



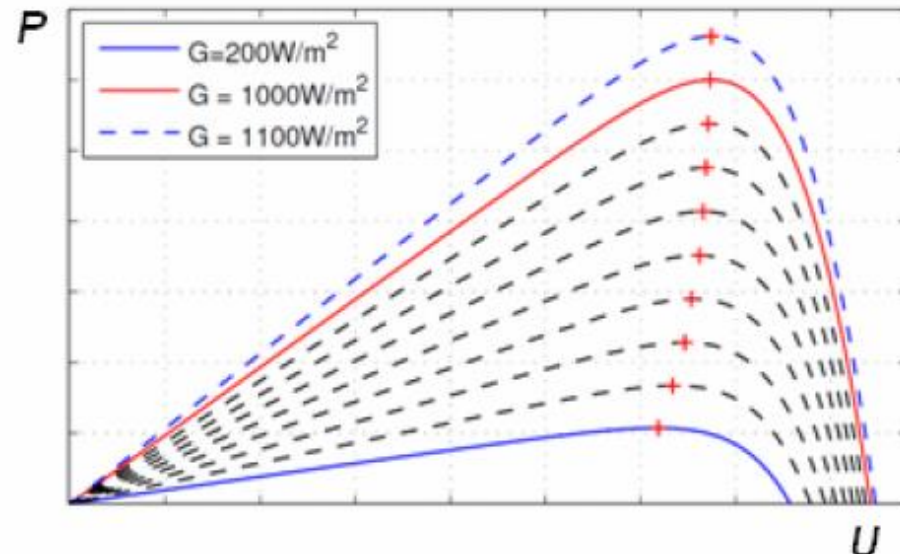
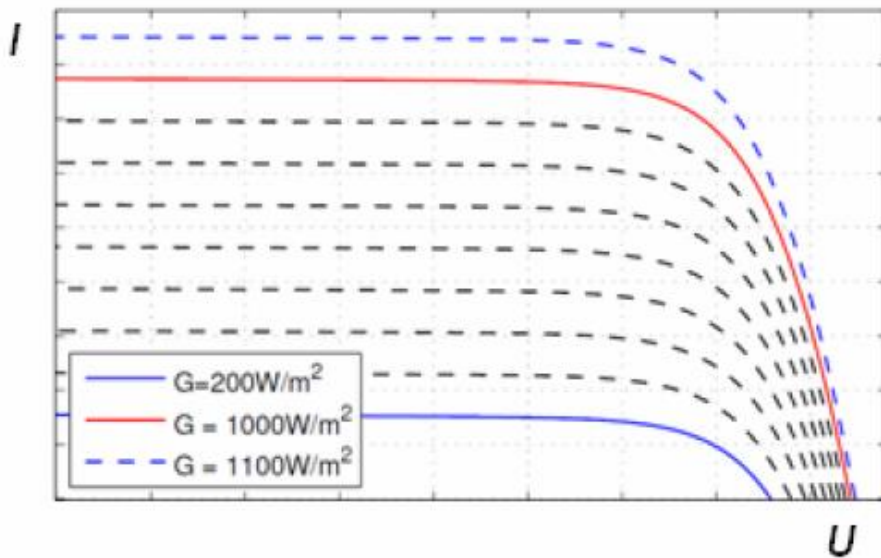
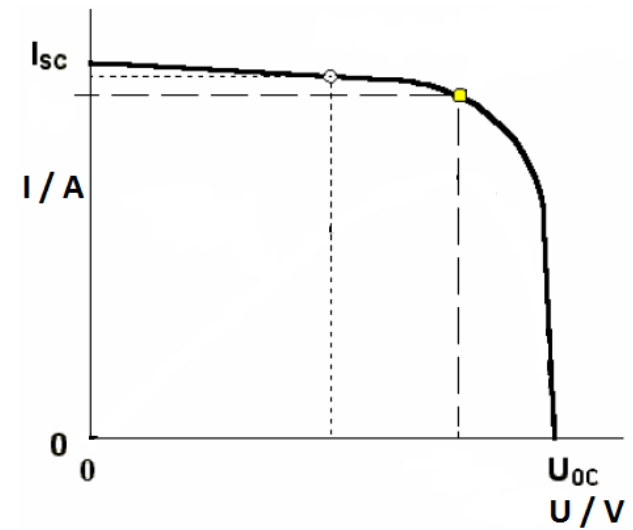
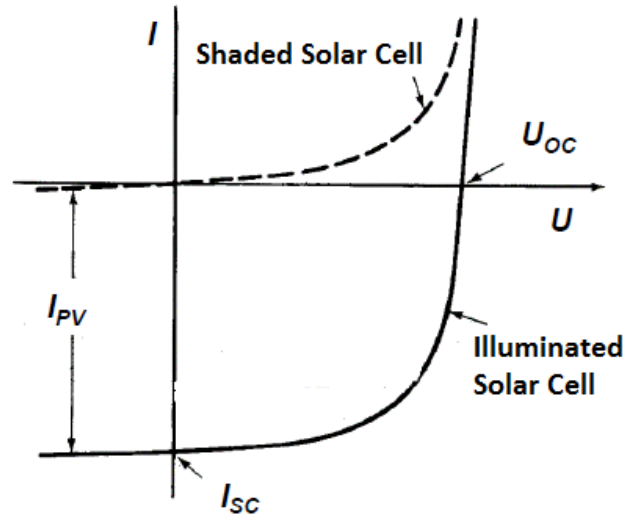
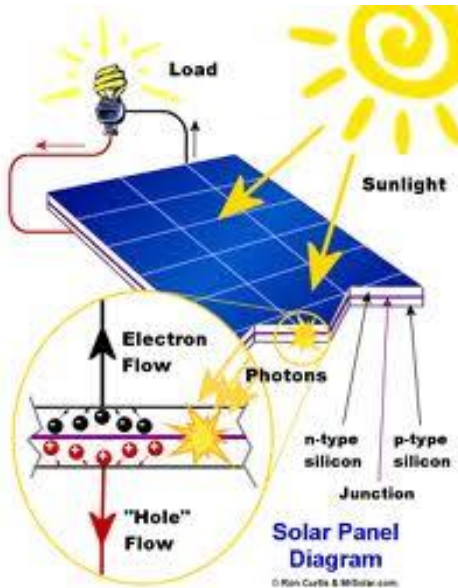
SOLAR ENERGY APPLICATION SYSTEMS

Concentrator Photovoltaics

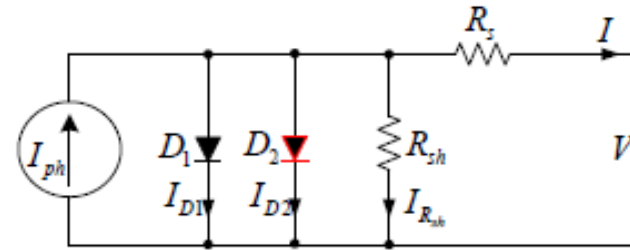
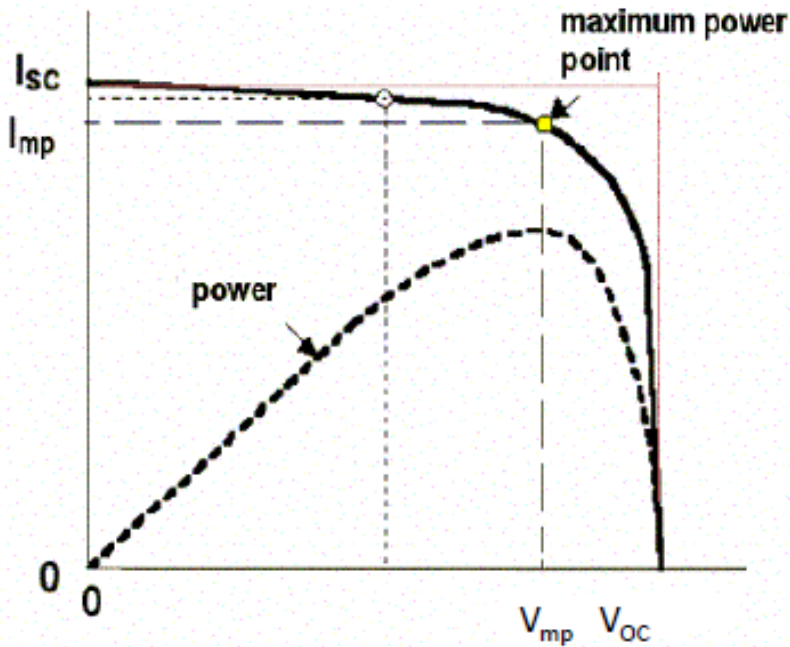
Ing. Peter Pikna



Solar Cell and Light



Standard Testing Conditions



$$I = I_{ph} - I_{01} \left(e^{\frac{V+IR_s}{V_{t1}}} - 1 \right) - I_{02} \left(e^{\frac{V+IR_s}{V_{t2}}} - 1 \right) - \frac{V + IR_s}{R_{sh}}$$

A_1, A_2 - diode ideality factors, I_{01}, I_{02} - dark saturation currents
 R_s - series resistance, R_{sh} - shunt resistance

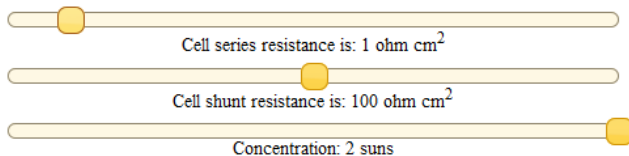
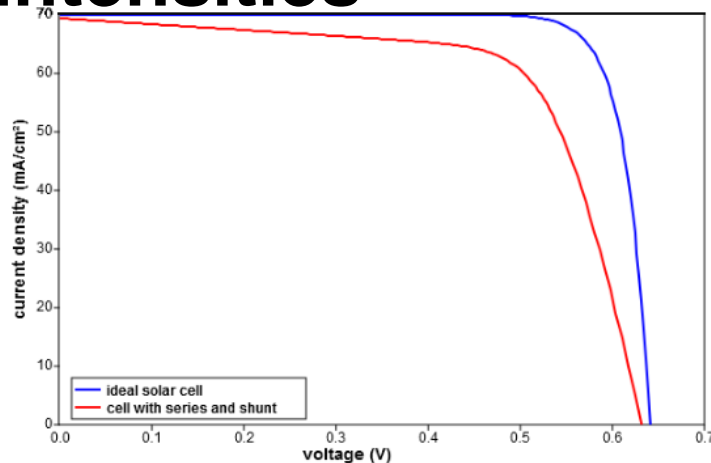
- Direct measurement of voltage and current (V_{oc} and I_{sc})
- Standard Testing Conditions: 25°C, **1000 W.m⁻²**, AM = 1.5

1000 W.m⁻² = 1 SUN

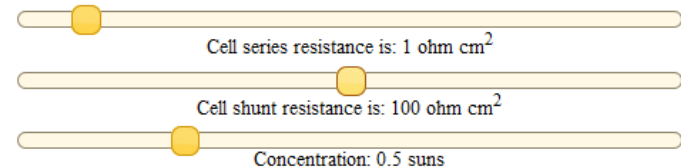
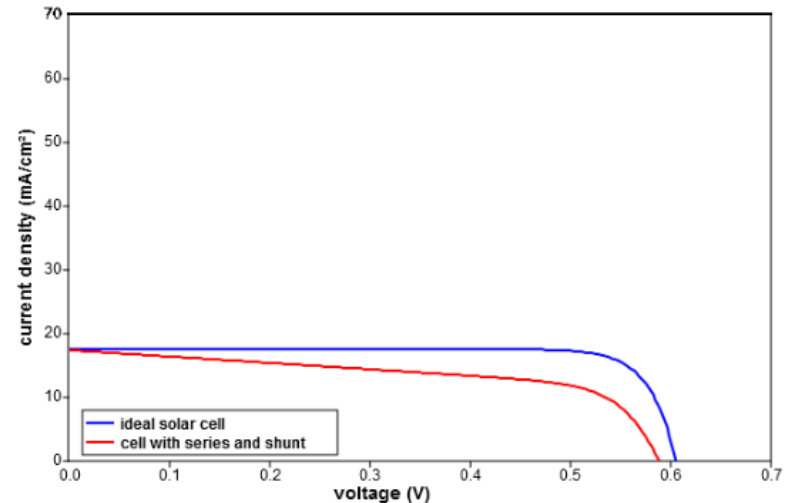
Effect of Light Intensity



- <http://pveducation.org/pvcdrom/solar-cell-operation/effect-of-light-intensity>
- R_{SS} greater effect on performance at **high light intensities**
- R_{SH} greater effect on performance at **low light intensities**



Ideal Cell: $V_{oc} = 0.641$ $I_{sc} = 70$ mA/cm² $FF = 0.84$
 Real Cell: $V_{oc} = 0.632$ $I_{sc} = 69.3$ mA/cm² $FF = 0.69$



