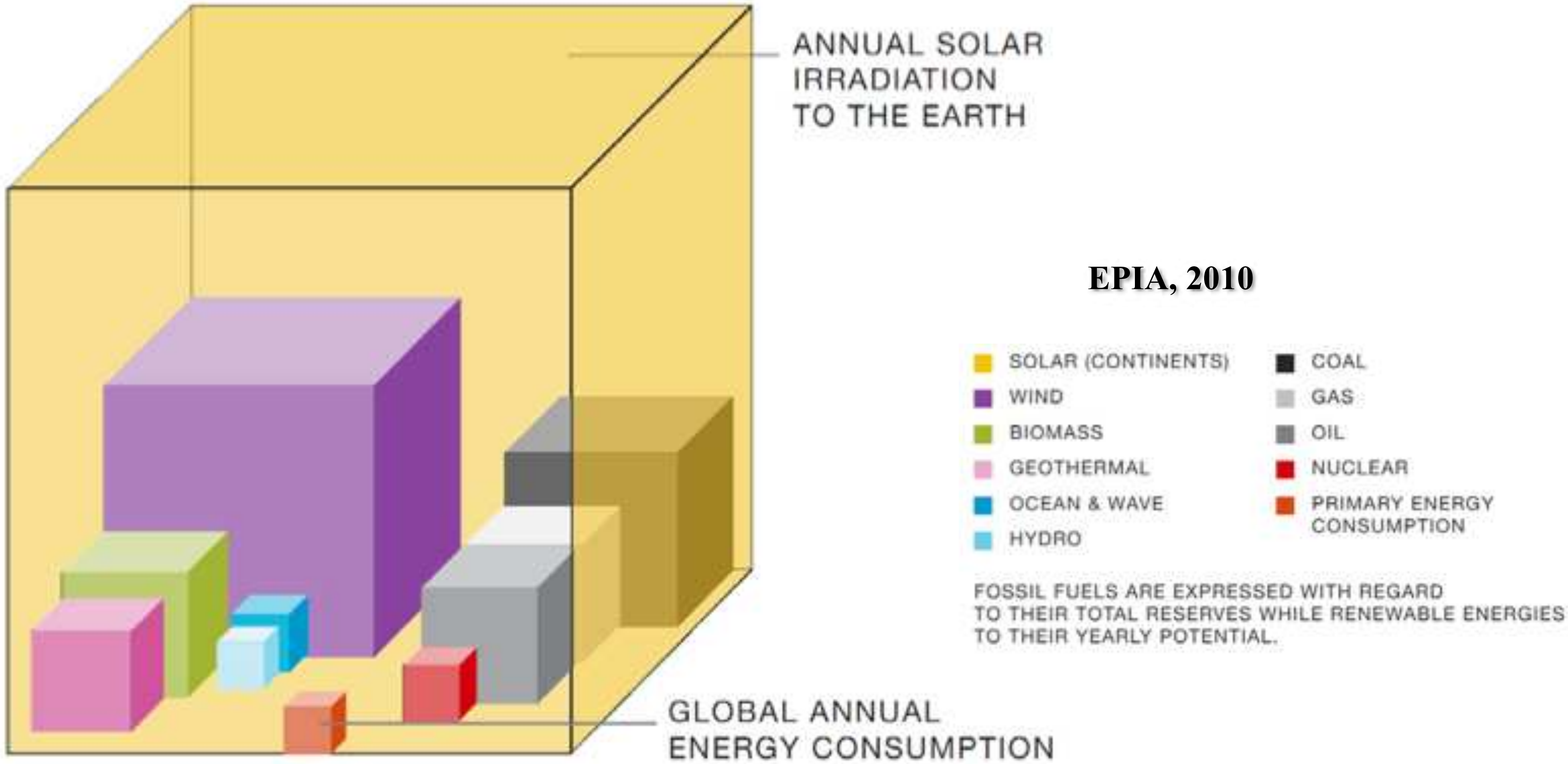
China's 2016 Power Generation Mix





Energetic context (III)

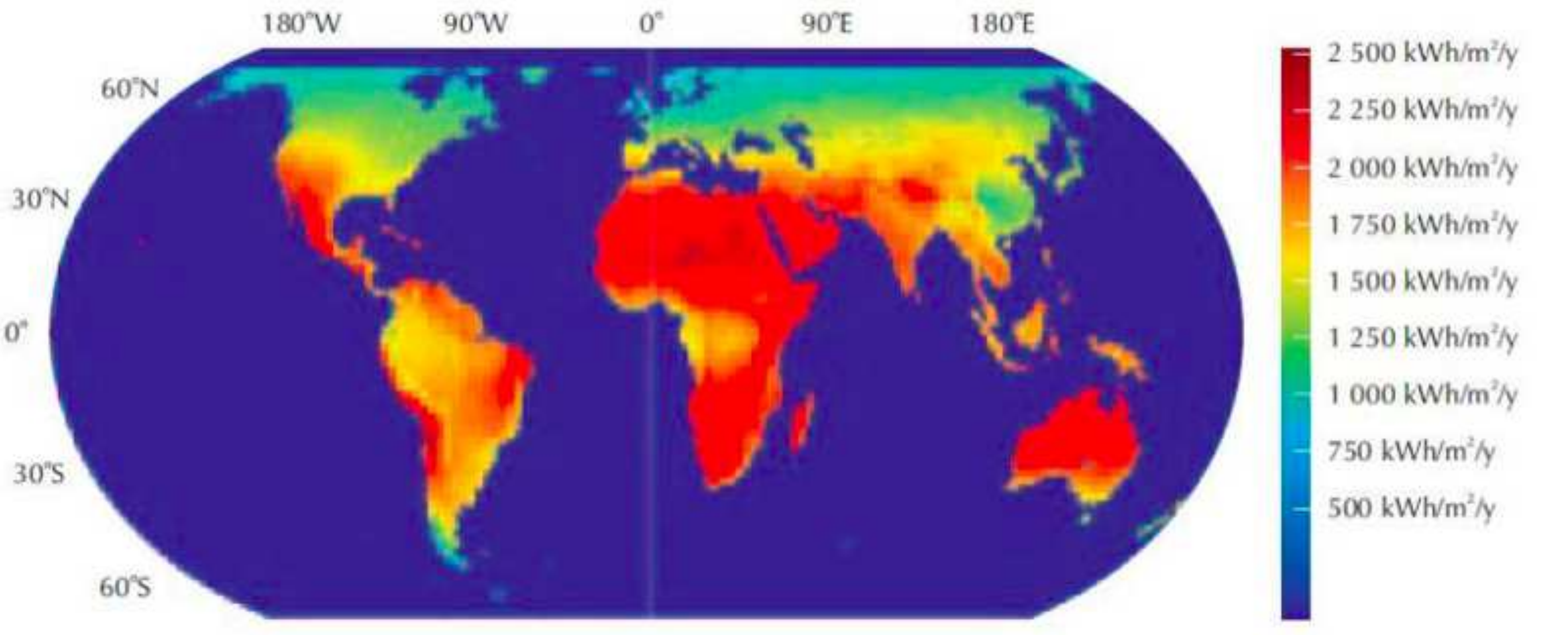
Solar photovoltaics: a potentially unlimited resource



EPIA, 2010

Energetic context (IV)

Solar photovoltaics: a potentially unlimited resource



Solar Flux at Earth Surface ($kWh/m^2/y$, 2009)

Solar irradiance is of fundamental importance and is deemed good to excellent between 10° and 40° , South or North

Energetic context (V)

The French Case

- Corsica, French riviera and south Alpes : > 50% than northern areas
- Mistral wind influence
- Microclimate on Atlantic coast

Recoverable solar radiation on the French territory is 200 times the total energy consumption of the country (solar radiation: 4 kWh/m^2/year)

The only equipment half of the roof would cover 100% of the electricity needs (2,000 km^2 less than 0.4% of the territory)

Energy needs for a family of 4: 10-25 m^2 of solar panels.

Main characteristics of Solar energy :

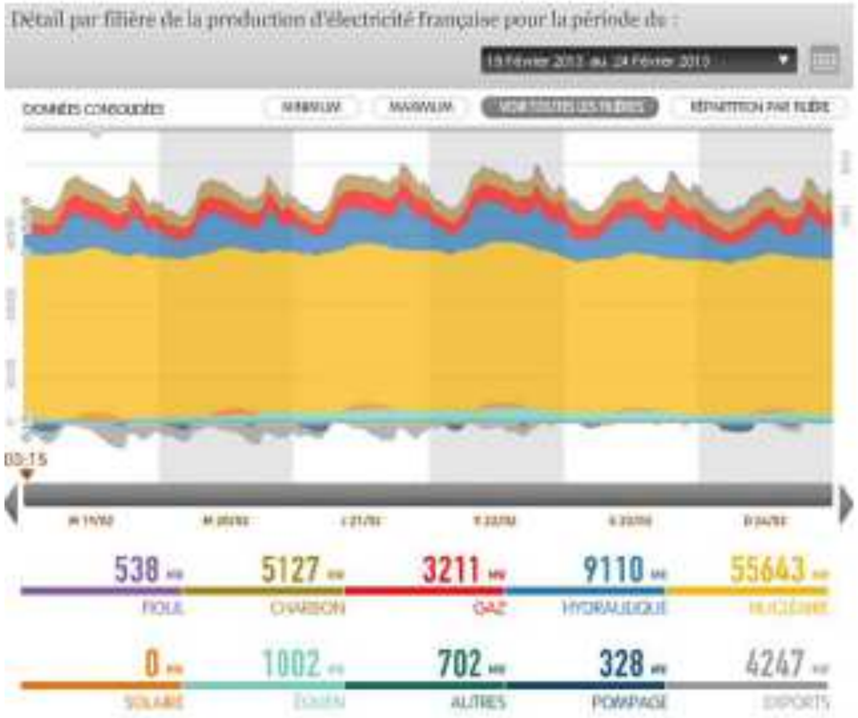
- **Dilute** (about 100 W/m^2 usable with mainstream technology)…
- **Intermittent** (for terrestrial applications) ⇨requires progress in storage technology and /or grid management (smart grids)

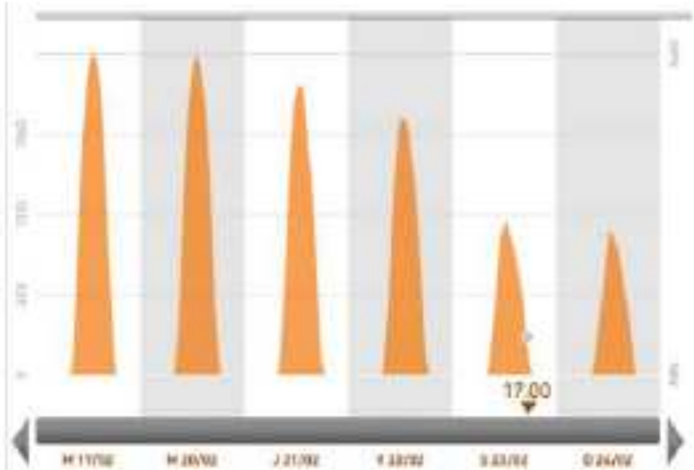
Energetic context (VI)

The French Case: real-time data publication

écomix Rte

Consommation, production, échanges commerciaux et contenu CO2 de l'électricité française.



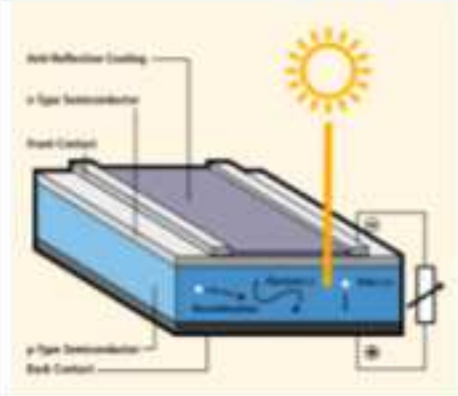


http://www.rte-france.com/fr/developpement-durable/eco2mix

Energetic context (VII)

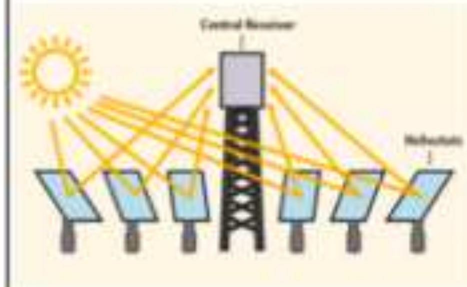
Solar energy technologies

Solar Photovoltaic (PV)



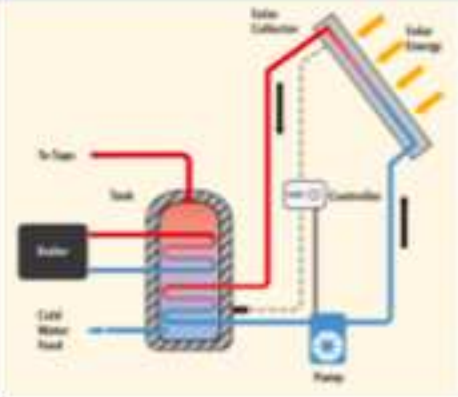
Electricity generation via direct conversion of sunlight to electricity by **photovoltaic cells** (conduction of electrons in semiconductors).

Concentrating Solar Power (CSP)



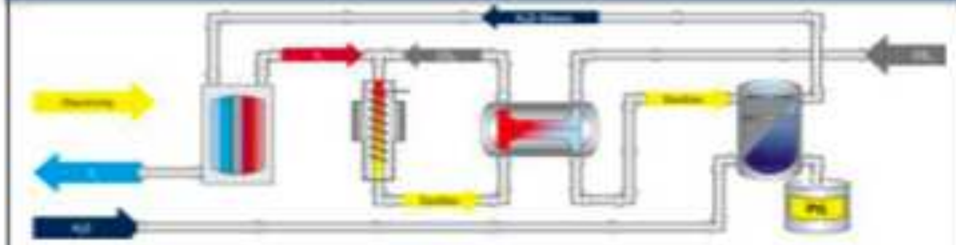
Electricity is generated by the **optical concentration** of solar energy, producing high-temperature fluids or materials to drive heat engines and electrical generators.

Solar Thermal



Solar panels made up of evacuated tubes or flat-plate collectors **heat up water stored in a tank**. The energy is used for hot-water supply and, occasionally, space heating.