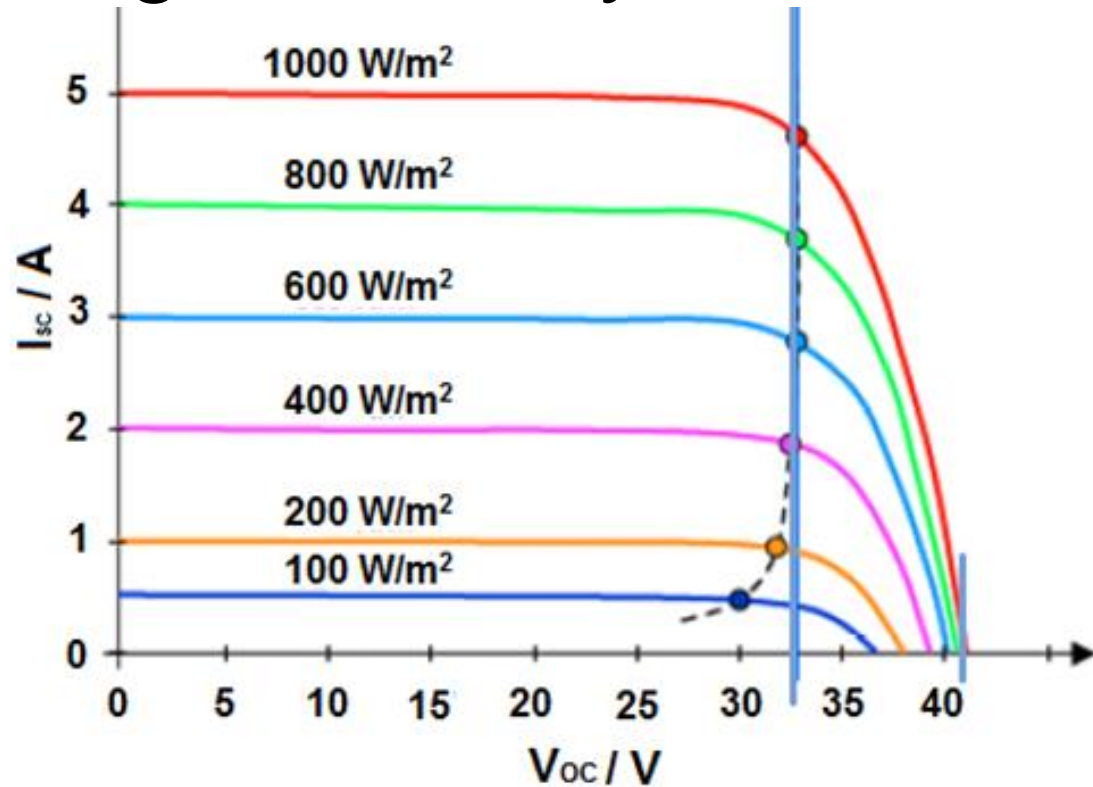
Ideal Cell: $V_{oc} = 0.606$ $I_{sc} = 17.5$ mA/cm² $FF = 0.83$
 Real Cell: $V_{oc} = 0.589$ $I_{sc} = 17.3$ mA/cm² $FF = 0.58$

Effect of Light Intensity



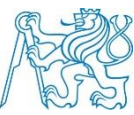
- I_{SC} increases linearly
- V_{OC} increases logarithmically
- η increases logarithmically

$$\eta = \frac{U_{MPP} \cdot I_{MPP}}{P_{IN}}$$



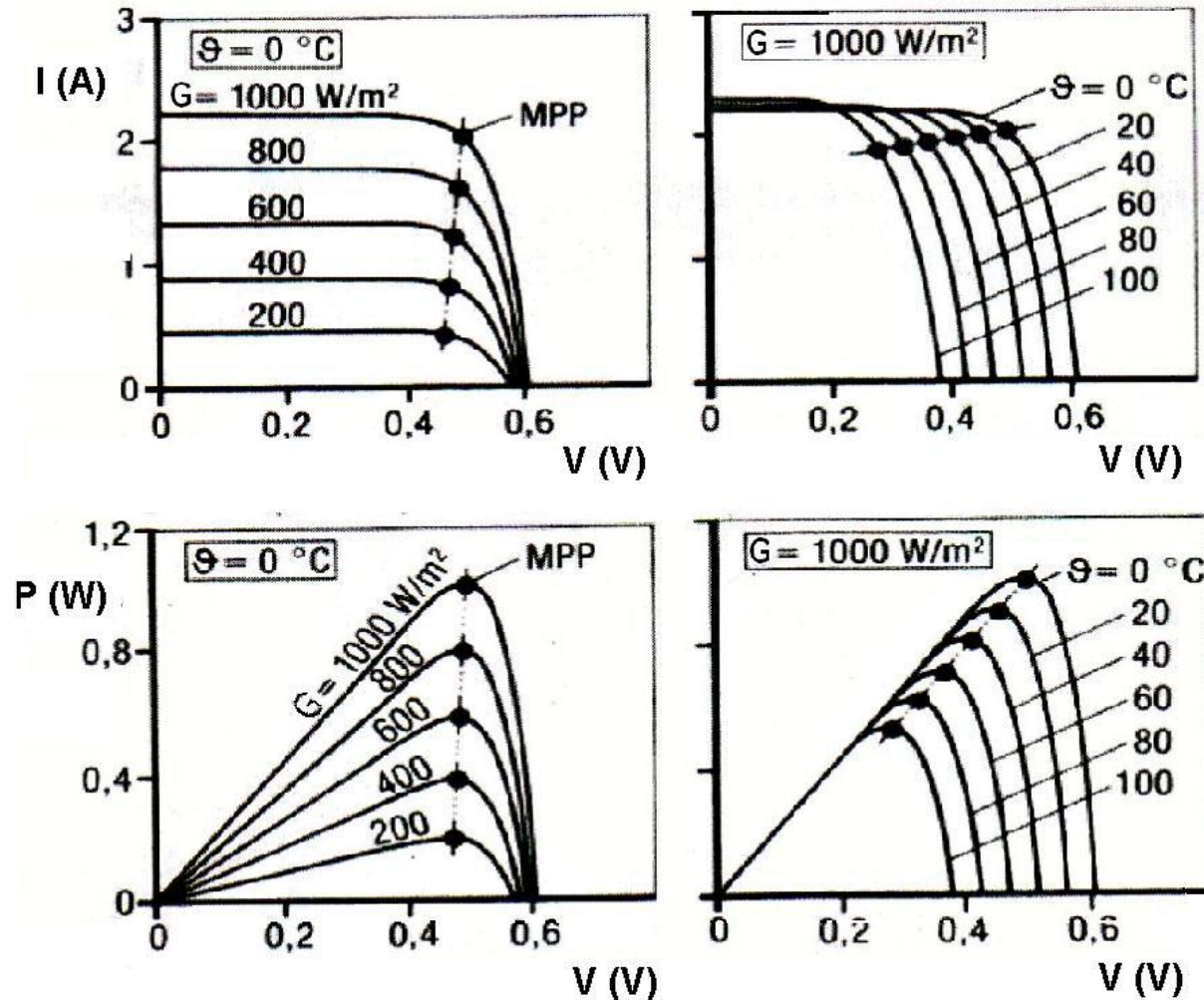
$$A_{ill} J_{PV} = I_{PV} \gg I_{01} + I_{02} \quad \longrightarrow \quad V_{OC} \approx \frac{kT}{q} \ln \frac{I_{PV}}{I_{01}}$$

$$V'_{OC} = \frac{nkT}{q} \ln \left(\frac{X I_{SC}}{I_0} \right) = \frac{nkT}{q} \left[\ln \left(\frac{I_{SC}}{I_0} \right) + \ln X \right] = V_{OC} + \frac{nkT}{q} \ln X$$



Effect of Light Intensity

- Benefit of higher efficiency can be compensated by losses in R_{SS} when I_{SC} and T increase



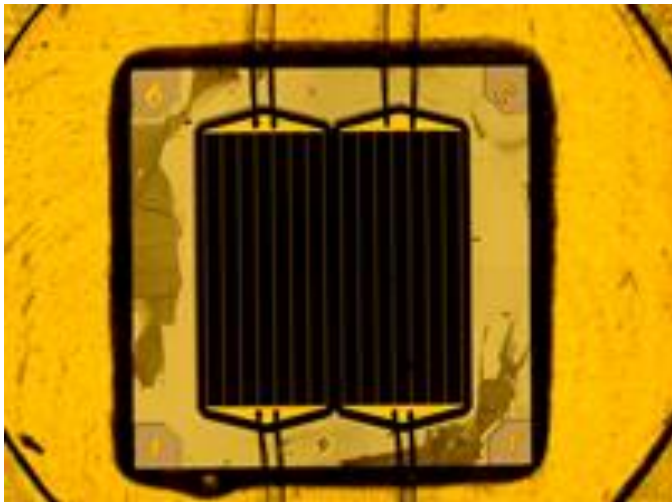
Why to Increase Light Intensity?



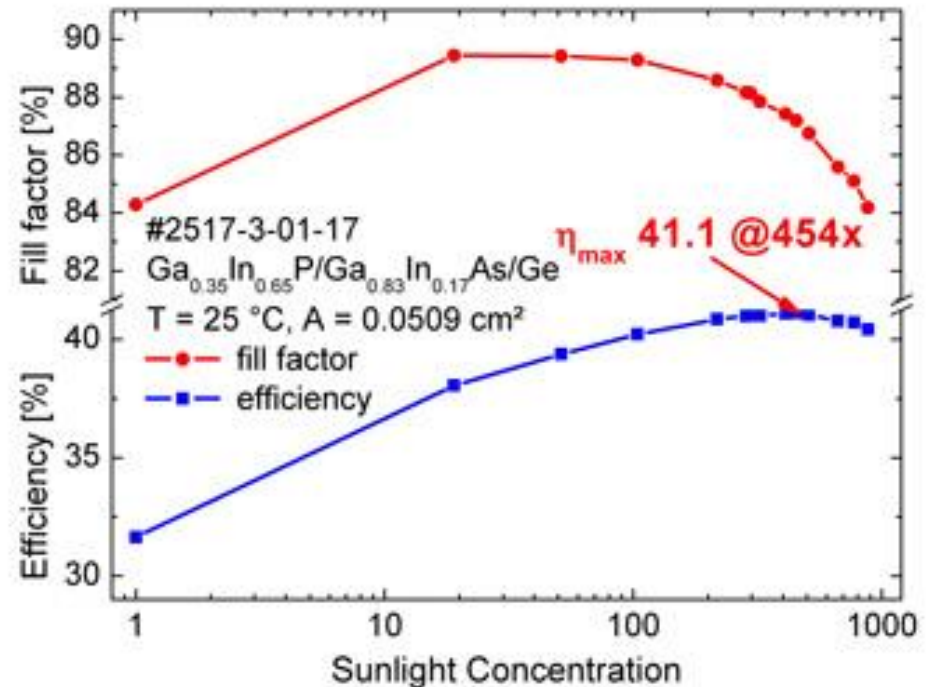
- Enhance of conversion efficiency
- Reduction of semiconductor material, costs

*Increase of a **solar cell efficiency** makes all the solar system more valuable*

Efficiency = f (Light Intensity)



Picture (above): Record $\text{Ga}_{0.35}\text{In}_{0.65}\text{P}/\text{Ga}_{0.83}\text{In}_{0.17}\text{As}/\text{Ge}$ solar cell, with a cell area of 5.09mm^2 .

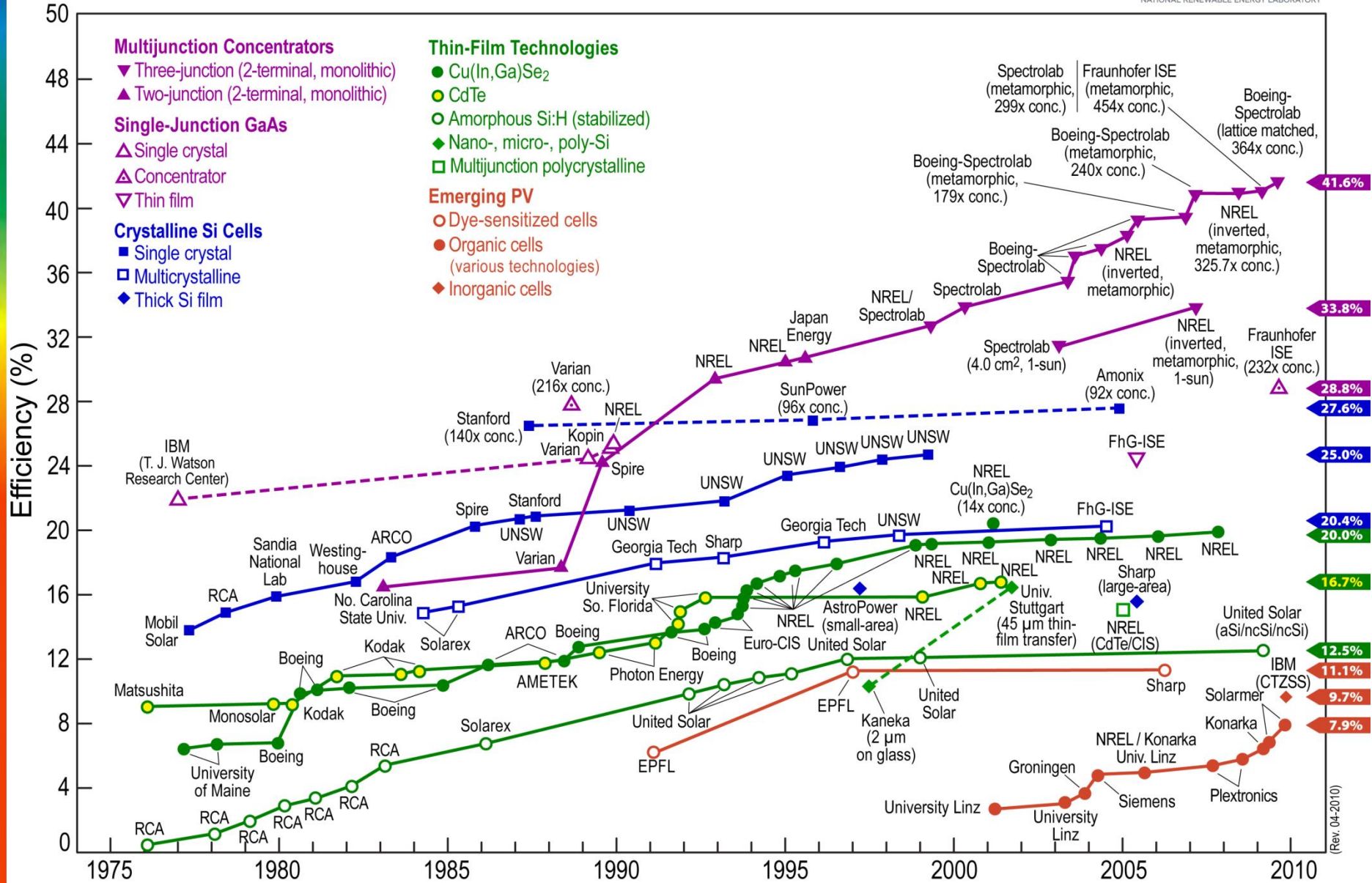


15/04/2013

http://www.semiconductor-today.com/news_items/2009/JAN/FISE_150109.htm



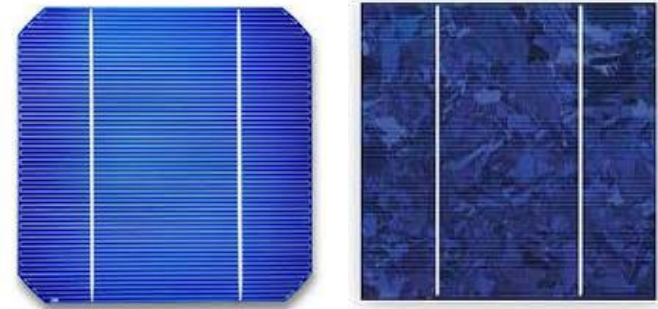
Best Research-Cell Efficiencies



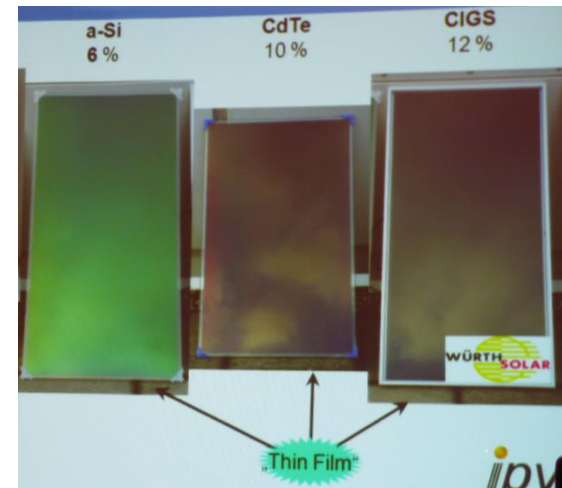
Solar Cell Generations



- 1st generation
 - Wafer-based solar cells



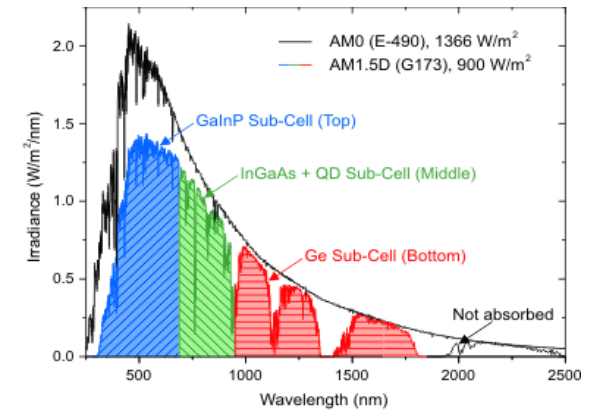
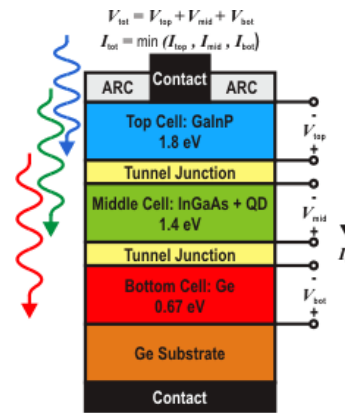
- 2nd generation
 - Thin film solar cells



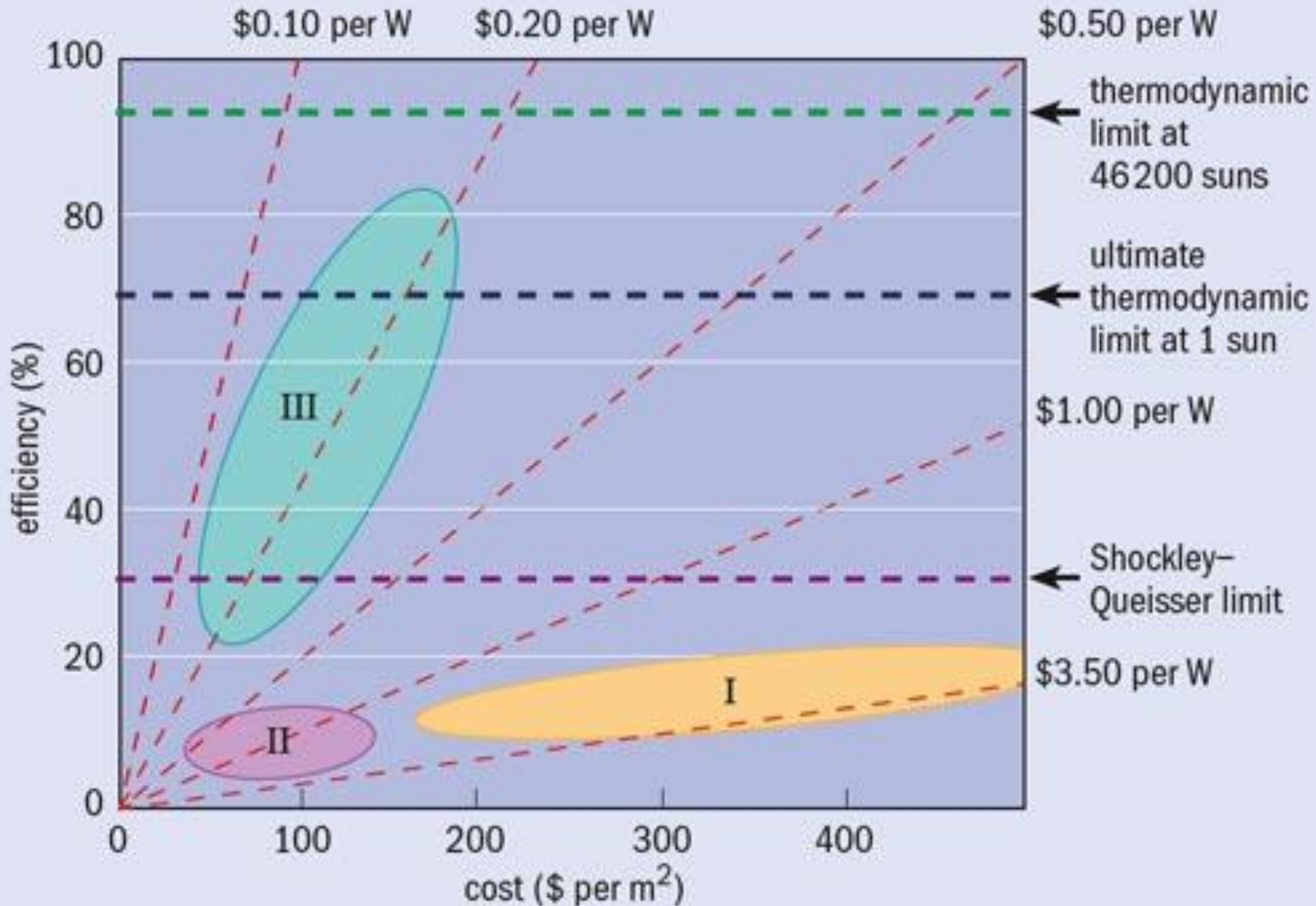
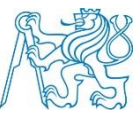
Prof. Weber,
Conference
HAWAII 2012

- 3rd generation
 - ??? maybe
multi-junction solar cells

15/04/2013



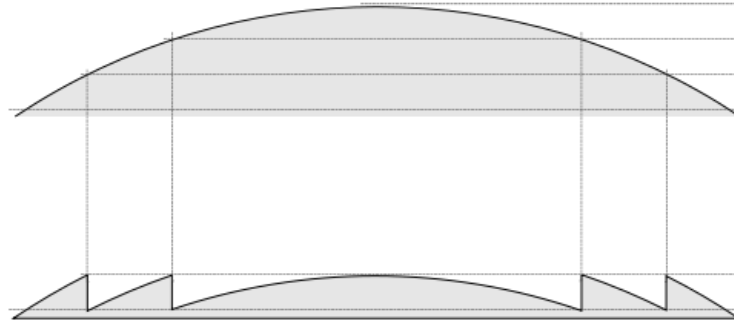
Costs versus Efficiency



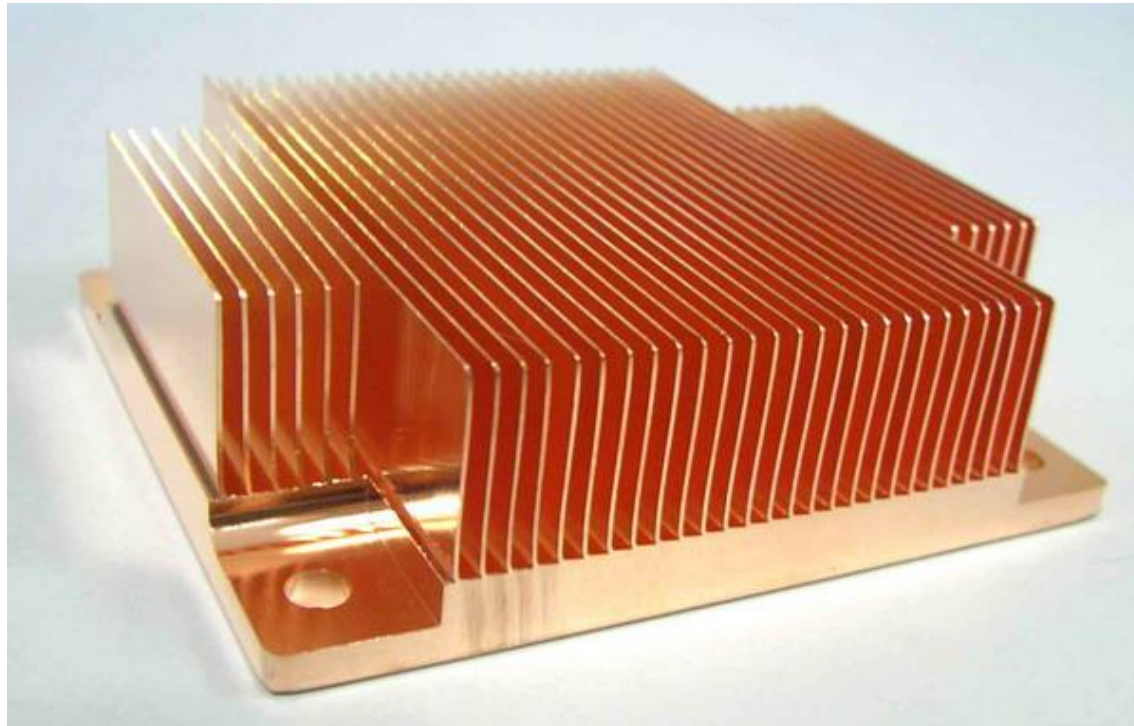
Components for Concentrator PV



- **Fresnel lens to concentrate light**



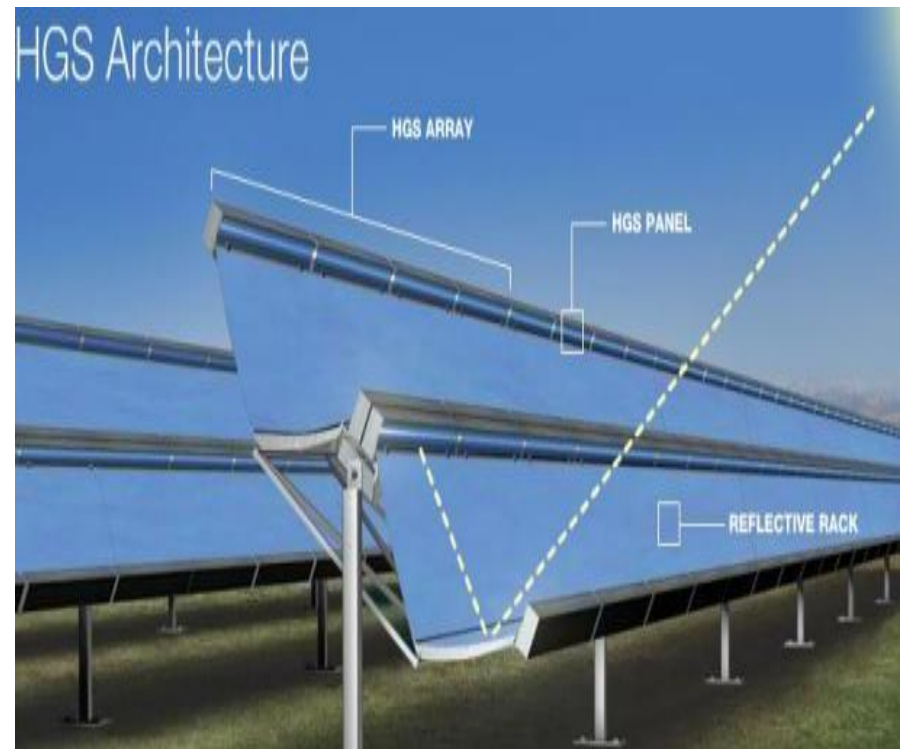
- **Heat sink to cool a solar cell**



Low Concentration Systems



- 1-axis tracking system
 - Advantages:
 - Higher efficiency
 - Less semiconductor material
 - Rather use of conventional material
 - Disadvantages:
 - Higher installation costs (balance the system)



http://news.cnet.com/8301-11128_3-10232586-54.html



Skyline Solar concentrates light onto strips of monocrystalline silicon cells

The Greenfield solar concentrator

This machine can concentrate sunlight to 900 times its original brightness on just a few square inches of solar cells — enough to produce 1,500 watts of electricity. The reason is a breakthrough in the cells' internal design, plus a clever array of mirrors and a sophisticated sun-tracking system. Two installers can assemble a concentrator in half a day from common and lightweight materials.