Solar fuels

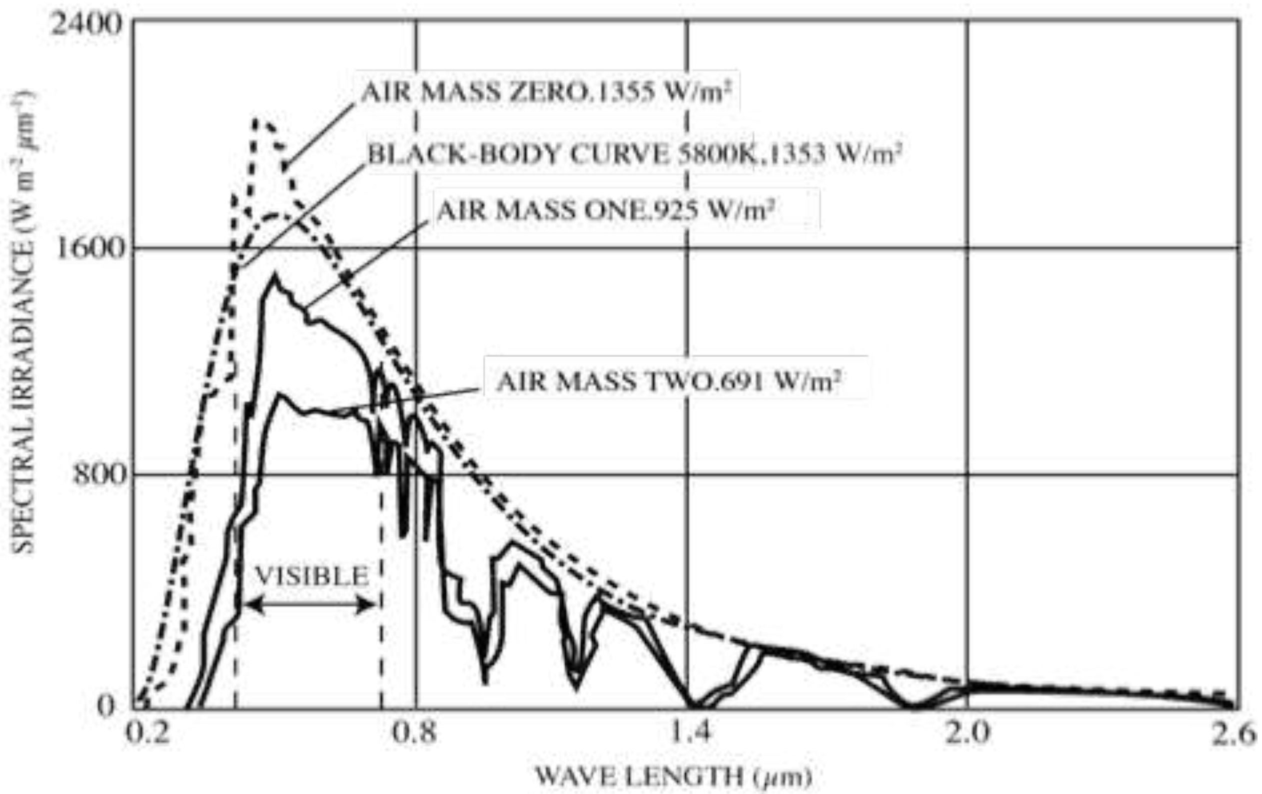


Solar Fuels processes are being designed to transform the radiative energy of the sun into chemical energy carriers such as hydrogen or synthetic hydrocarbons fuels (*e.g.* electrolysis, thermolysis, photolysis).

Solar Cells: Operating principle

Operating principle (I)

Solar spectrum



Effect of altitude:

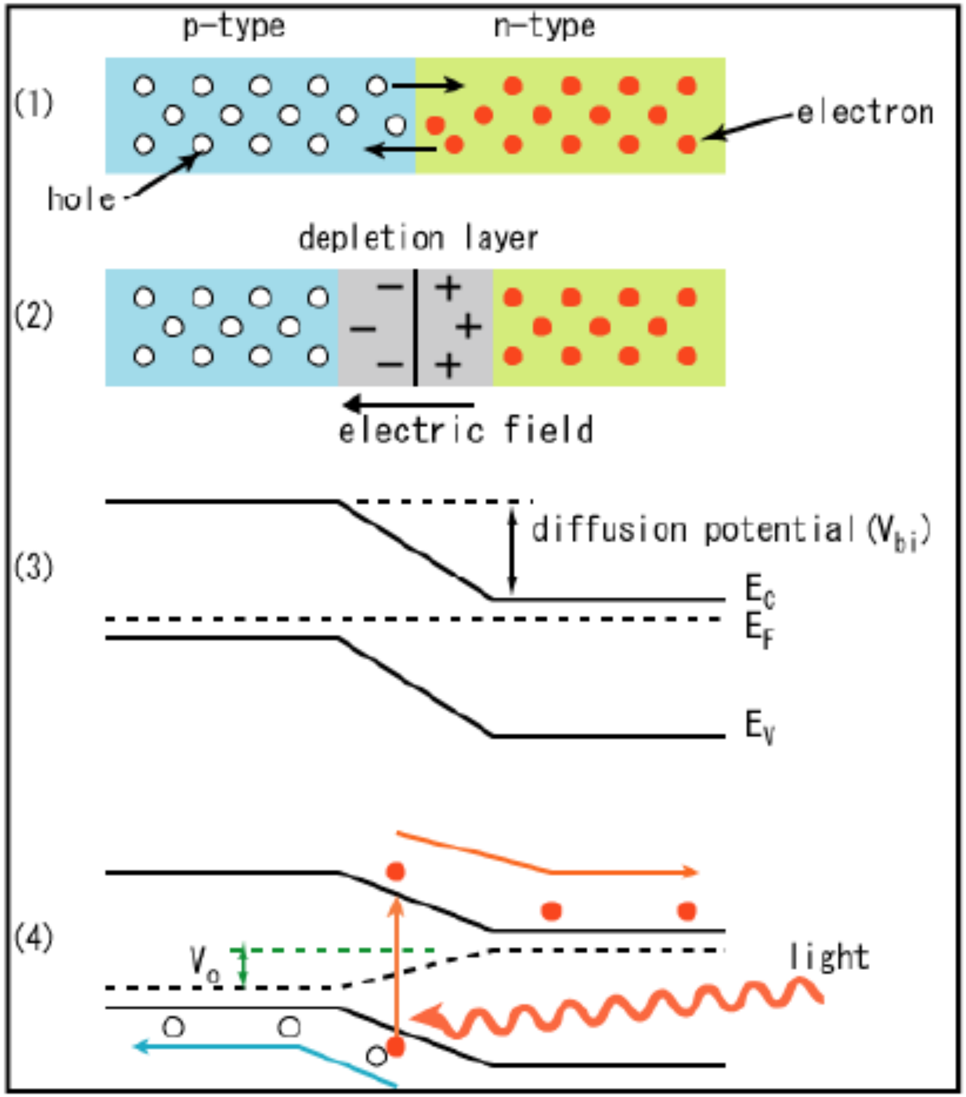
- **AM0**: solar spectrum outside the atmosphere (near blackbody 5800 ° K): space applications
- **AM1**: sun zenith (absorptions in the UV and IR)
- **AM2**: inclination of 60 ° relative to the zenith

Good approximation: AM 1.5 (844 W/m^2) tilt 45 °

Need large areas of conversion

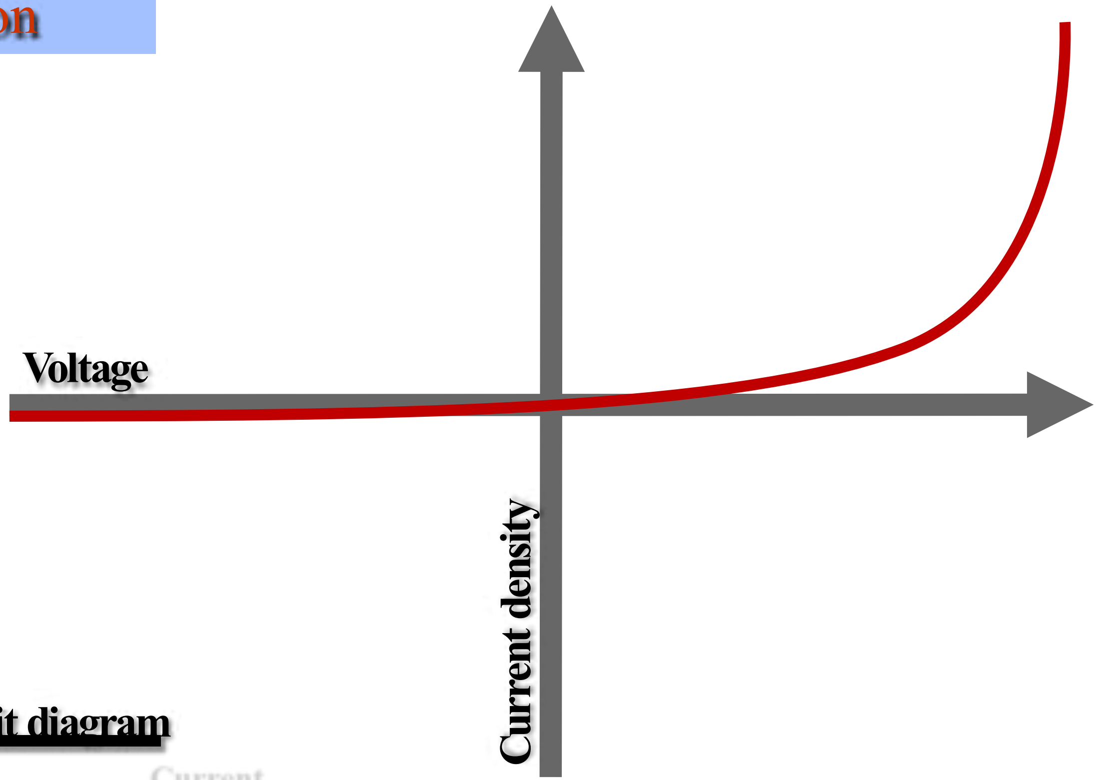
Operating principle (II)

Conventional p-n junction photovoltaic cell

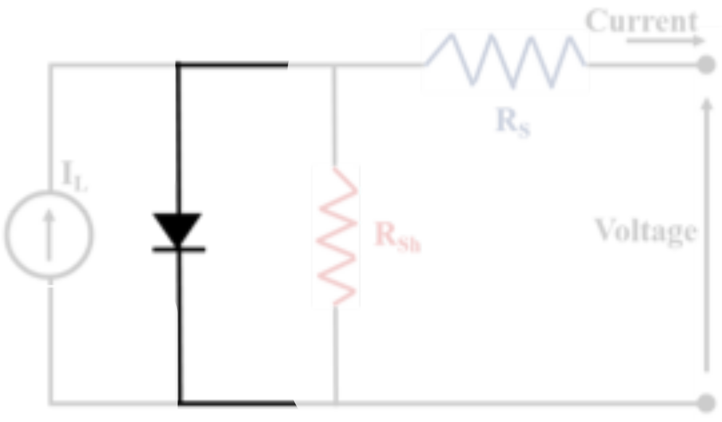


Operating principle (III)

In dark condition



Equivalent circuit diagram

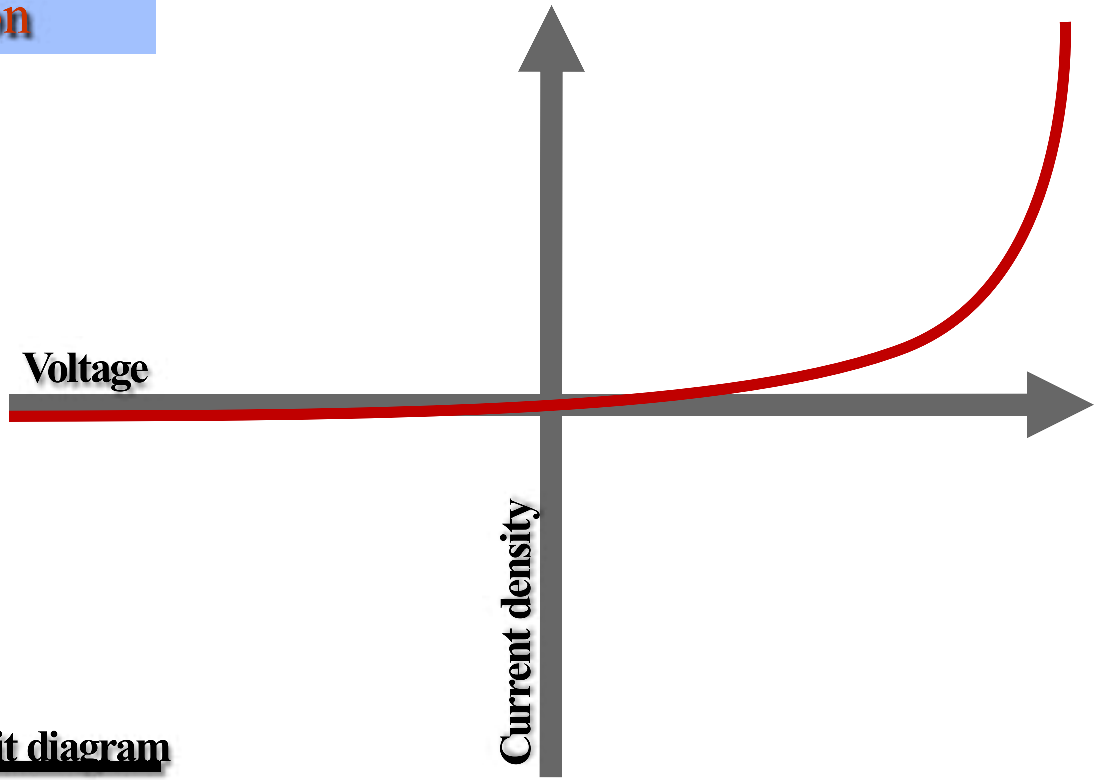


Without illumination

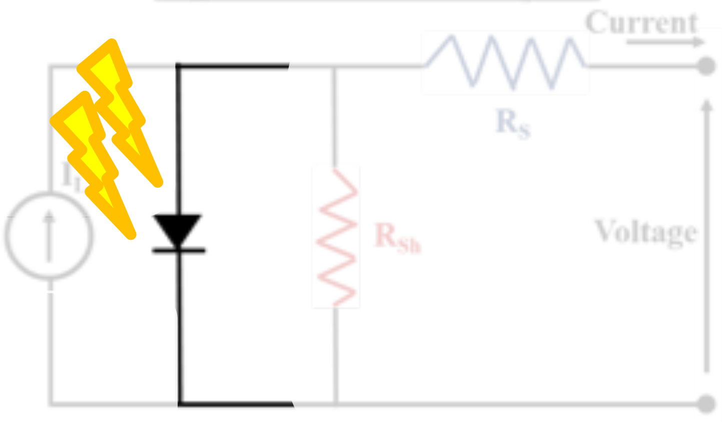
- **Diode** electrical characteristic

Operating principle (IV)