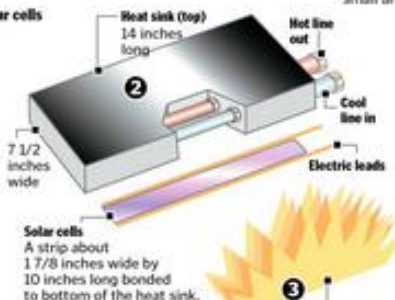
1. The light reflectors

The concentrator uses 28 mirrored aluminum panels arranged in a wing shape to form a parabolic curve — bending the light upward and inward as they reflect it. They concentrate a narrow beam onto the solar cells, which are held on a boom above the wing. The interchangeable panels can be replaced as easily as swapping out the rubber strip in an automotive windshield wiper. Though identical, each panel is held at a slightly different angle along the wing to create the reflective curve.



2. The heat sink for solar cells

The solar cells are bonded to an aluminum block containing internal piping. A coolant is pumped through those channels, maintaining working temperatures under 120 degrees Fahrenheit. Without cooling, temperatures would soar, frying the solar cells.



3. Focusing 900 times the light of normal sun rays

Sunlight is focused in "layers," one on top of the other, in a line across the solar cells, not in a single focused point as with a magnifying glass.

SOURCE: Greenfield Solar Corp.

5. Keeping track of the sun

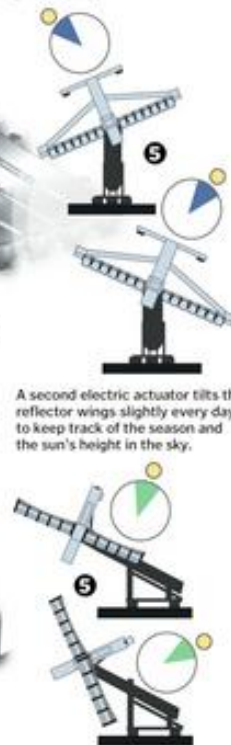
The concentrator automatically tracks the sun across the sky so that its mirrors can reflect the maximum available light onto the solar cells. A microprocessor is programmed to know the geographic location. It also receives input from light sensors. The tiny computer continuously signals a small motor drive system to rotate the reflectors, tracking the sun throughout the day.

Polar mount with electric motors

Solar cells are mounted here

Single-coated aluminum panels

The panels are identical and easy to produce, a key factor in cost control.



A second electric actuator tilts the reflector wings slightly every day to keep track of the season and the sun's height in the sky.

4. Densely stacked solar cell design

Concentrated sunlight floods into tiny unit cells, generating high power in a small area between each solar cell.

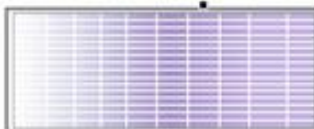
Known as "edge illumination" to researchers, these cells are stacked and turned on their edges to receive the light.

Normal solar design

Conventional solar cells require a much larger area to generate an equal amount of power because the cells are placed side by side.

Size of 40 layered cells is smaller than a penny.

Many unit cells are connected in a series, producing high voltage.



JOHN FUNK, JAMES OWENS | THE PLAIN DEALER

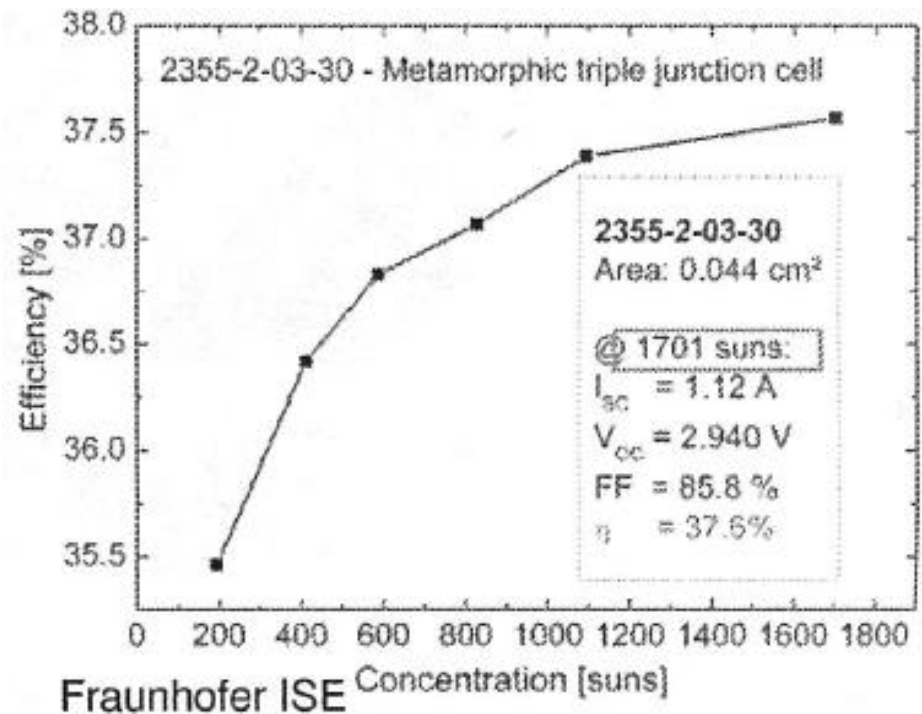


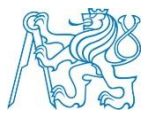
Concentrators



● Issues

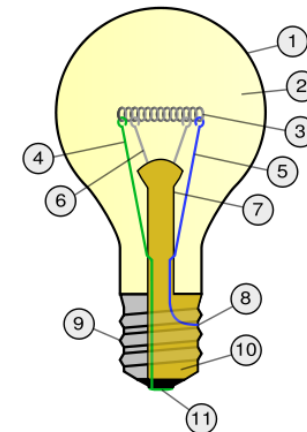
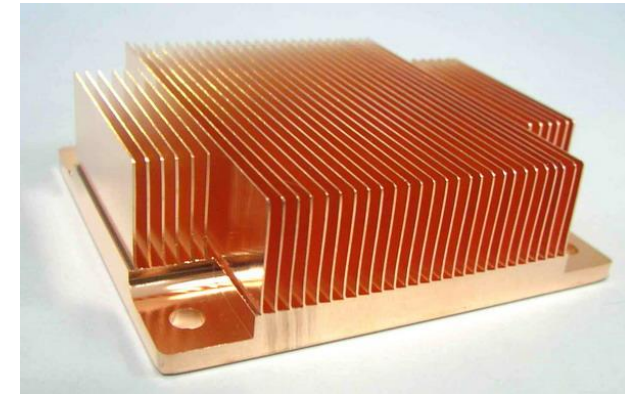
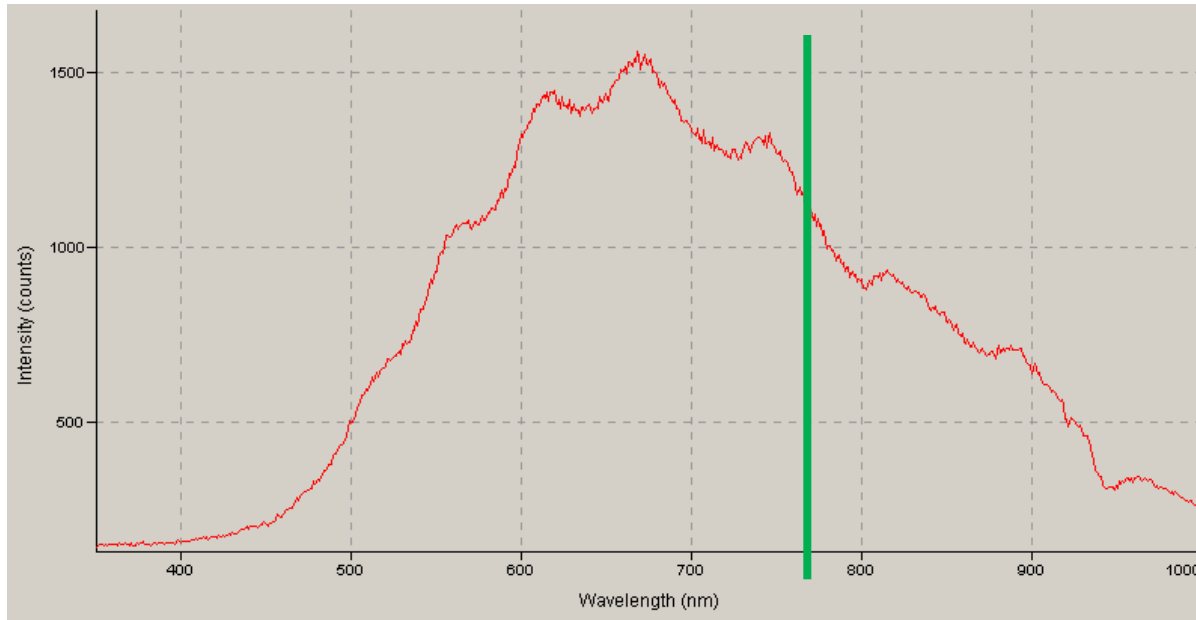
- Cell efficiency
- Module efficiency
- Balance of system
- Tracking
- Cooling





Why Cooling of Concentrator Cells?

- Light intensity at 1000 SUNS = 1 MW/m^2 .
- Cell size $10\text{ mm}^2 \rightarrow$ power of incident light 10 W
- Solar cell efficiency $\eta = 40\%$ \rightarrow 4 W into electricity and **6 W into heat** \rightarrow active cooling needed

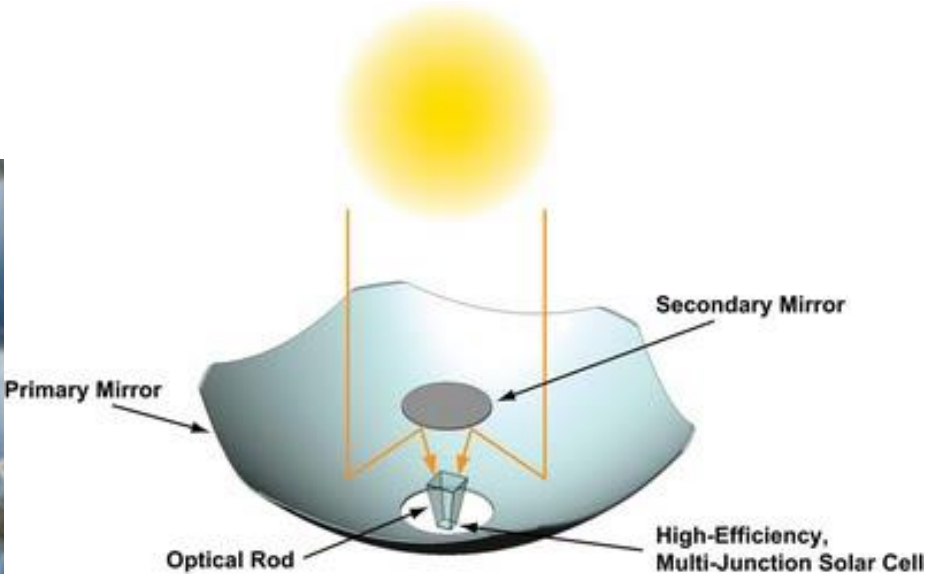


1. Glass bulb
2. Low pressure inert gas
3. Tungsten filament
4. Contact wire (goes out of stem)
5. Contact wire (goes into stem)
6. Support wires
7. Stem (Glass mount)
8. Contact wire (goes out of stem)
9. Cap (Sleeve)
10. Insulation (Vitre)te
11. Electrical contact

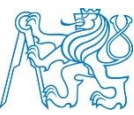
15/04/2013

30% of power transferred into heat
 $100\text{ W} \rightarrow 33\text{ W}$ is heat

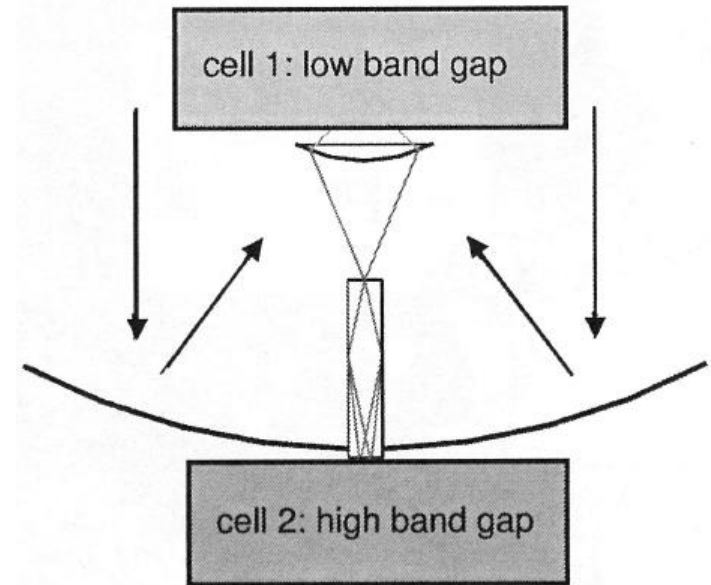
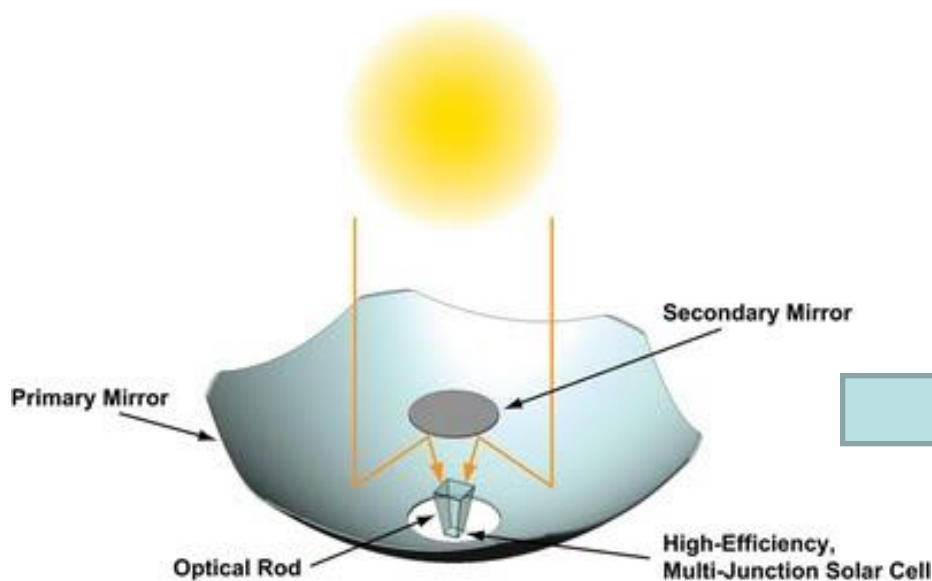
SolFocus



Spectrum Splitting



- Based on “cassegrainian” photovoltaic module
- Low energy solar cell and high energy solar cell



Heliostat Solar Concentrator





High Concentrated Photovoltaic (HCPV) / Combined Heat & Power (CHP) solar energy

How it works

Z20 features two 11m² collectors, mounted on a dual axis tracker that concentrates incoming solar power onto a receiver. The receiver consists of a multi junction PV coupled to heat exchanger that converts concentrated solar flux into electrical power (A) and thermal power (B).