Light absorption



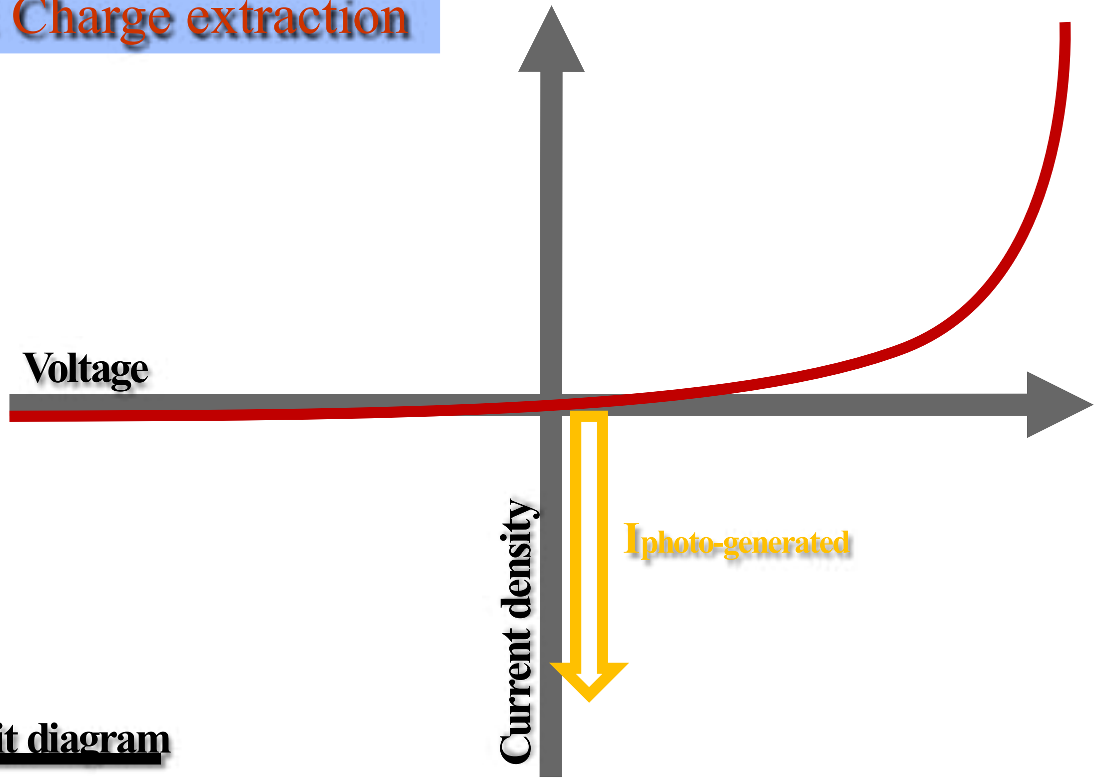
Equivalent circuit diagram



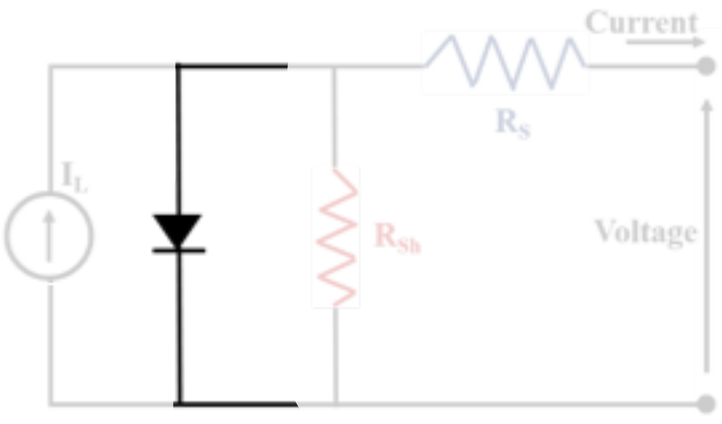
- Energy of **light** > **Eg** of **active layer**
- Light **absorption**
- **Electron-hole pair (EHP)** generation

Operating principle (V)

Carrier diffusion & Charge extraction



Equivalent circuit diagram



Diffusion current generation

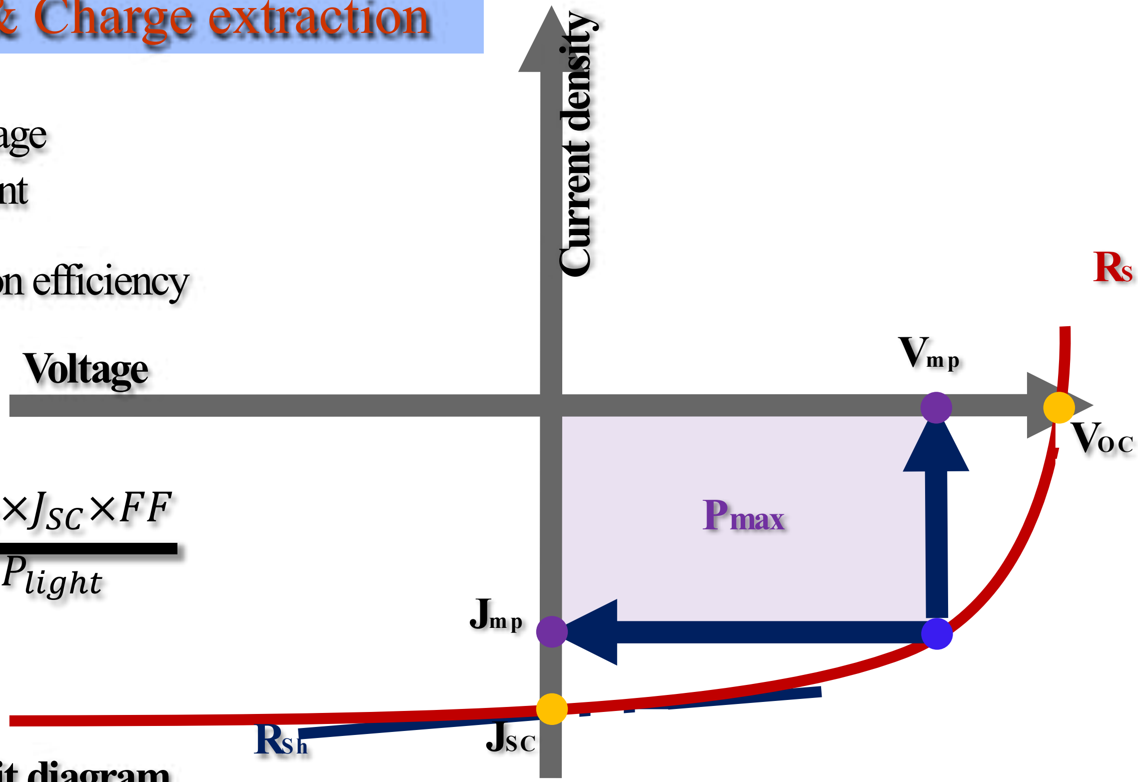
- Due to the photo-generated carriers
- JV curve shift and power generation
- The greater the light intensity, the greater the amount of shift

Operating principle (VI)

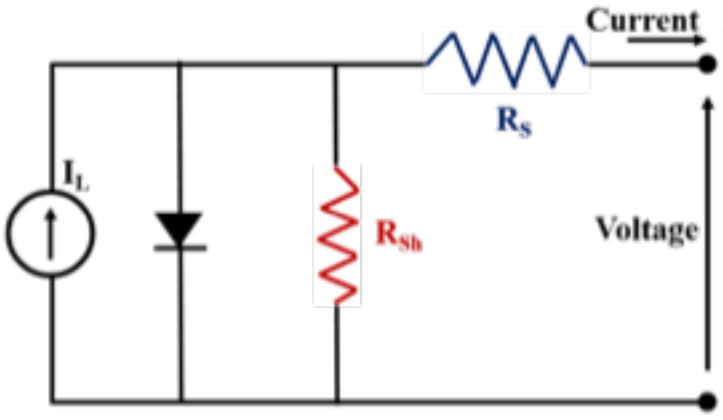
Carrier diffusion & Charge extraction

V_{OC} : Open circuit voltage
J_{SC} : Short circuit current
FF : Fill factor
PCE : Power conversion efficiency

$$\text{PCE} = \frac{P_{max}}{P_{light}} = \frac{V_{OC} \times J_{SC} \times FF}{P_{light}}$$



Equivalent circuit diagram



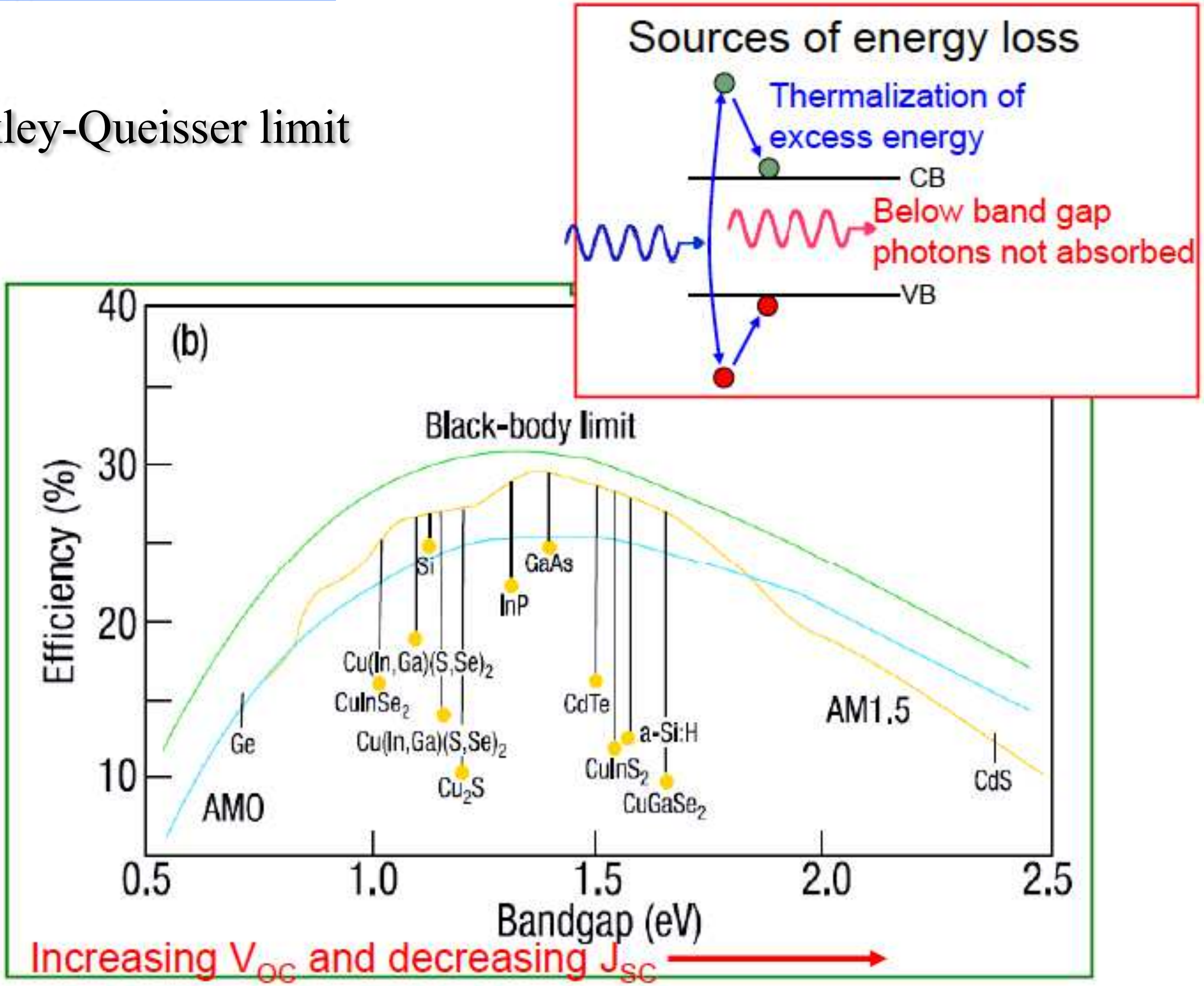
Shunt resistance (R_{sh})
- Leakage current through the edge
- Defect of solar cells

Series resistance (R_s)
- Contact resistance between active layer and metal electrode
- Active layer thickness

Operating principle (VII)

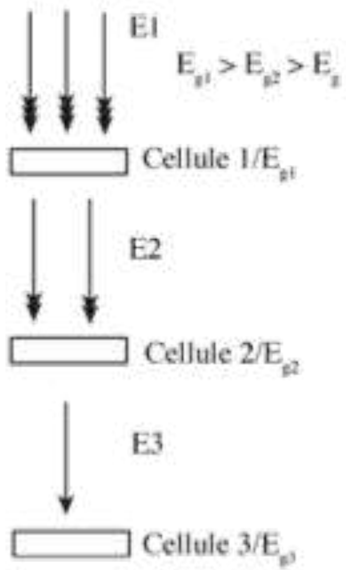
Efficiency limits

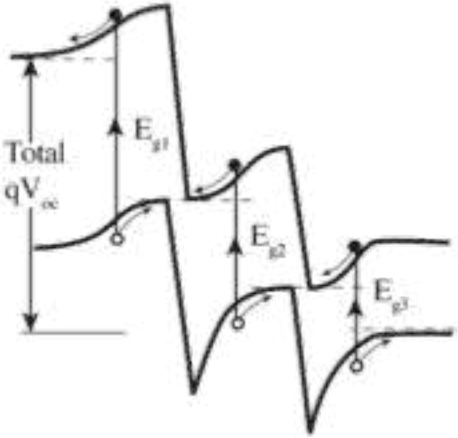
Shockley-Queisser limit

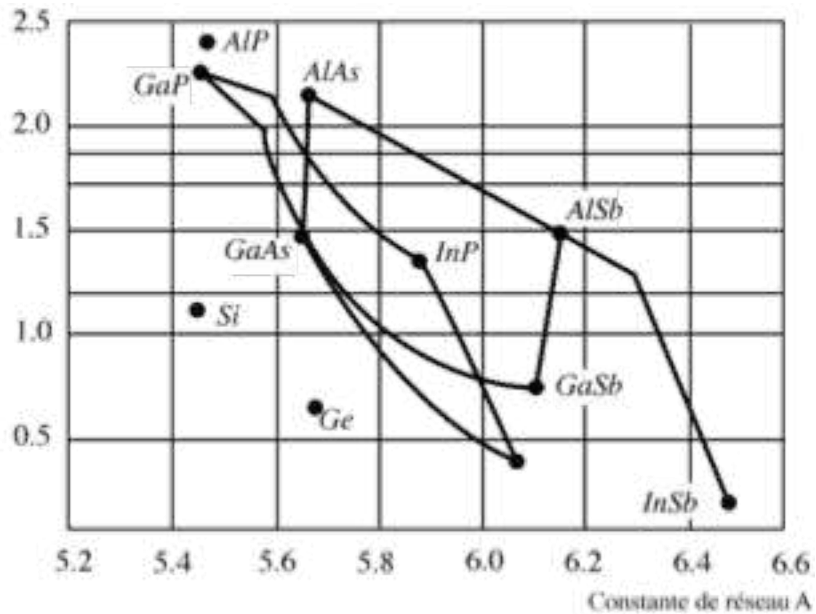


Operating principle (VIII)

multispectral cells







Efficiency increase:

$E_{g1} = 1.56$ eV $\quad E_{g2} = 0.94$ eV $\quad : \eta = 50\,\%\ (C = 1000)$

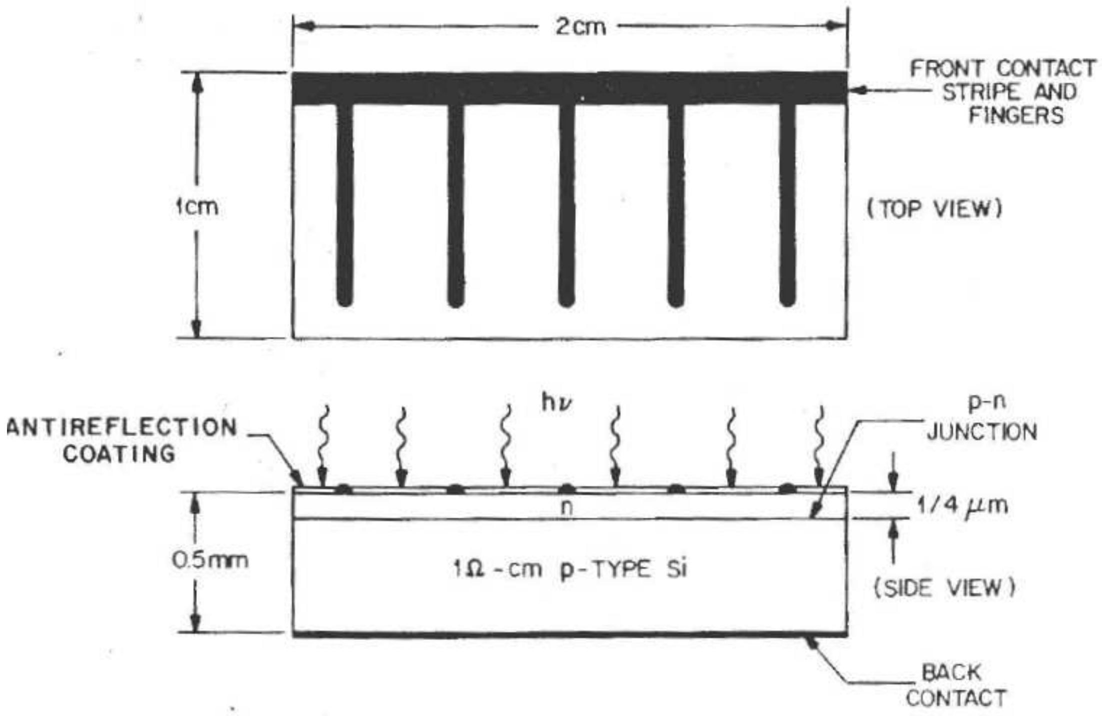
$E_{g1} = 1.75$ eV $\quad E_{g2} = 1.18$ eV $\quad E_{g3} = 0.75$ eV $: \eta = 56\,\%\ (C = 1000)$

Low gain beyond three materials

Difficult realization with c-Si, ***easy with amorphous***

Operating principle (IX)

Example of c-Si solar cell

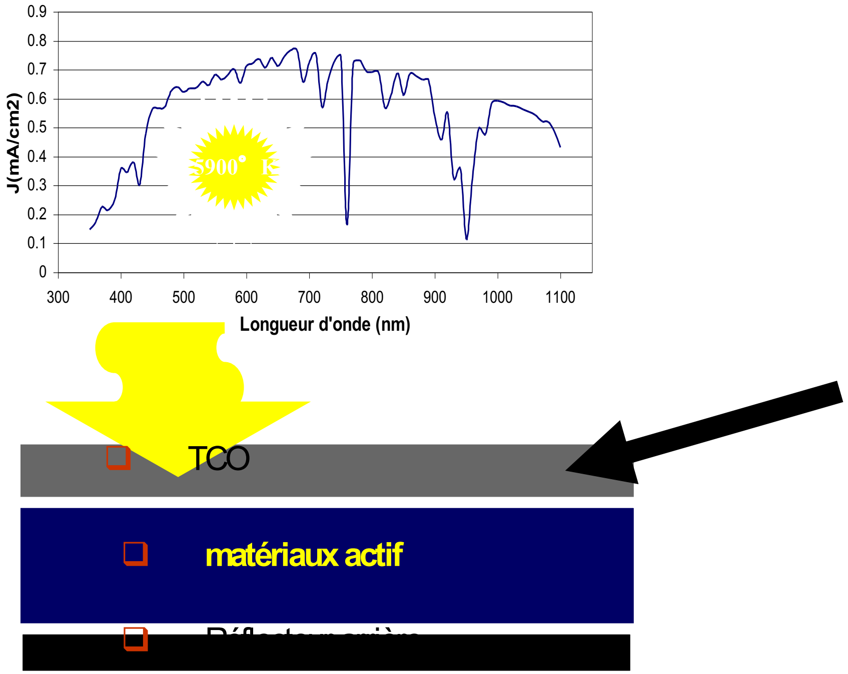


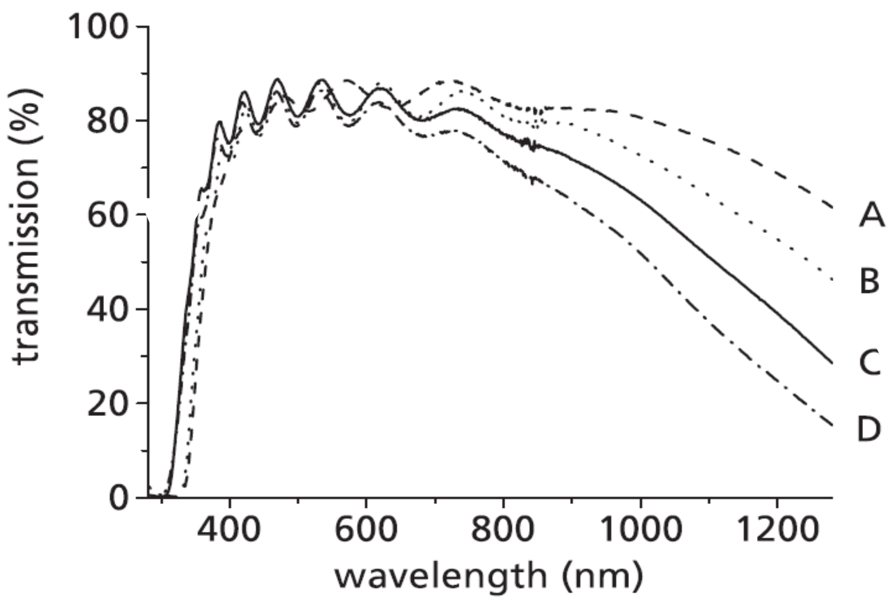
- Need a transparent conductive layer TCO (Transparent Conductive Oxide)
- Need metallic stripe and fingers to collect carriers.
- Need an anti-reflective layer (semiconductor reflectivity of the order 25% in the visible rang)

Operating principle (X)

Transparent Conductive Oxide TCO

- Must be simultaneously conductive(<10Ω☐) and transparent to solar spectra
- Requirements met by large bandgap layers (>3eV) with degenerate N-type doping (Fermi level in the conduction band)





ZnO:Al transmission

- Applications other than photovoltaic:
  - flat panel display
  - architectural glass for thermal insulation

Operating principle (XI)

Optical trapping: ex c-Si (texturing the front contact)

Best efficiency for c-Si cells
0.696V, 42 mA/cm2, FF= 0.836, h = 24.4%

- Absorption is strongly dependent on the wavelength
  - high reflexion (n= 3-4 dans les SC)
- Use of complex structures to increase the optical path in the solar cell (diffraction gratings ...)

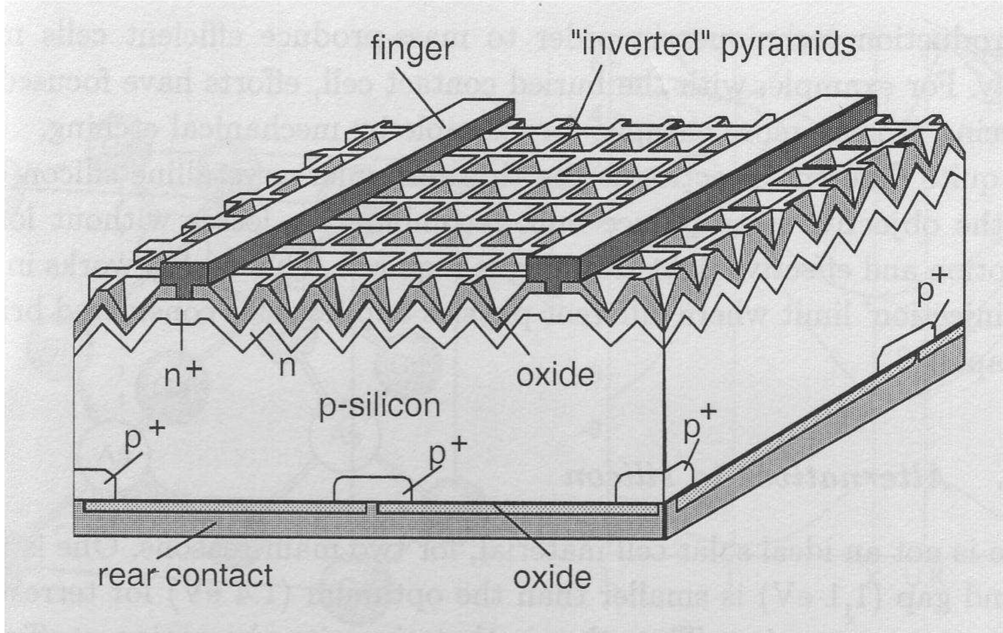
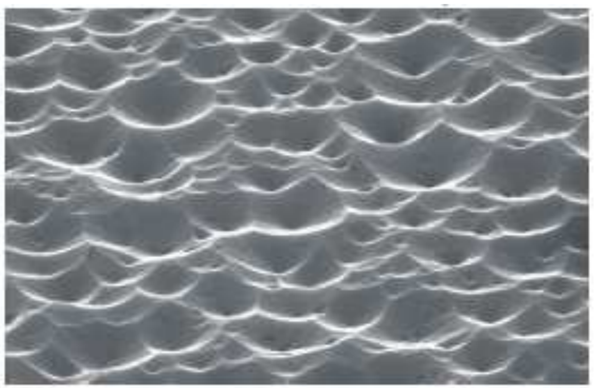


Fig. 7.15. PERL cell [Green, 1995].