(A) DC electrical power from the PV cells is converted to A.C power and fed to the grid.

(B) Thermal energy is pumped through a closed loop system to the various users and applications such as:

- Municipalities and district heating
- Hotels, Hospitals and resorts
- Industrial process heat: ideal for textile, food and pharmaceutical industry
- Thermal energy cooling can be converted into cooling or desalination and brackish water purification

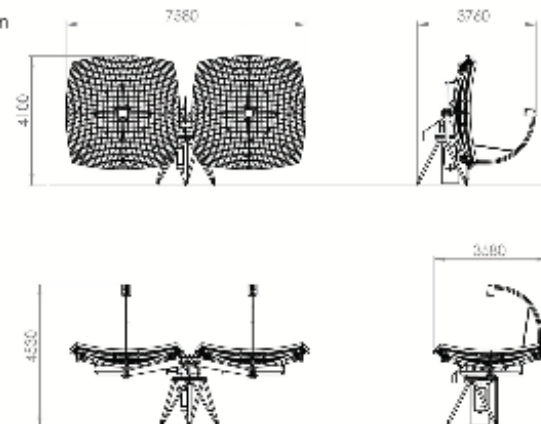
Benefits

- Combined Heat and Power (CHP) generation
- Lowest cost per watt
- Industry highest combined efficiency of >72%
- Shortest possible return on investment
- Most suitable for hot climates
- Modular installations
- System design for easy upgrade - Multi Junction PV is the most progressing solar technology
- Best space utilization of land
- Proven field performance



Featuring

- 2-axis high precision tracking mechanism with zero backlash, using performance feedback-driven, closed loop that continually positions the mirrors for maximum effectiveness
- State-of-the-art high efficiency Multi Junction PV cells
- Engineered high efficiency multi-channel heat exchanger
- Designed for 20 year service, constructed from highly durable materials
- Environmentally friendly, 99% recyclable by weight
- Reliable operation, easy installation and servicing
- Required minimal area, only 70-90m² for a single Z20 unit, 15.5kWp combined output (< 6m²/kWp)
- Packaged equipment, minimizing balance-of-system cost



Engineering Data

Data	Units	Z20	
General	Number of modules (dishes)	EA	2
	Total aperture area	m ²	22
	Tracking technology	2-axis	
	Azimuth range	deg	0-360 ^o
	Elevation range	deg	0-90 ^o
Electricity	Tracking control	Sensorless closed loop	
	Peak electrical power	kWp	4.5 (*)
	Operating voltage	VDC	160-230
Thermal	Peak thermal power	kWp	11 (*)
	Fluid	Water or coolant	
	Maximum supply temperature	deg C	100
	Nominal flow (both modules)	l/min	1.2
Physical Dimensions	Operating wind speed	km/h	40
	Permissible wind speed	km/h	160
	Weight	kg	1,500
	Height in stowed position	m	4.53
	Height in operation	m	4.10
	Depth	m	3.76
	Width	m	7.58
Compliance	IEC 62108, CE		
Inverter	Mounting ready		

Notes: (*) Tested at 1 kW/m² irradiance. Allowing up to 4% yield losses, due to shading (northern latitude 200-400). Data is subject to changes.

The Light-guide Solar Optic (LSO)

What makes the Sun Simba different is its unprecedented solar concentrator, the patented **Light-guide Solar Optic (LSO)**.

The LSO is a thin optical structure made from simple acrylic and glass components that internally traps and redirects sunlight, concentrating it onto a small, high efficiency photovoltaic cell attached at the optic's centre. Designed to capture and concentrate sunlight – not the image of the sun – the need for focal depth and the related bulky enclosures of competing Concentrated Photovoltaic (CPV) systems are eliminated:

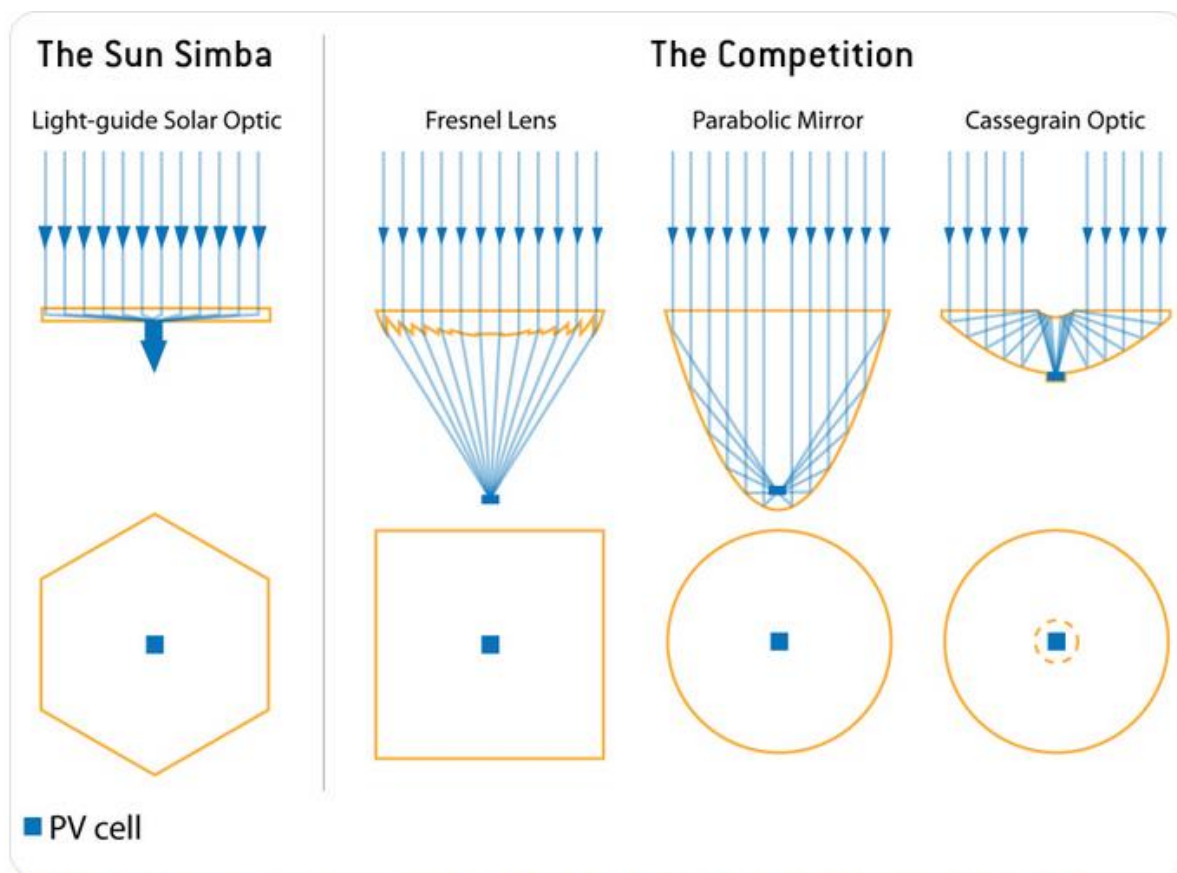


Figure 1: Morgan Solar's LSO vs. Competition Optics: Our LSO has a lower profile and uses less material than any other concentrating system, with equivalent or better concentration factors and angular acceptance.

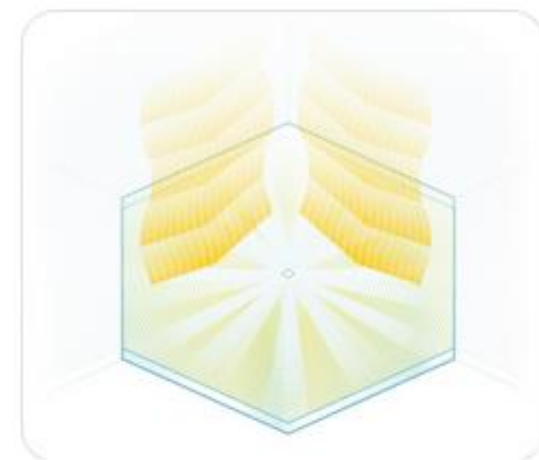
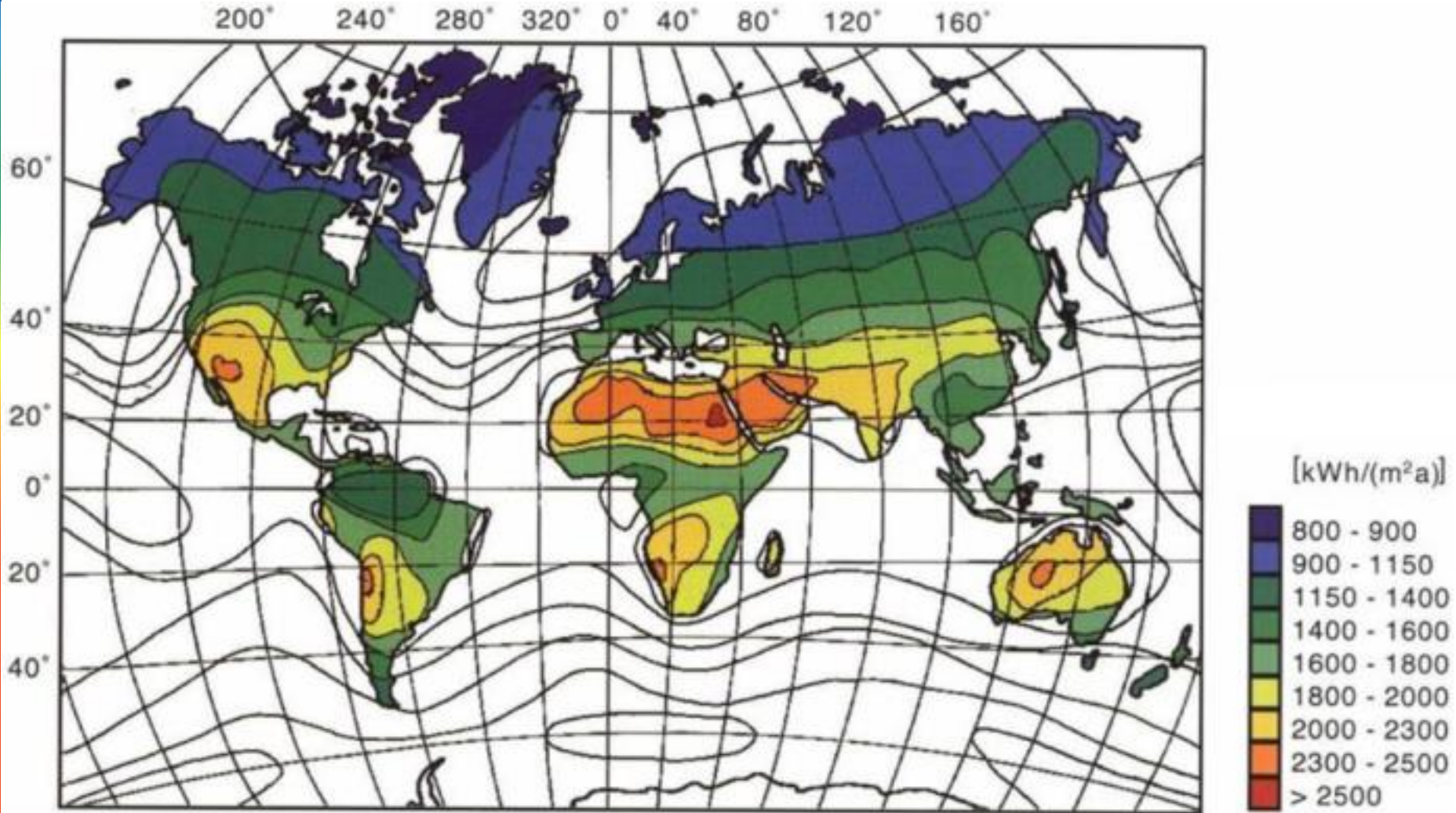
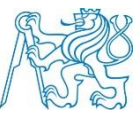


Figure 2: Light striking the top of the LSO is trapped and transported inside the optic to a high efficiency, multi-junction PV cell located at the optic's centre.