Operating principle (XII)

Textured TCO

- Can appear naturally during deposition(SnO_2) ou créée après dépôt (ZnO)



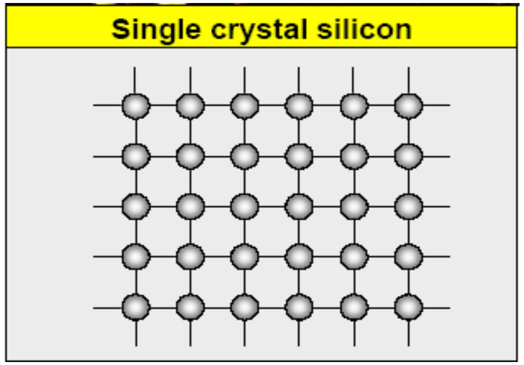
Depostion technic

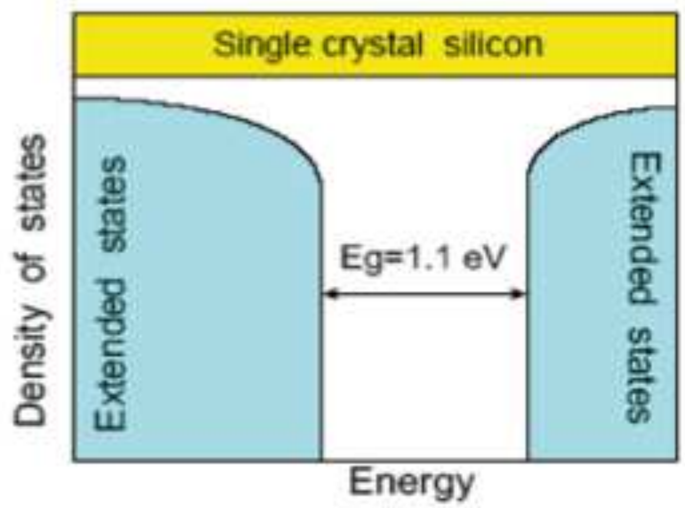
- **Sputtering**
- **MOCVD**
- **LPCVD**

Technology	Cell types	benefits / drawback
Indium Tin Oxide (ITO)	**HIT cells, a-Si:H (rear reflector)**	**High efficiency** **Indium=costly** **Non-textured**
Tin Oxide (SnO_2:F)	**a-Si:H, CdTe**	**Low cost** **Textured during deposition** **High temperature**
Zinc Oxide (ZnO:Al)	**a/µc-Si:H, CIGS**	**Low cost** **Resistant to H_2 plasma** **Textured in/ex-situ** **Deposition process difficult to control**

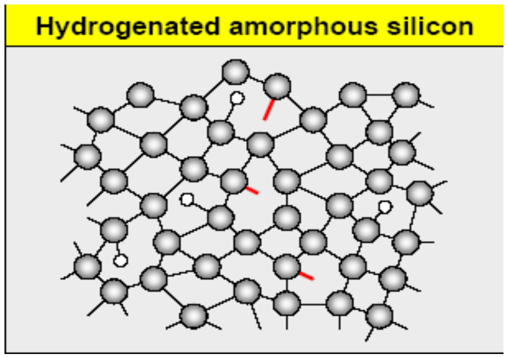
Amorphous & Crystalline Silicon solar cells

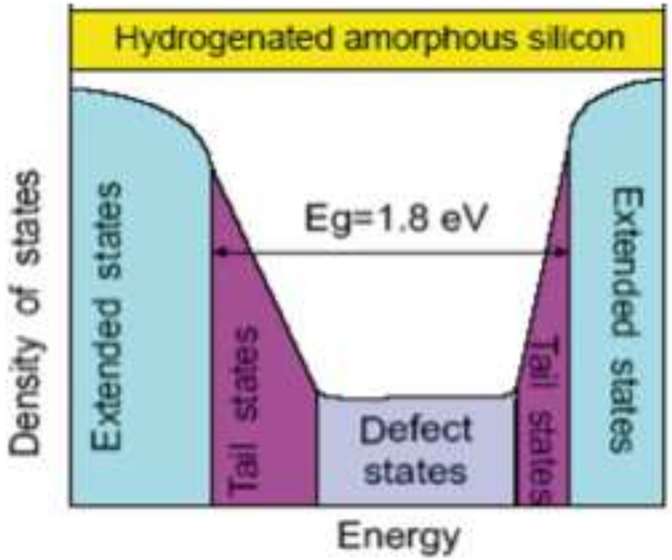
Amorphous & Crystalline cells (I)





High mobility TFTs
PolySi ~ 300 cm^2/V.s
***n* and *p* type**





Low mobility TFTs
~ 1 cm^2/V.s
***n* type**

Amorphous & Crystalline cells (II)

Parameters	C-Si	a-Si:H
Atomic arrangement	Order	disorder
Band gap (eV)	1.12	1.6 -1.8
Absorption coeff	Low	Very high
Diffusion length (um)	10 to 200	0.1 to 2
Electron mobility (cm^2/V/s)	500 to 1000	0.05 to 1
Conductivity (S/cm)	10^{-4} to 10^{4}	10^{-13} to 10^{2}
PN junction	Rectifier	ohmic
Cell thickness (um)	100 to 400	0.4 to 1

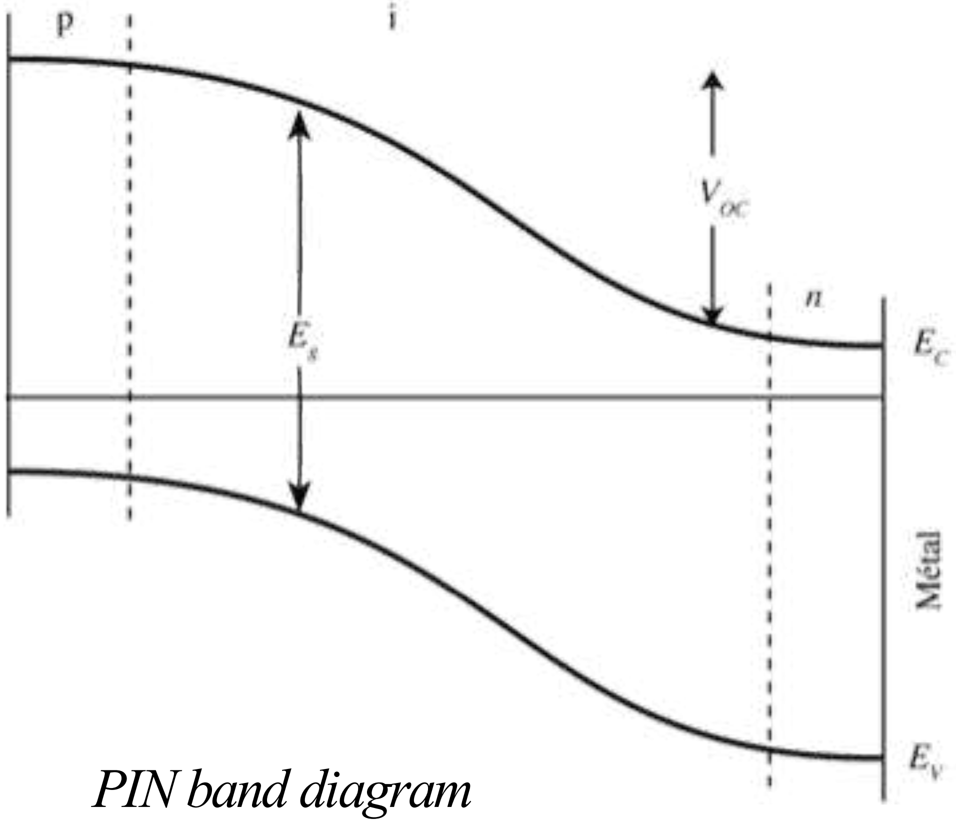
Negligible diffusion effects in a-Si: H (low mobility). The charge collection is only made in the space charge zone: ***need to extend this area.***.

a-Si:H cell is not a PN junction

Amorphous & Crystalline cells (III)

a-Si:H cells

P-I-N junction



PIN band diagram

Depletion zone thickness:

a-Si:H I W ≤ 1µm

a-Si:H P-N W ~10-20 nm
The P and N regions are used to determine the Internal electrical field but do not contribute To carrier collection.

Technological problem:

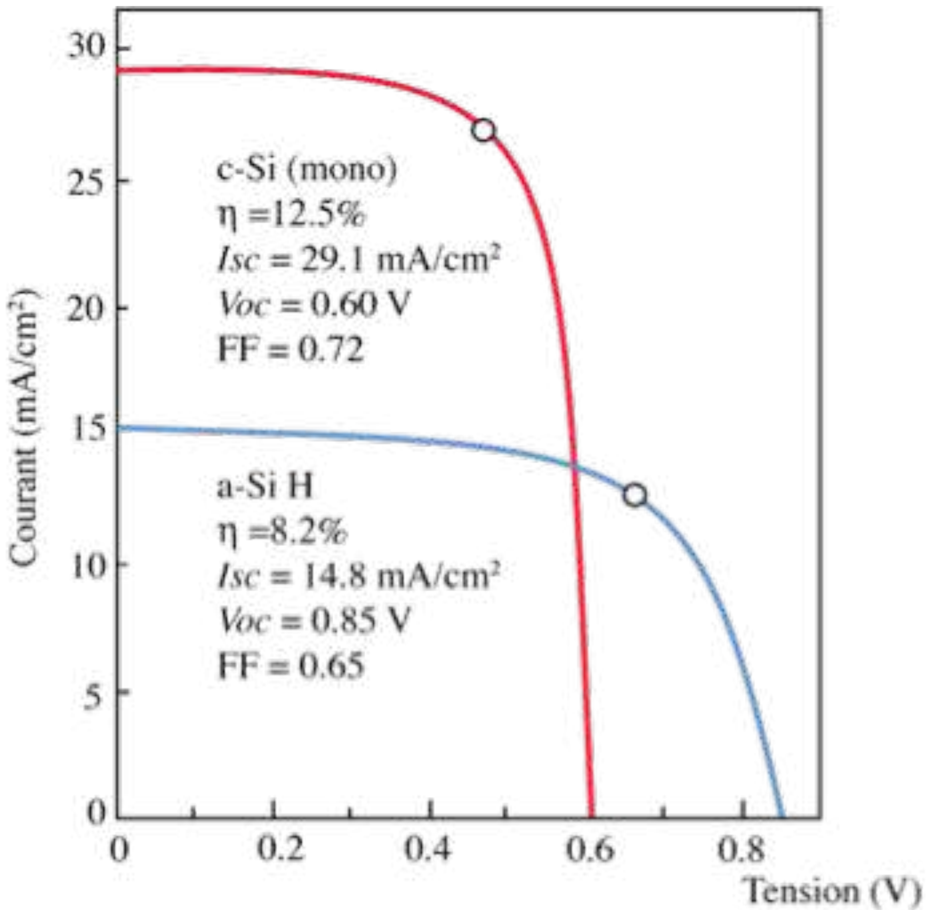
- Blue photon absorption

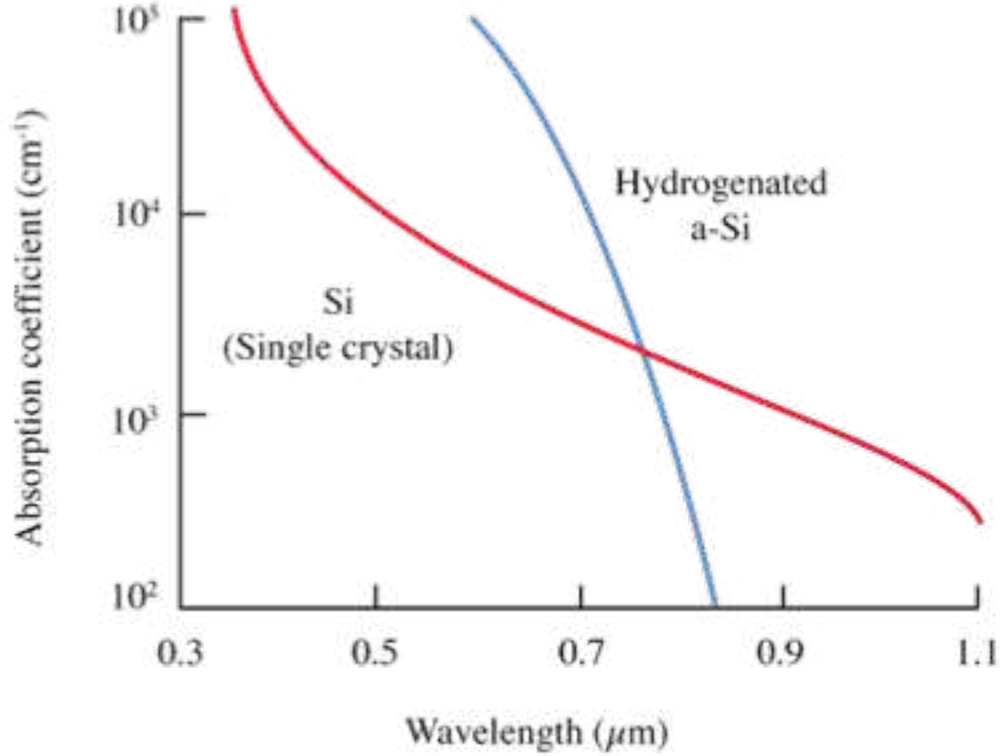
  (penetration depth : 12-20 nm)

- Red photon absorption

  (depth limited by width of space charge zone: 0.5 - 1 µm)

Amorphous & Crystalline cells (IV)

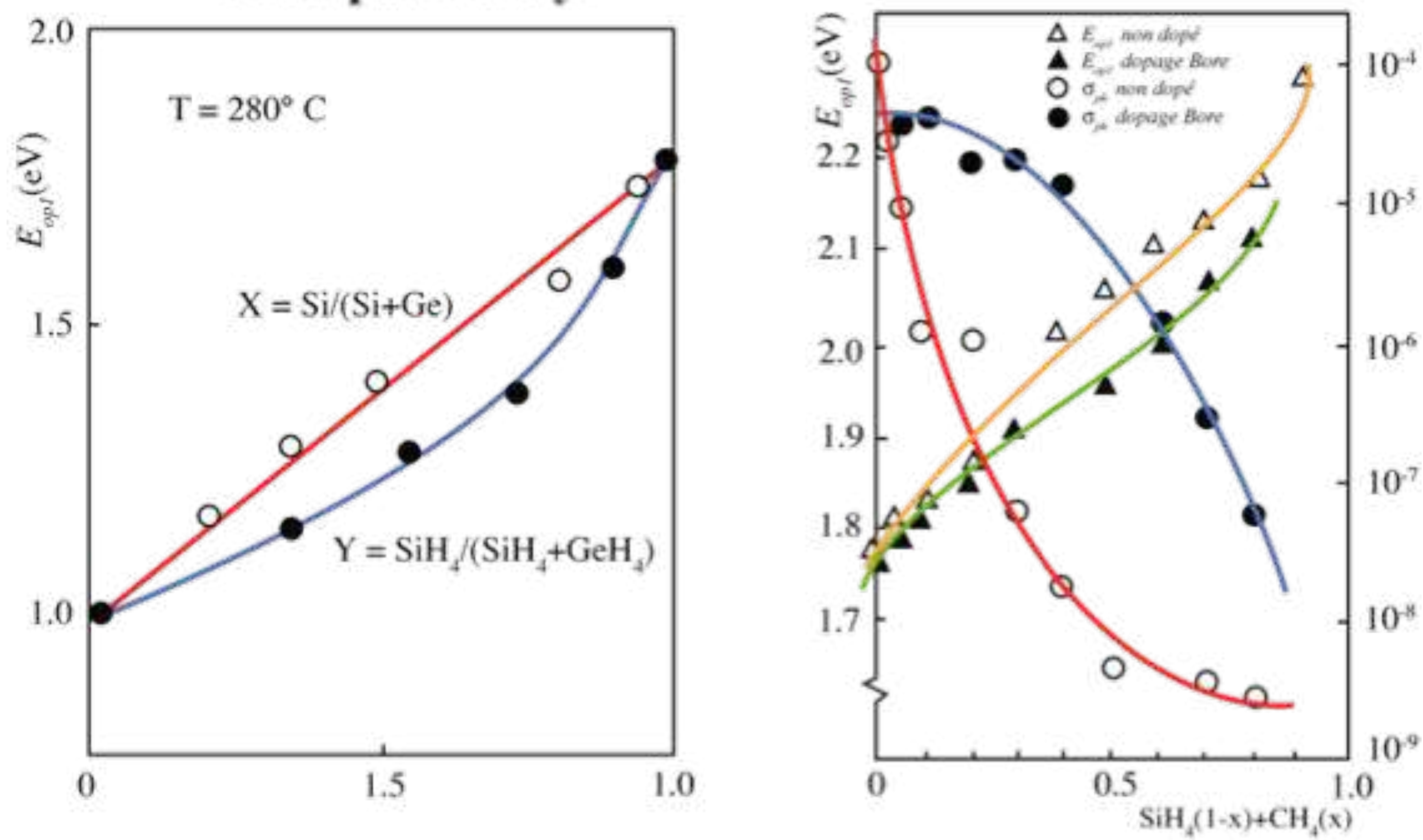




Despite the decrease in conversion efficiency, the use of a-Si:H allows a reduction in the cost of energy produced.

Amorphous & Crystalline cells (V)

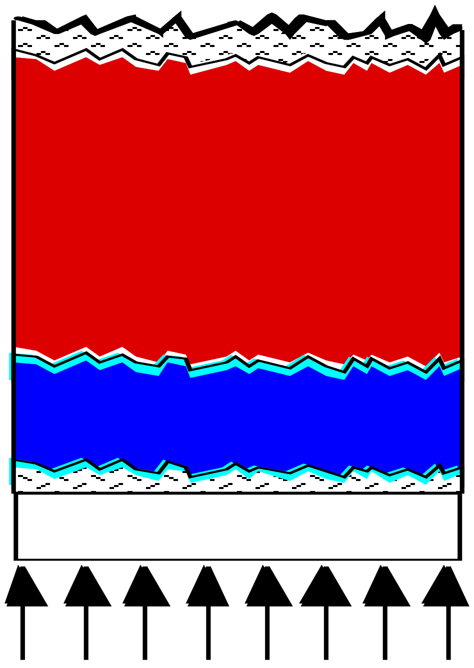
Amorphous alloys

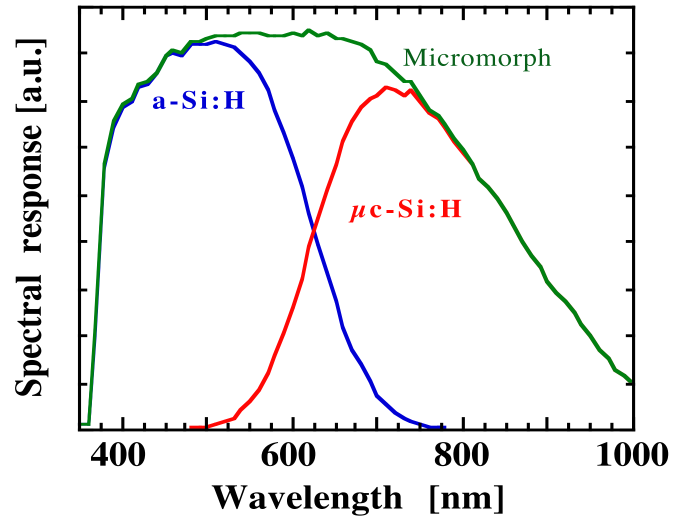


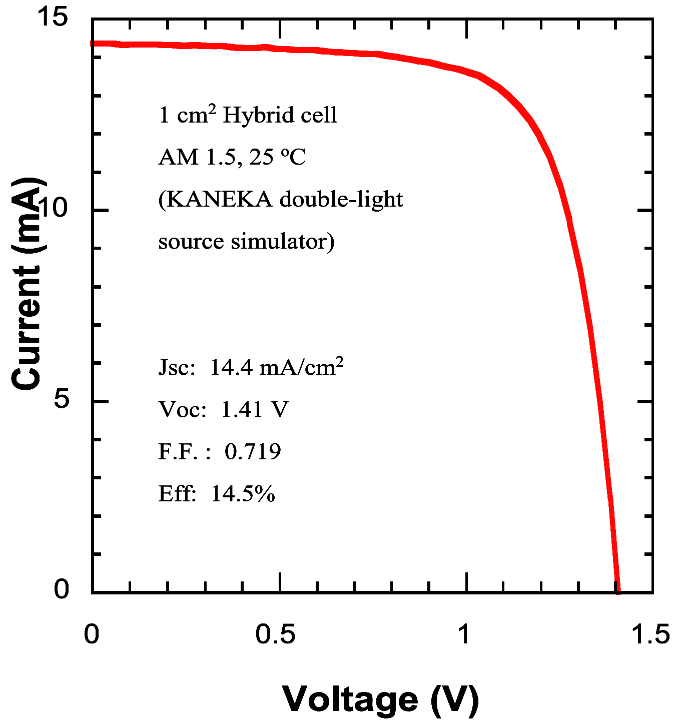
Ability to vary the gap between 1.0 and 2.2 eV, from a gaseous mixture (plasma deposition).

Amorphous & Crystalline cells (VI)

Tandem
PIN/PIN

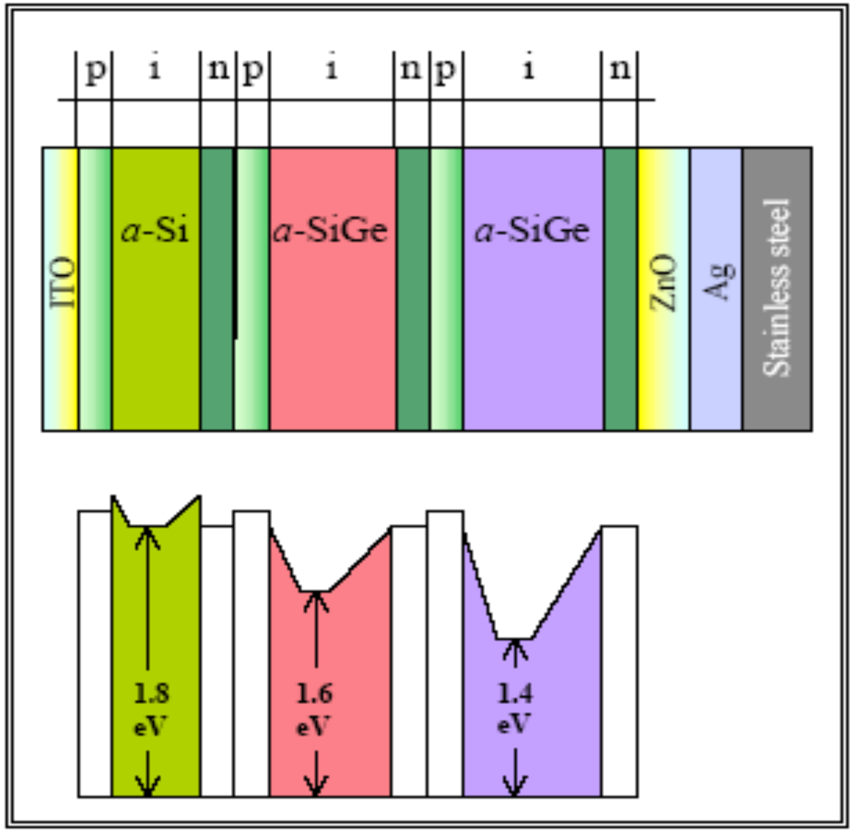






Amorphous & Crystalline cells (VII)

United Solar System Corp.

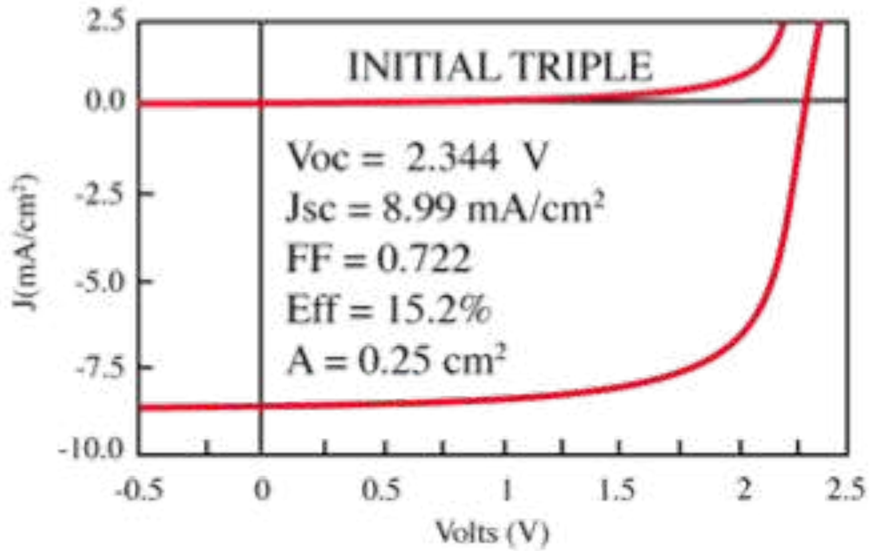


Best results :

Initial efficiency : **14.6%**

Stabilized efficiency : **13.0%**

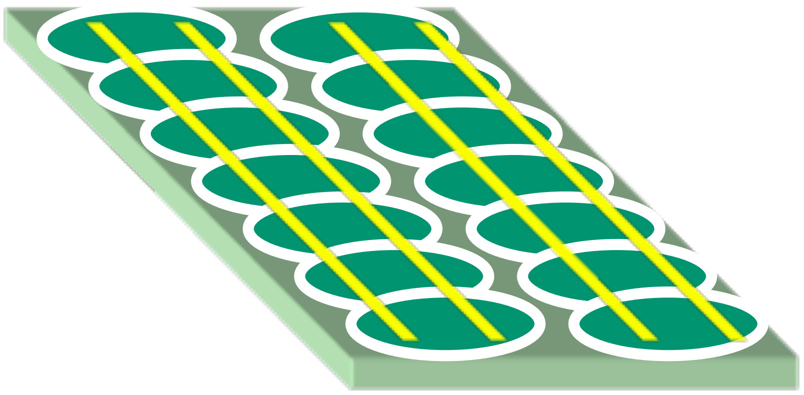
Area : 0.25 cm²



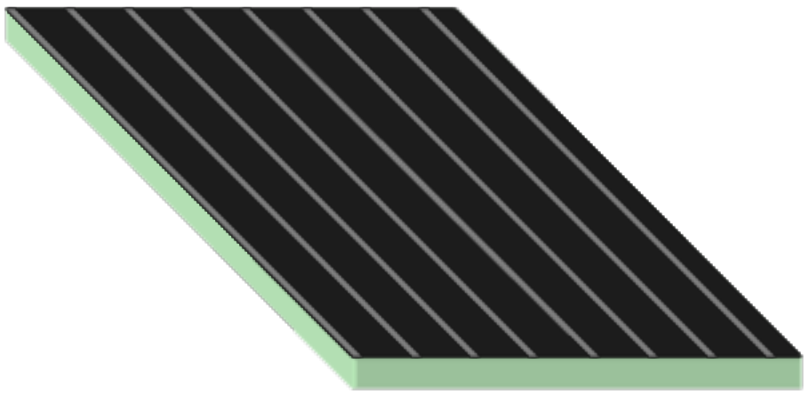
Amorphous & Crystalline cells (VIII)

- **Easy to make thin film solar modules**
  - A solar cell gives about 0.5 volt
  - Many cells connected together make a solar module
  - Thin film solar cells are interconnected during the fabrication of the thin layers - no handling of individual cells as in the conventional techniques
  - Encapsulation needed to protect the solar cells

Crystalline Si module



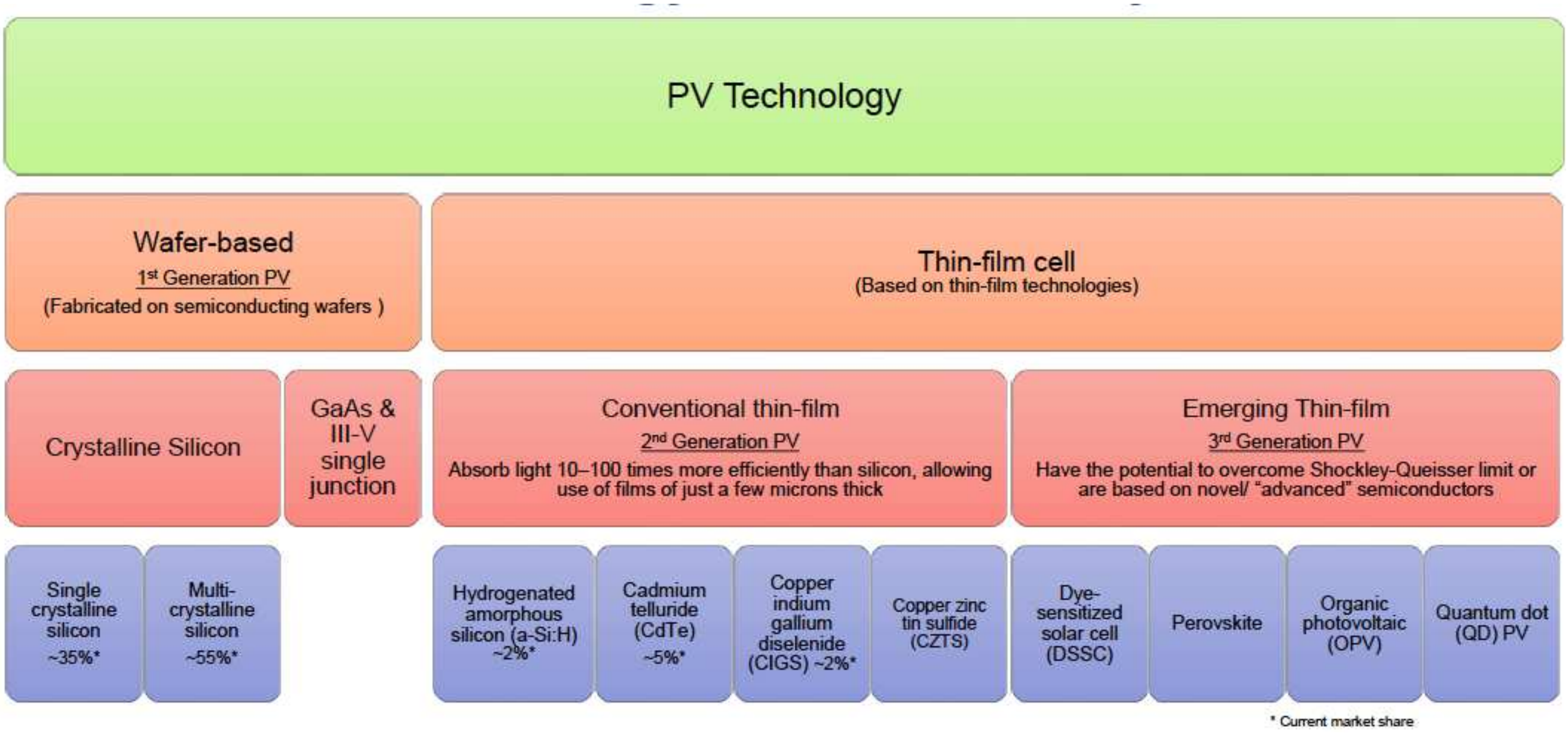
Thin film module



Photovoltaic industries

Photovoltaic industries (I)