Advantages of the LSO

- ▶ concentrates sunlight by up to 1000 suns with higher concentrations possible
- ▶ eliminates the bulkiness of existing CPV systems
- ▶ not affected by thermal expansion
- ▶ is extremely low cost
- ▶ light-weight and rugged
- ▶ easy to manufacture
- ▶ no toxic or exotic materials, 100% recyclable

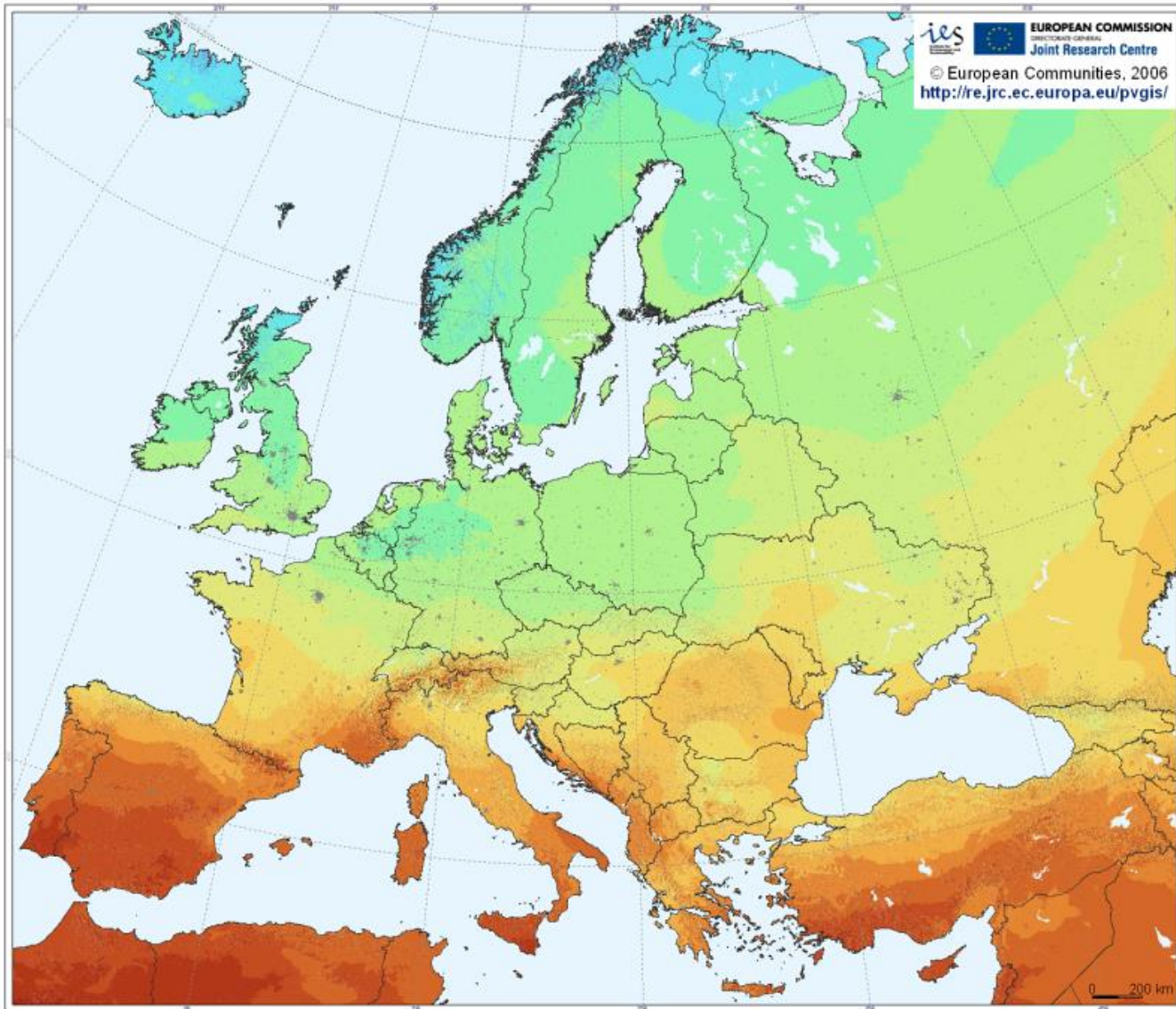
World Solar Radiation



Europe Solar Radiation



Photovoltaic Solar Electricity Potential in European Countries



ies
EUROPEAN COMMISSION
DIRECTORATE GENERAL
Joint Research Centre
© European Communities, 2006
<http://re.jrc.ec.europa.eu/pvgis/>

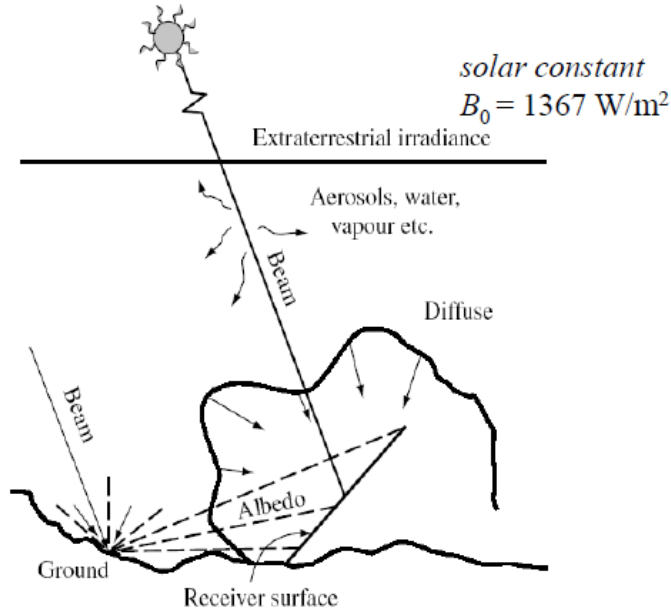
Yearly sum of global irradiation incident on optimally-inclined south-oriented photovoltaic modules
Global Irradiation [kWh/m²]
<600 800 1000 1200 1400 1600 1800 2000 2200>

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>

Direct versus Diffused Solar Radiation



Irradiance means density of power falling on a surface, and is measured in W/m^2



beam radiation, made up of beams of light that are not reflected or scattered - B

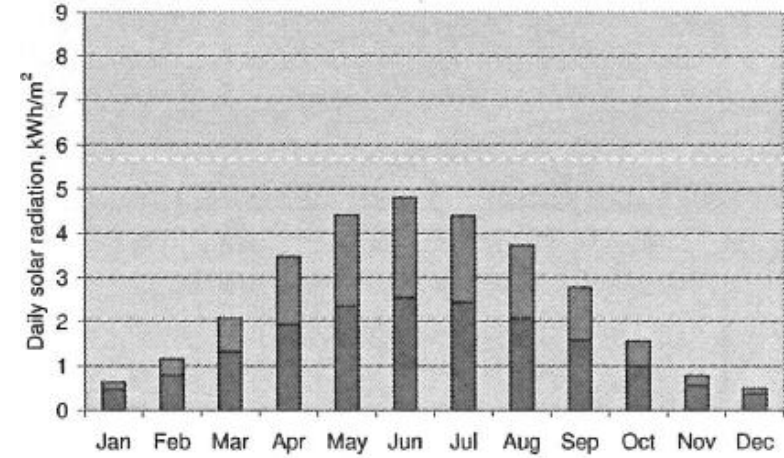
diffuse radiation, coming from the whole sky apart from the sun's disc - D

albedo radiation is radiation reflected from the ground - R

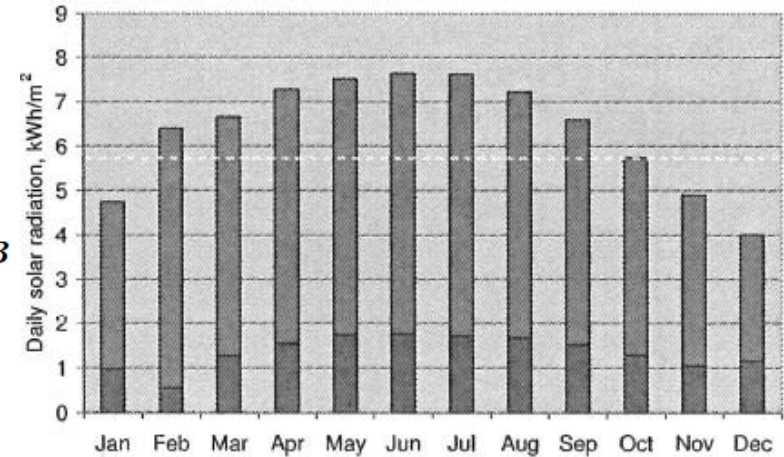
global radiation (direct + diffuse + albedo). $G = B + D + R$

■ diffuse ■ direct beam

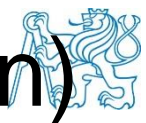
London



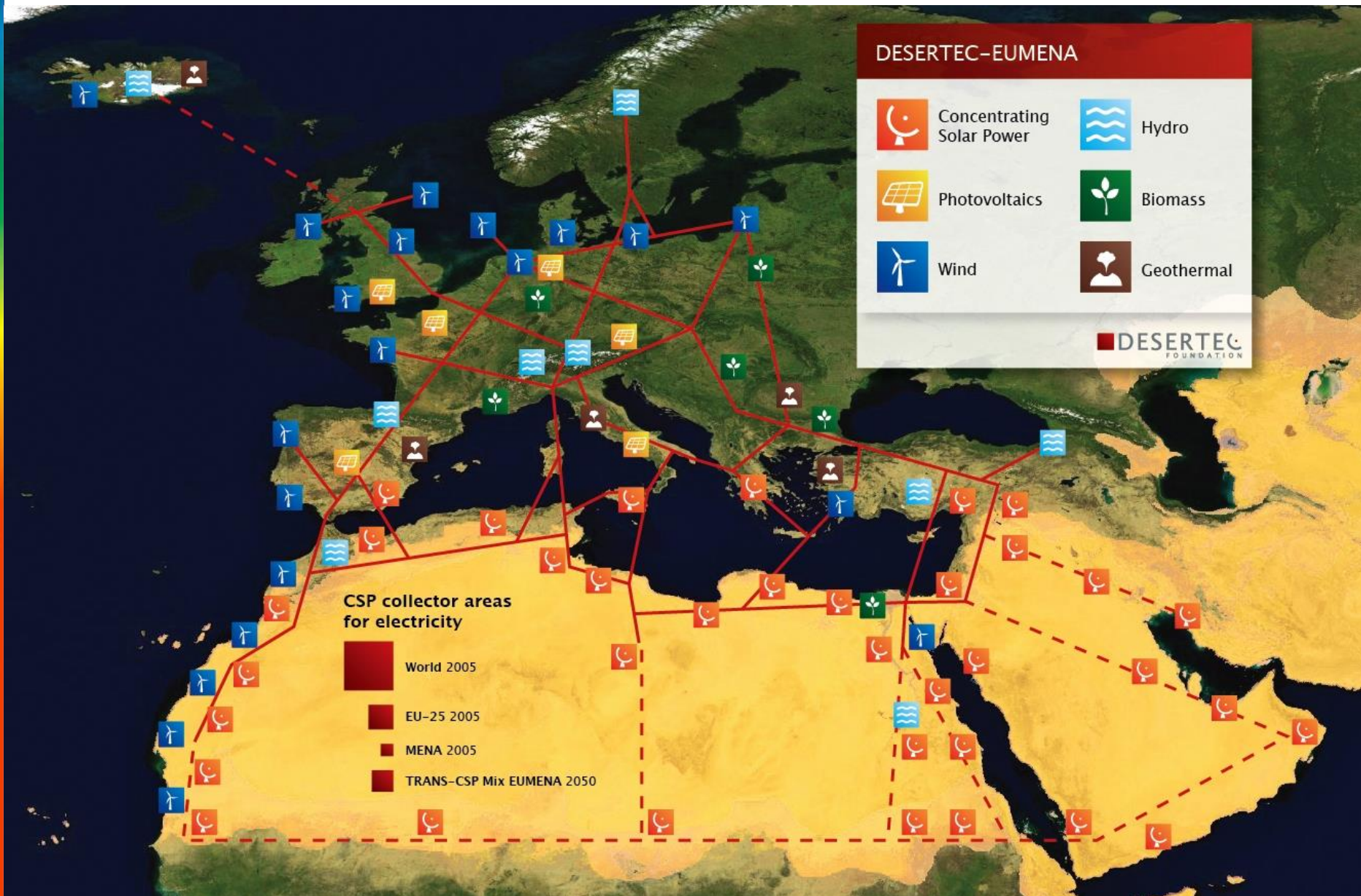
Sahara desert



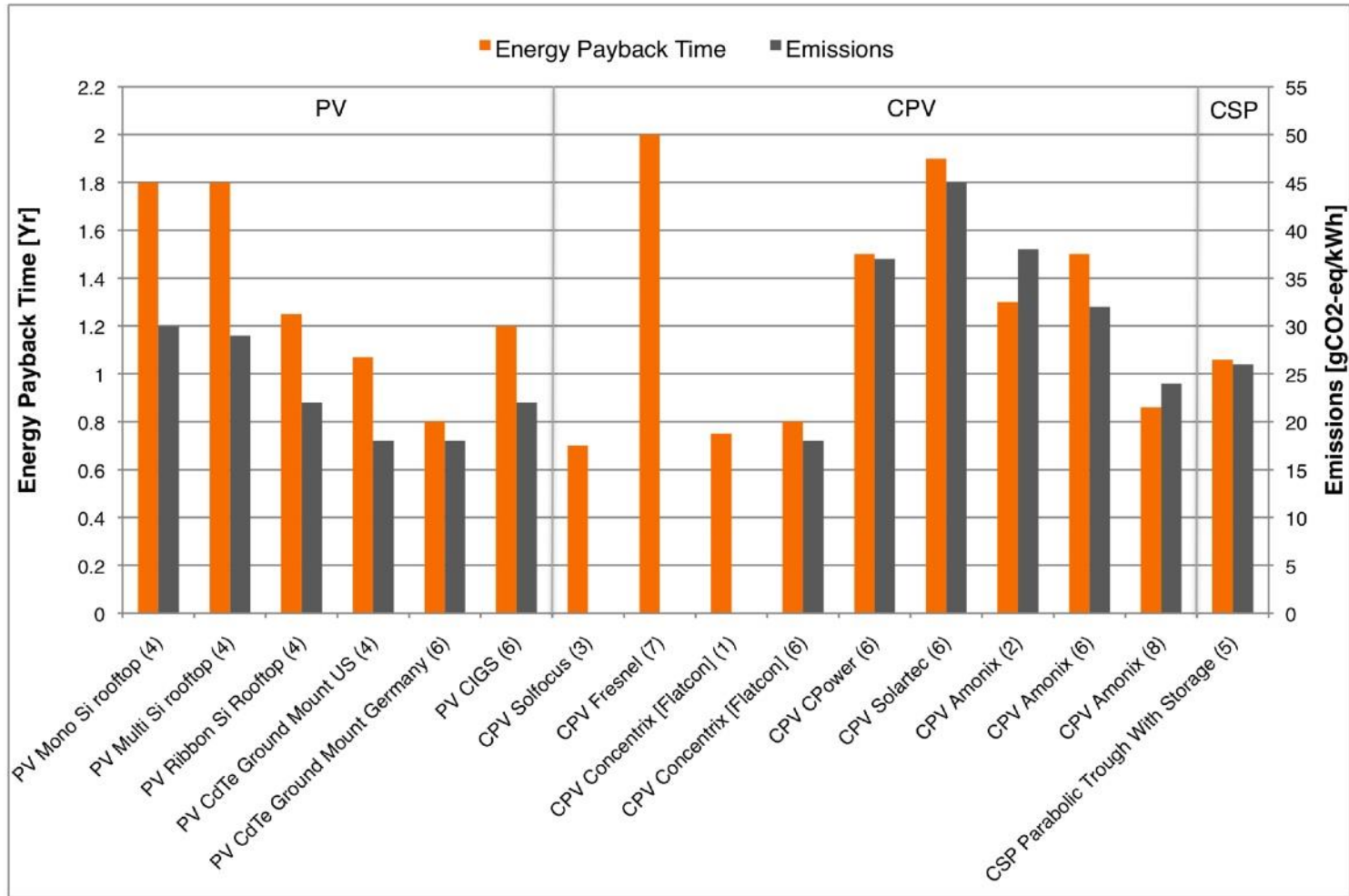
Desertec = 400 billion euros (\$514 billion)



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



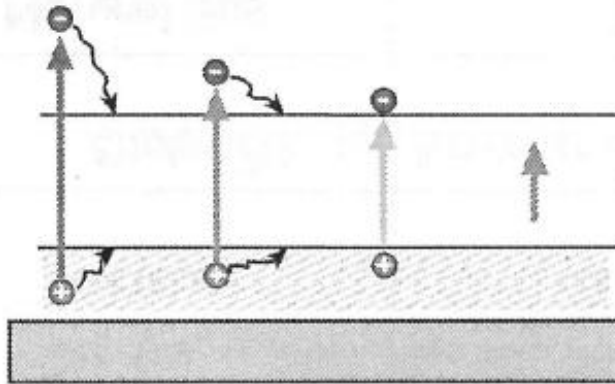
Energy Payback Time and GHG Emissions



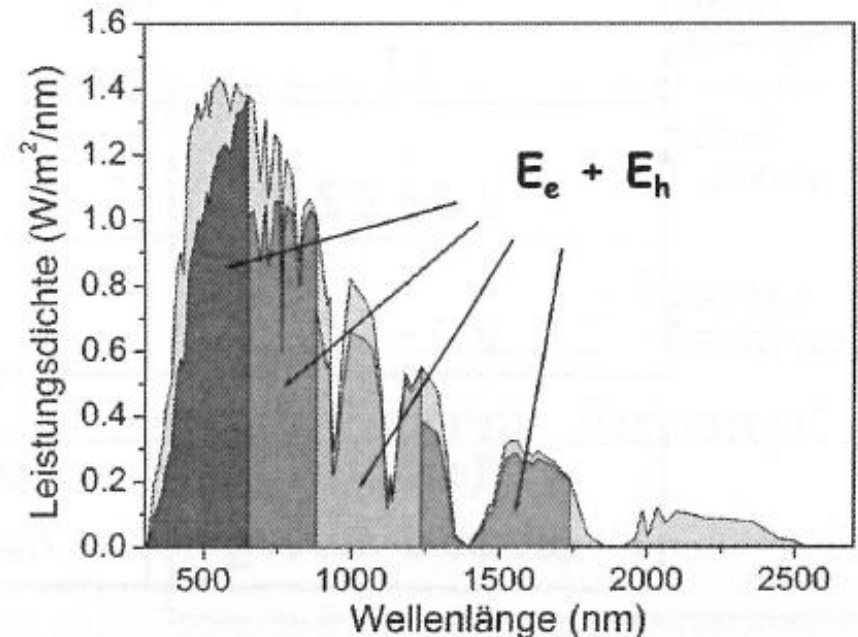
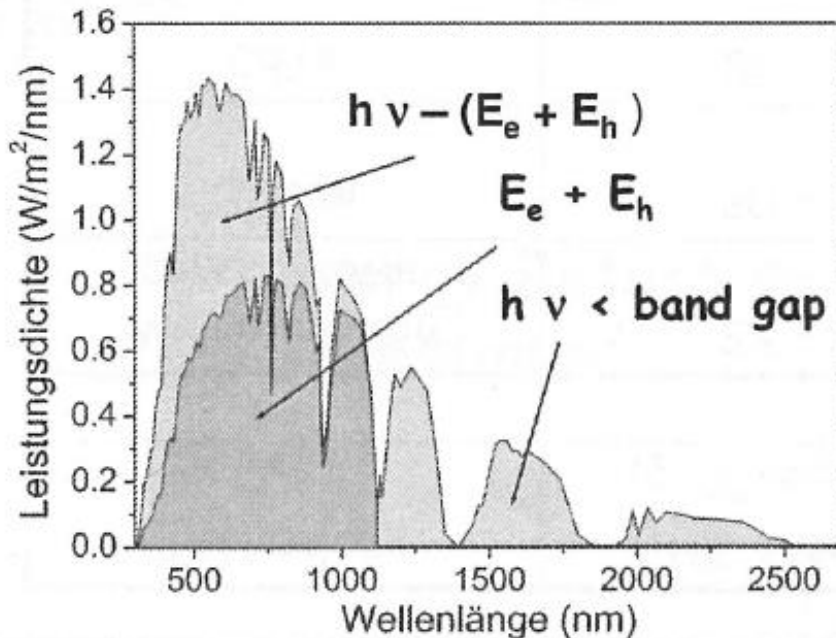
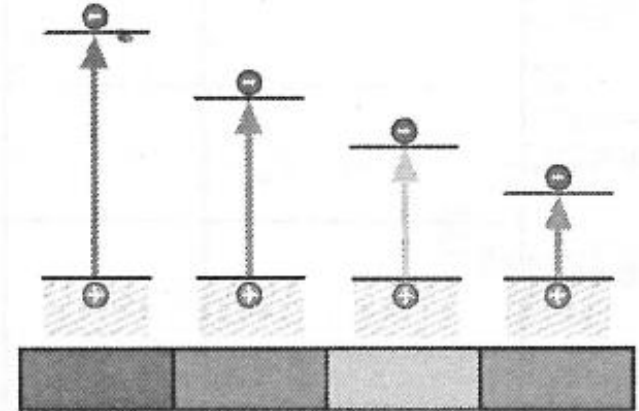
Solar Cells for Concentrators



Single junction



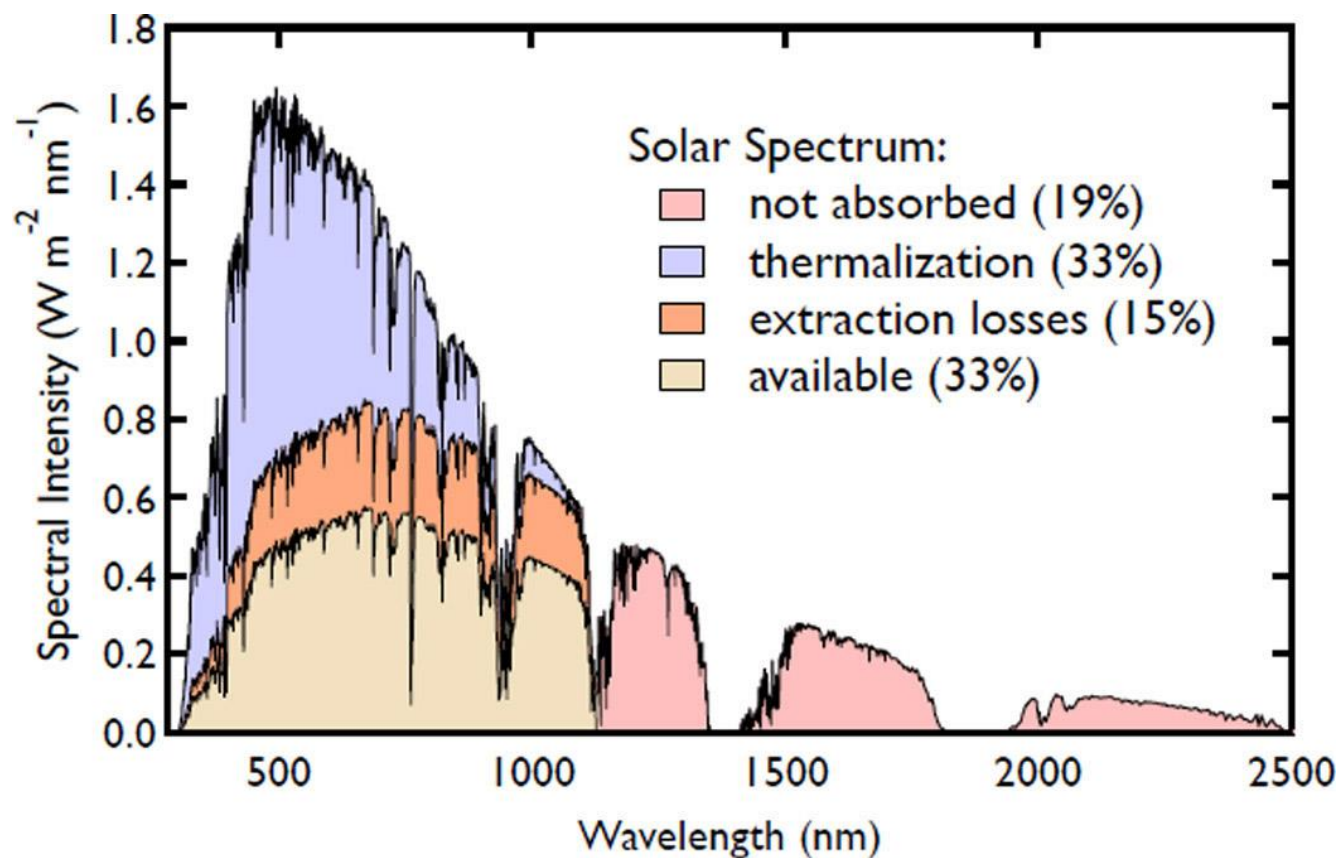
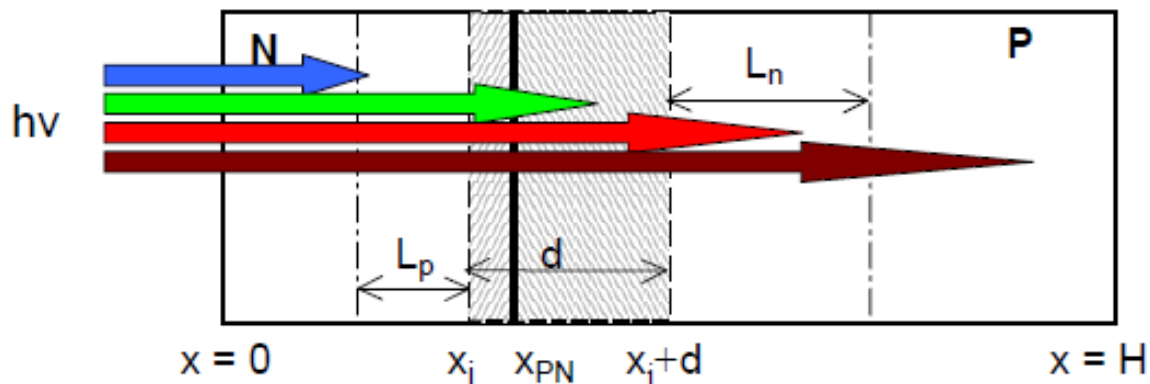
Multi junction