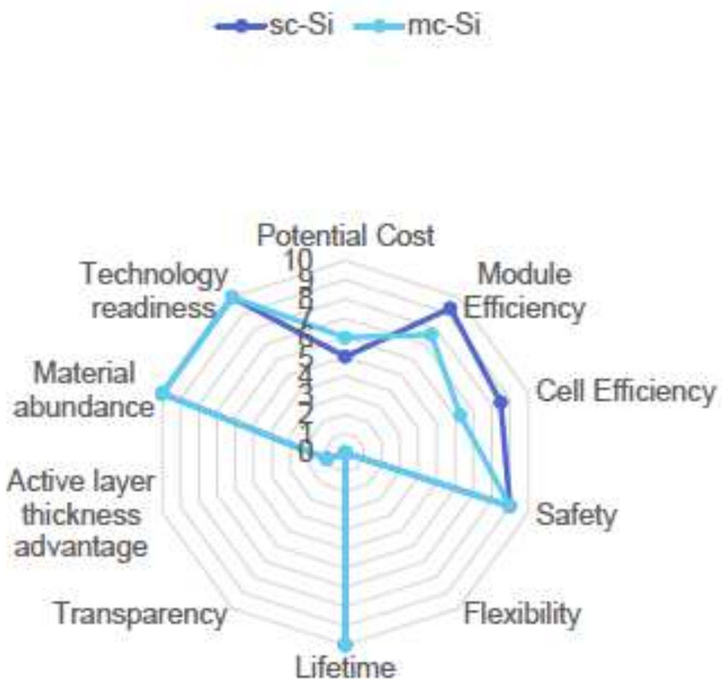
Photovoltaic technology classification by generation



2015 IDTechEx

Photovoltaic industries (II)

Crystalline silicon



Companies

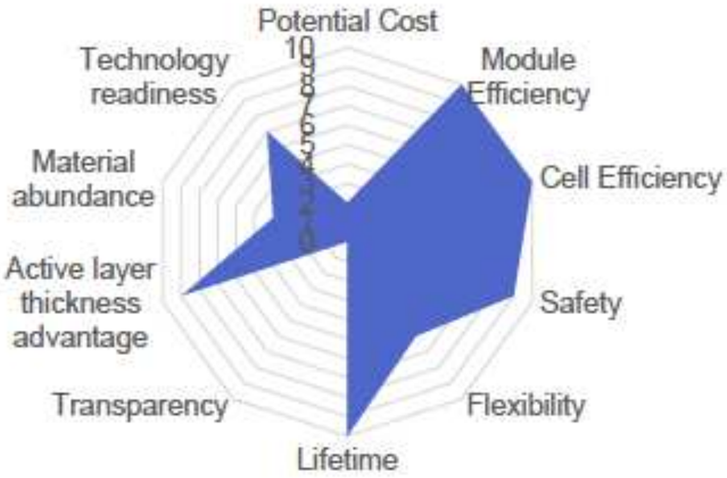
Many companies including Asian manufacturers

2015 IDTechEx

Strengths	Weaknesses
• Most mature of all PV technologies • Constitute 90% of current global production capacity • High efficiency • Long lifetime • Low cost • Abundant materials	• Indirect bandgap, which leads to weak light absorption and requires thick wafers in the lack of advanced light-trapping strategies • Difficult to reduce cost • Not flexible/transparent
Opportunities	**Threats**
• Many companies working on crystalline silicon solar cells including Asian manufactures • Dominating technology at least in the next decade • Emerging research direction with the use of thin c-Si membranes (2-50 µm) instead of wafers as starting material.	• Crystalline silicon cannot fulfil special needs for some niche applications, where other solar technologies will find their places.

Photovoltaic industries (III)

Gallium Arsenide



Strengths

- Strong absorption, with a direct bandgap well matched to the solar spectrum
- Very low non-radiative energy loss
- Highest efficiency of all PV technologies
- Relatively long life time
- Well-established know-how

Weaknesses

- High manufacturing and material cost
- Not transparent
- Based on wafer technology
- No mass production

Opportunities

- There are companies working on epitaxial lift-off technology to create thin flexible GaAs films.
- There are works on further reducing the cost
- Applications requiring very high efficiency such as defence and space may favour this technology.

Threats

- Compared with the high cost, most applications would rather sacrifice the high efficiency so there is a threat that GaAs still find no place if the cost is too high

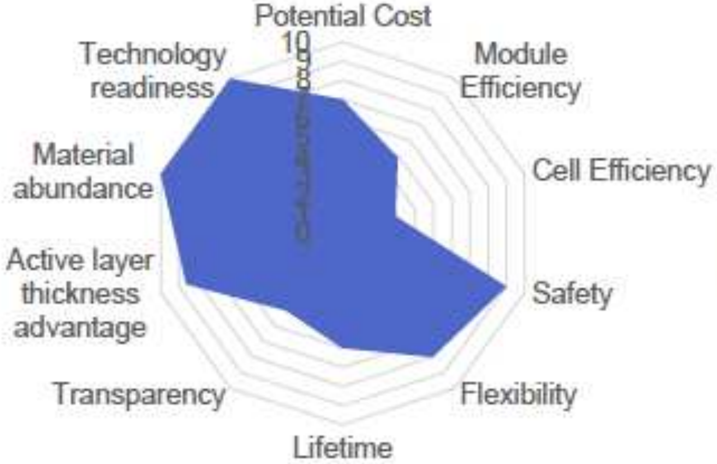
Companies

Alta Device

2015 IDTechEx

Photovoltaic industries (IV)

Hydrogenated Amorphous silicon



Strengths

- Offer stronger absorption than c-Si
- Light weight, thin-film and flexible substrates possible
- Potential for roll to roll processing unavailable for mono- or poly-Si
- Can be combined with cells based on nano-crystalline Silicon (nc-Si) or amorphous silicon-germanium (a-SiGe) alloys to form a multi-junction cell without lattice-matching requirements.
- Abundant and cheap material

Weaknesses

- Constant degradation
- Low efficiency compared with other mature thin-film technologies
- Not tightly rollable
- Most commercial a-Si:H modules today use multi-junction cells, instead of single junction

Opportunities

- Suitable for small-scale and low-power applications
- Can be combined with nc-Si and a-SiGe cells

Threats

- The flexible features can be achieved by other PV technologies as well. The latter may have even higher and stable performance.

Companies

United Solar, Mitsubishi

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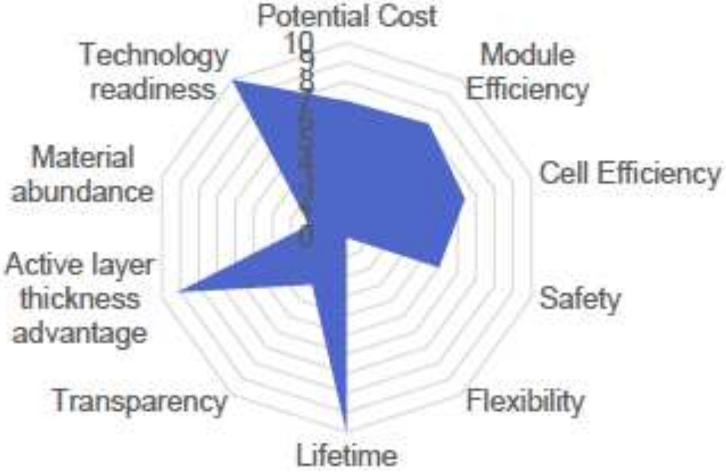
Photovoltaic industries (V)

Cadmium Telluride



Companies

First Solar, Calyxo, Abound, PrimeStar

Strengths	Weaknesses
• Strong absorption across the solar spectrum and a direct bandgap • Highest cell/module efficiencies among thin-film solar cells • Lowest module cost of any PV technology on the market today & lowest cost/watt over life	• Relatively high processing temperatures (~500°C) • Toxicity of cadmium, controlled disposal only • Scarcity of tellurium • Not tightly rollable

Opportunities	Threats
• Leading thin-film PV technology • Commercial module efficiencies continue to improve.	• Scarcity and toxicity of the materials may limit its applications and motivate researchers to move to other PV technologies with similar ease of manufacturing but reply on abundant and non-toxic materials

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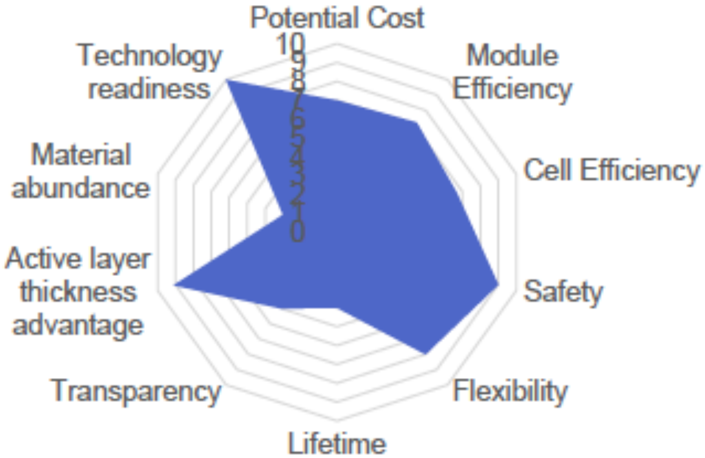
Photovoltaic industries (VI)

Copper Indium Gallium Selenide



Strengths

- A direct bandgap and good absorption
- Can be deposited by solution- and vapor-phase methods, Printable
- Possible on flexible metal or polyimide substrates
- High radiation resistance—a necessary metric for space applications
- Highest efficiencies among commercial thin-film technologies
- Transparent
- No disposal problems

Weaknesses

- High cost
- Low open-circuit voltage
- High variability in film stoichiometry, making high-yield, uniform, large-area deposition challenge
- Scarcity of indium
- Sensitive to moisture and oxygen so more expensive encapsulation is required

Opportunities

- CIGS solar cells have been already commercialized and have a better chance to be applied in special applications requiring flexible and transparent feature than other emerging and commercial thin-film PV technologies
- Potential for the applications in BIPV and space applications

Threats

- Value propositions can be replaced by other PV technologies, e.g. CZTS
- The relatively high cost (high price of indium and expensive encapsulation) may limit its large-scale application

Companies

HONDA, Global Solar, Wurth, Nanosolar, Ascent, Miasole

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Photovoltaic industries (VII)

Organic photovoltaic

Strengths	Weaknesses
• Potential for very low cost • Large-area, high-throughput deposition methods possible • Tightly rollable • High indoor performance • Ease of manufacturing for multi-junction cells • Different colours and transparency possibility • High defect tolerance • No disposal problems	• High cost today • Low ultimate efficiency limit • Poor long-term stability and short lifetime, maximum 2-3 years • Poor absorption which is less than thin-film silicon

Opportunities	Threats
• Some OPVs have been applied as off-grid application for third countries where low efficiency but cheap, flexible PV can fulfil their requirements • OPV products have been used in very small volume for low-power BIPV applications • New material systems may lead to breakthrough	• Low efficiency and poor life time are major issues for a PV device. Expensive encapsulations may be required to improve the device stability. Those limit the wide deployment of OPV.

Companies

Plextronics, Heliatek, Belectric, Solarmer, Eight19

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Photovoltaic industries (VIII)

Hybrid Perovskite

Strengths	Weaknesses
• Low potential processing and material cost • Broad and strong absorption • Thin-film, light-weight, conformal and flexible • High open-voltage • High charge carrier mobilities • Low non-radiative carrier recombination rates • Possibility to tune the bandgap • High indoor performance	• Sensitive to humidity, leading to poor stability and short lifetime without encapsulation • Toxicity from lead, a common element for high efficiency cells. • Scaling-up capability has not been demonstrated • Expensive sealing may be required • No commercial module yet

Opportunities	Threats
• Knowledge transferrable from DSSC technologies • Tremendous R&D attention internationally • Rapid improvement of the efficiencies, from 3.8% in 2009 to 20.1% of today's record • High efficiency and cheap manufacturing & material cost, together with transparent, flexible features make it a good candidate for a number of applications • Can be combined with commercial silicon solar cells for higher efficiencies • Potential for BIPV applications	• The technology is at the early commercialization stage. • Restrictions in lead in some countries may limit its applications and lead to controlled disposal • Stability issue is a big obstacle

Companies

Dyesol, FrontMaterials, G24 Power, Oxford Photovoltaics, Saule Technologies, Weihua Solar

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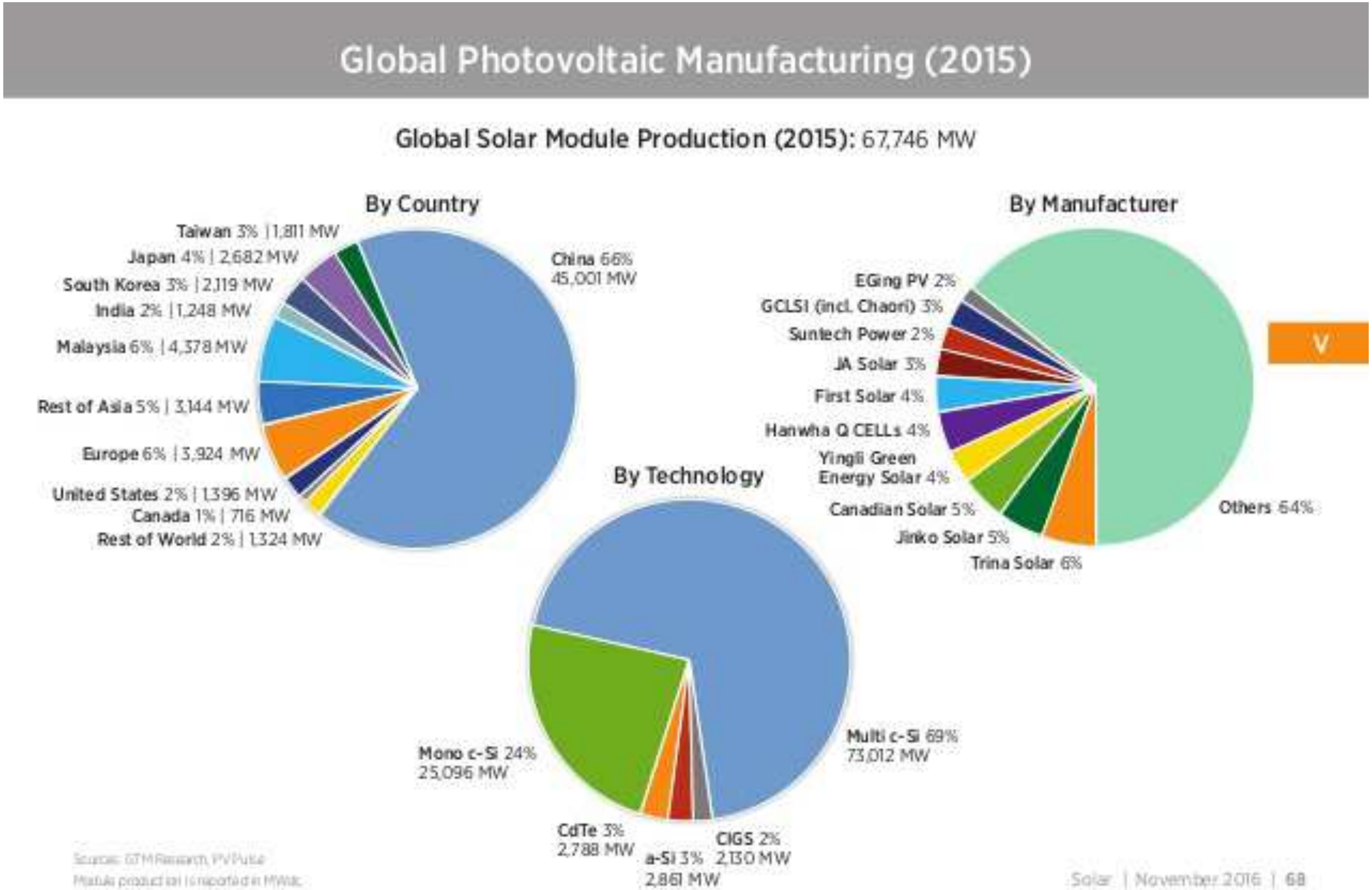
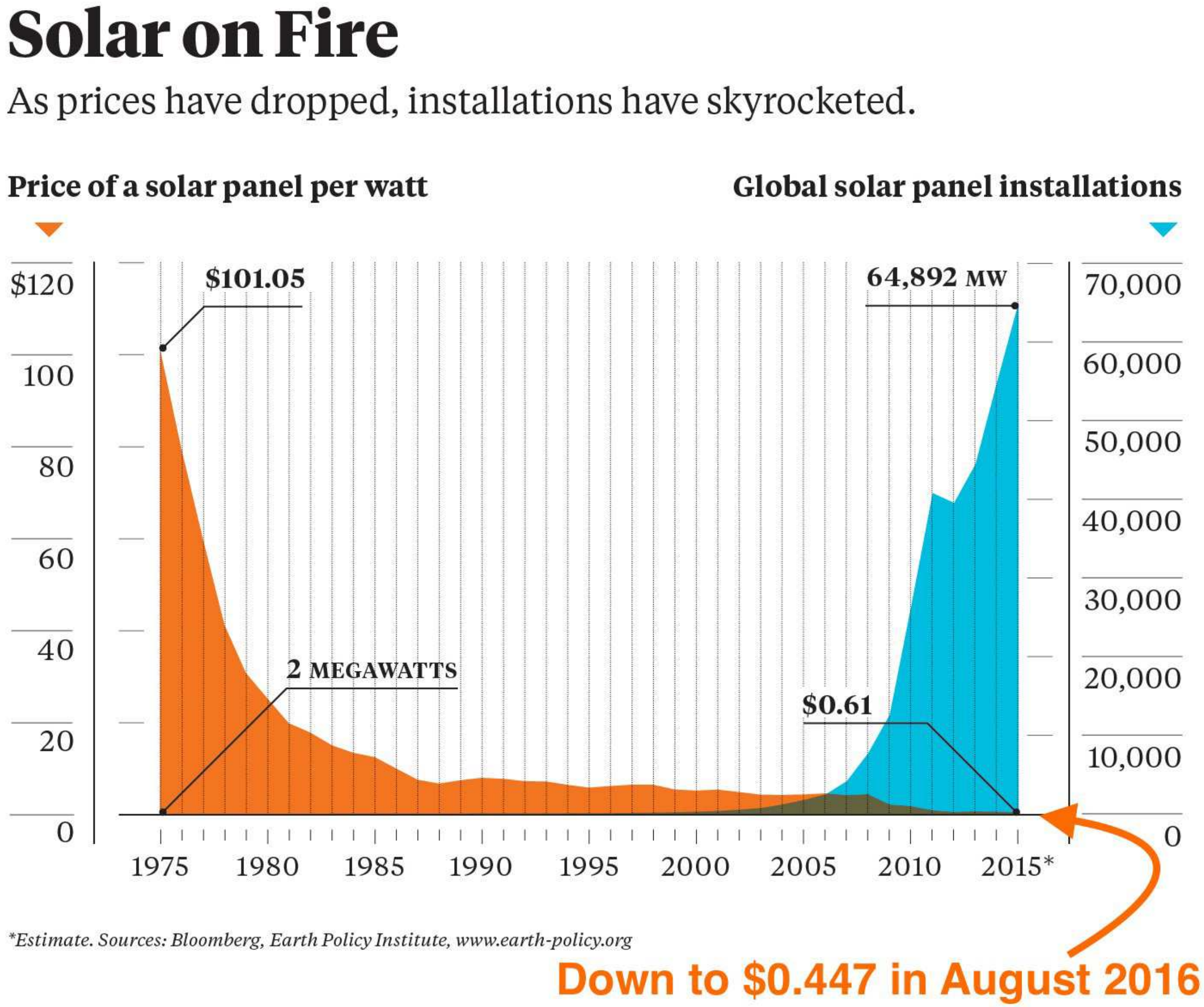
Photovoltaic industries (IX)

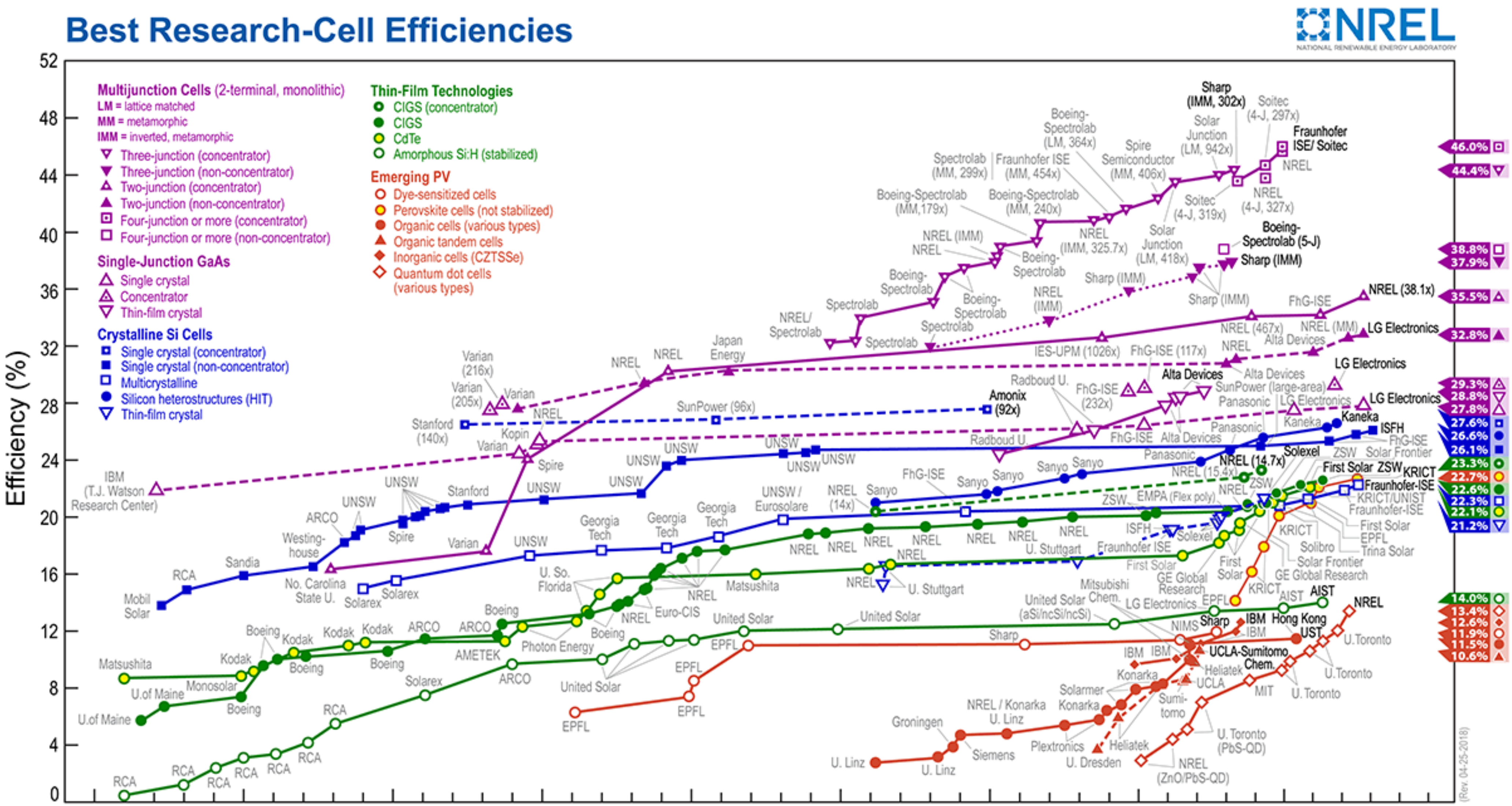


Photovoltaic industries (X)



Fast decrease of the cost of electricity mostly due to the evolution of Silicon cost

Photovoltaic industries (XI)



https://www.nrel.gov/pv/assets/images/efficiency-chart.png

Photovoltaic industries (XII)

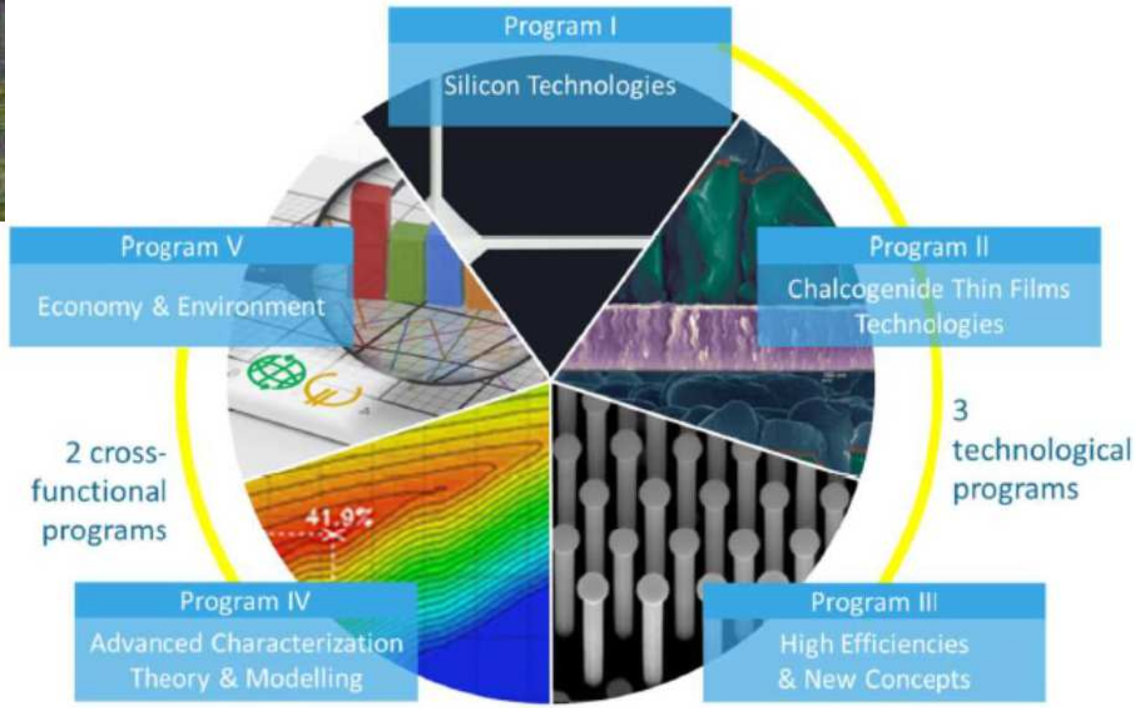
INSTITUT PHOTOVOLTAÏQUE D'ILE-DE-FRANCE (IPVF)

HORIBA JOBIN YVON · AIR LIQUIDE · RIBER · l'X École Polytechnique · CNRS · TOTAL · EDF

8,000 M^2 BUILDING

4,000 M^2 OF LABS

200 OFFICES



The End