Solar Cells for Concentrators



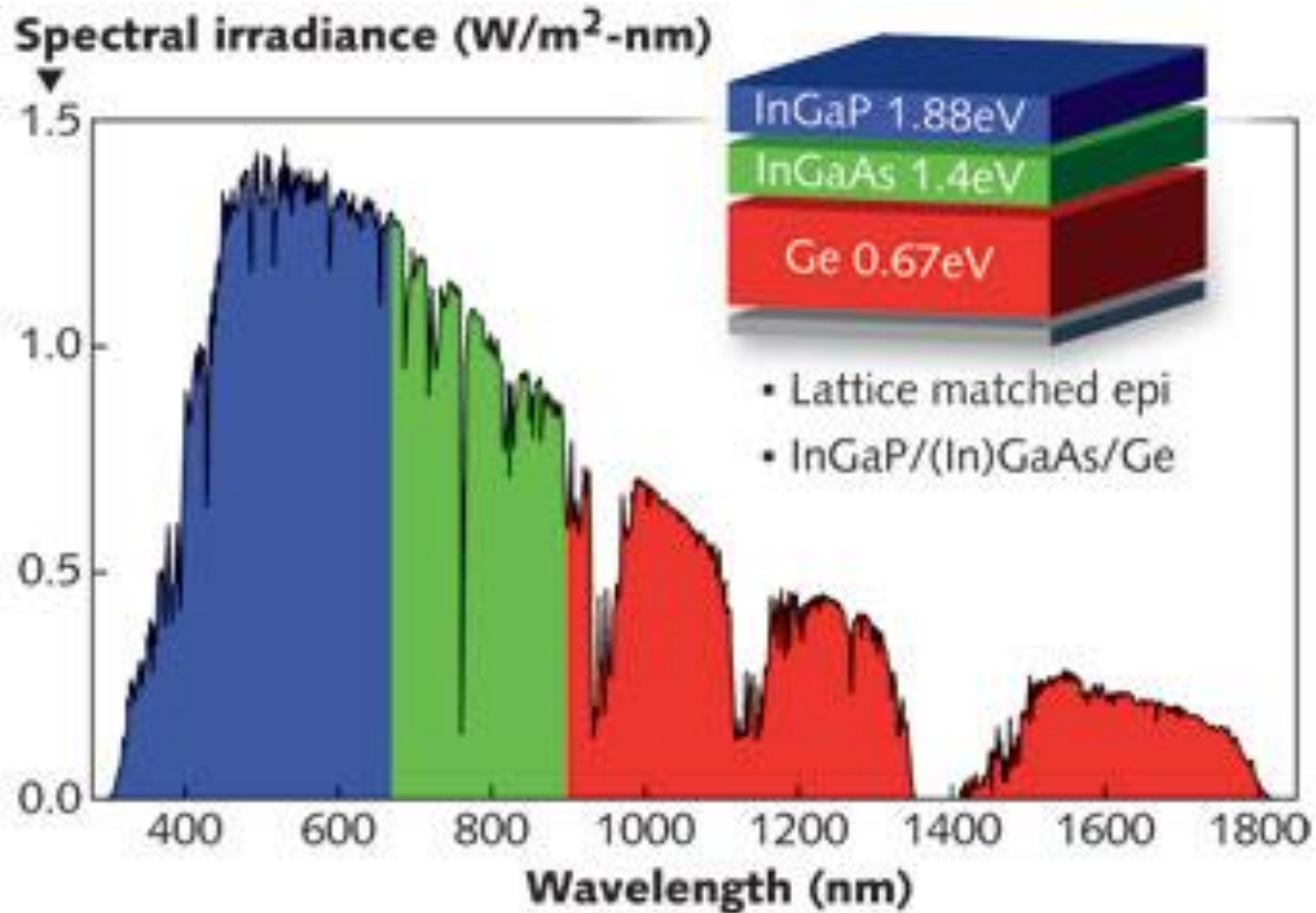
- Single-junction



Solar Cells for Concentrators

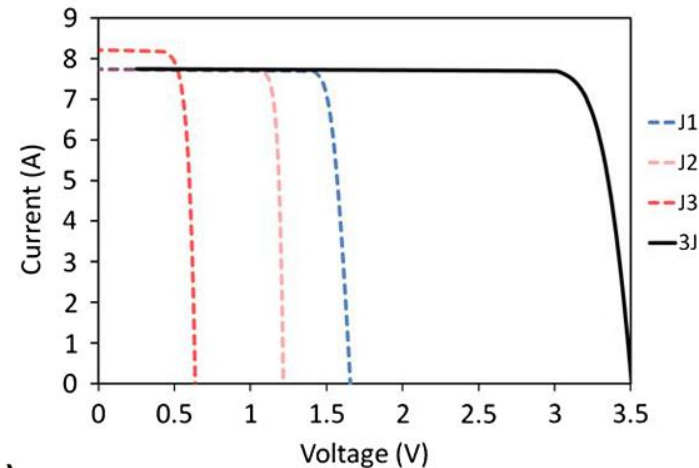
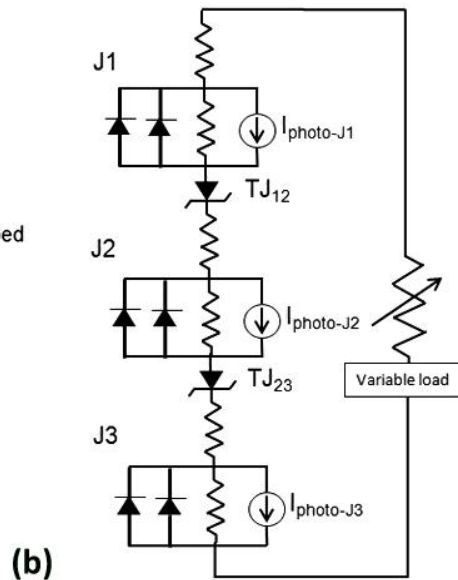
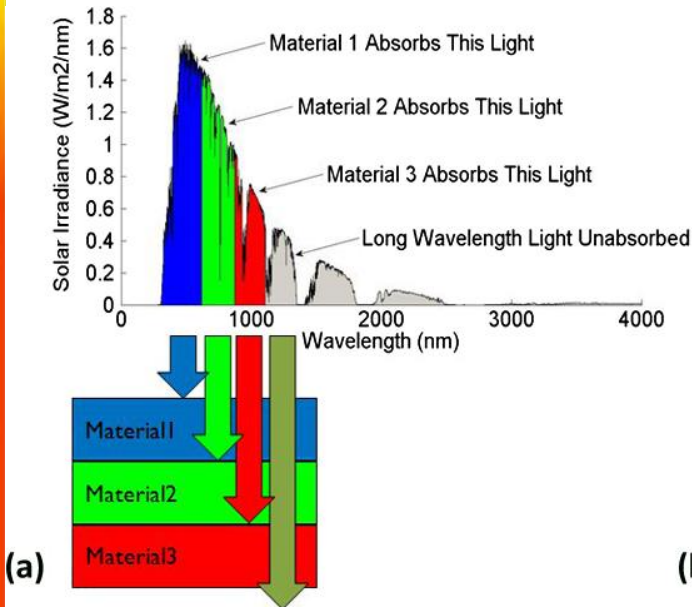


- Multi-junction



Monolithic and Non-Monolithic Concept

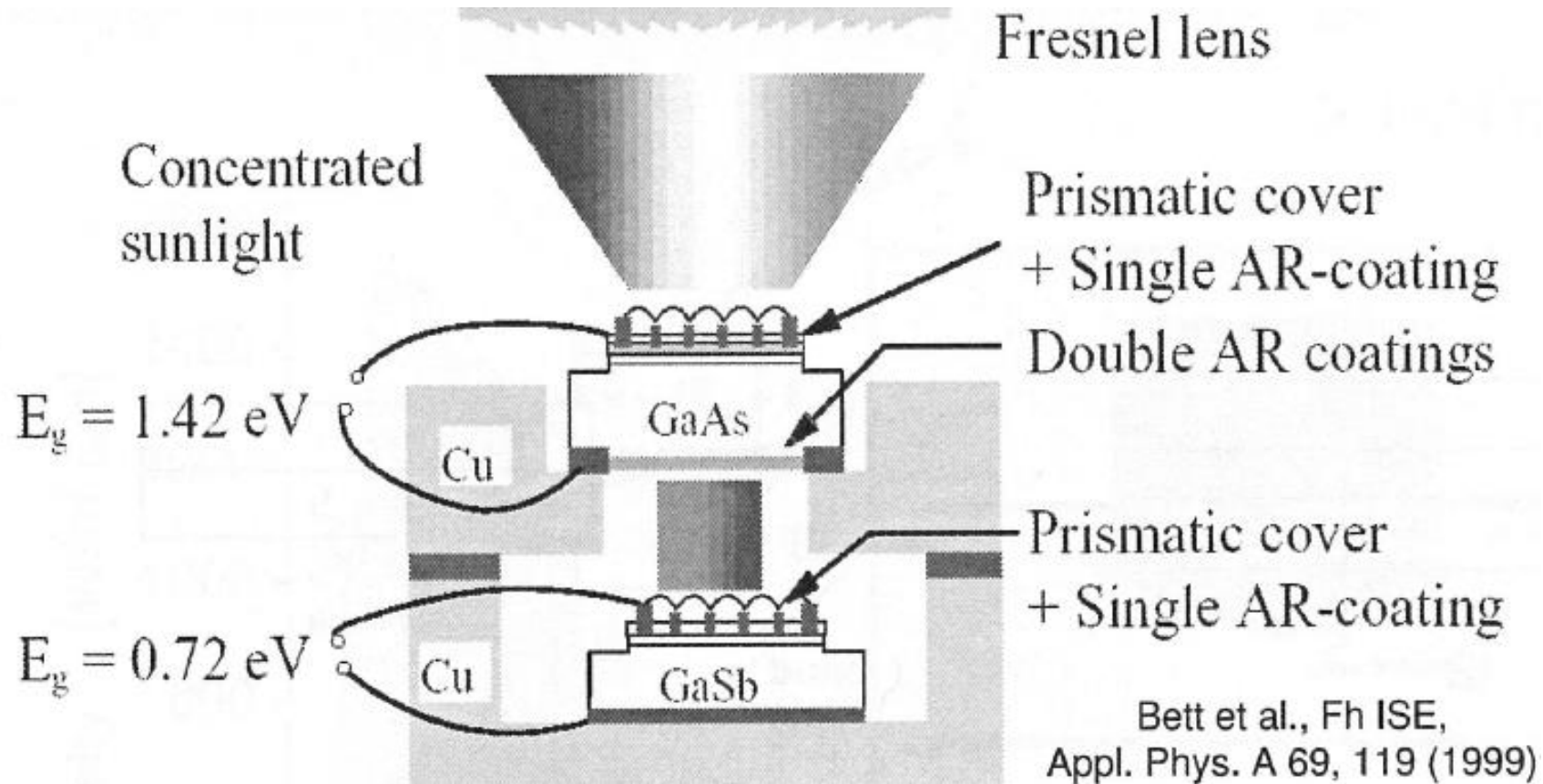
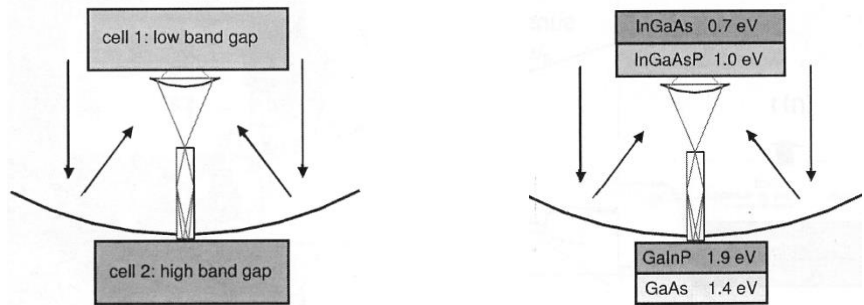
- Monolithic concept of multi-junction solar cells
 - Lattice-matched solar cells
 - Grading the lattice constant
 - Wafer bonding
 - Current matching



Monolithic and Non-Monolithic Concept

- Non-monolithic concept of multi-junction solar cells

- Spectrum splitting
- Mechanical stacking



Mechanically Stacked Solar Cells

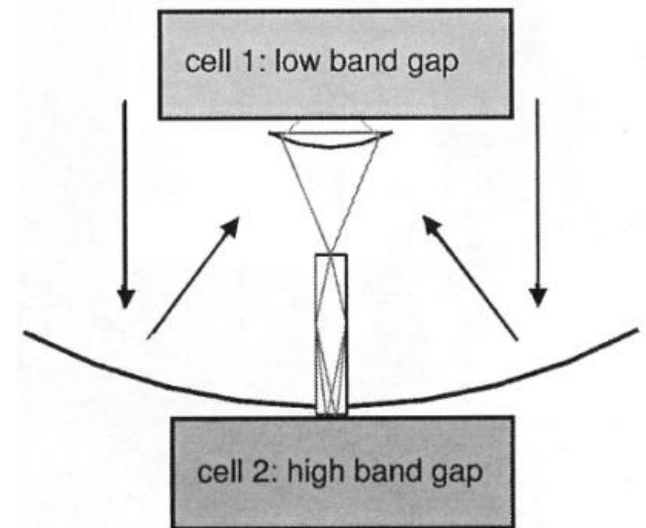


- Advantages

- No current-matching required
- No lattice-matching required
- Each layer optimized separately to produce maximum power

- Disadvantages

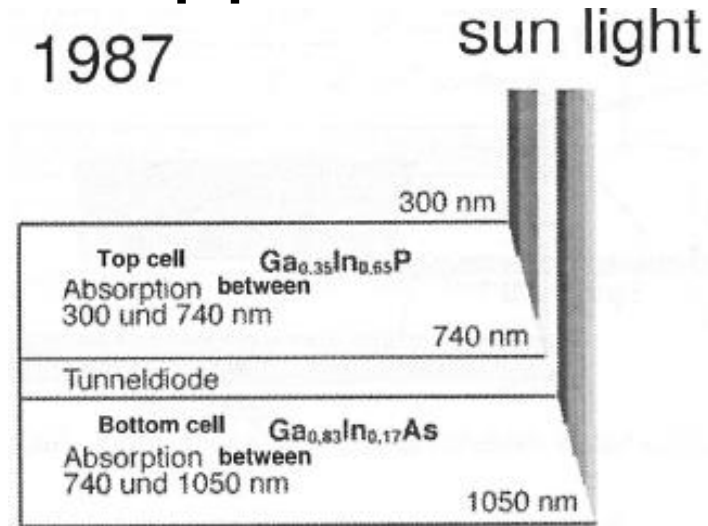
- Processing challenges
- Expensive (2 wafers)
- Heavy
- Multiple metal interconnects shadow part of the device



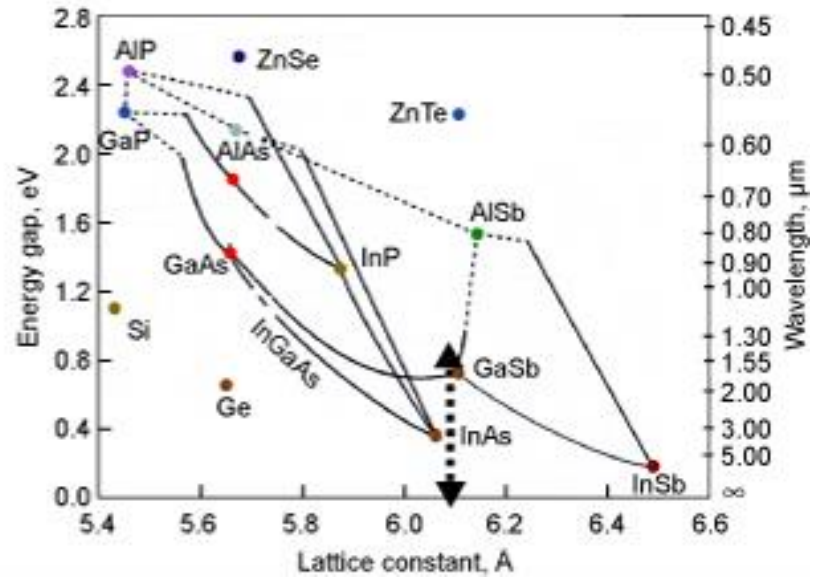
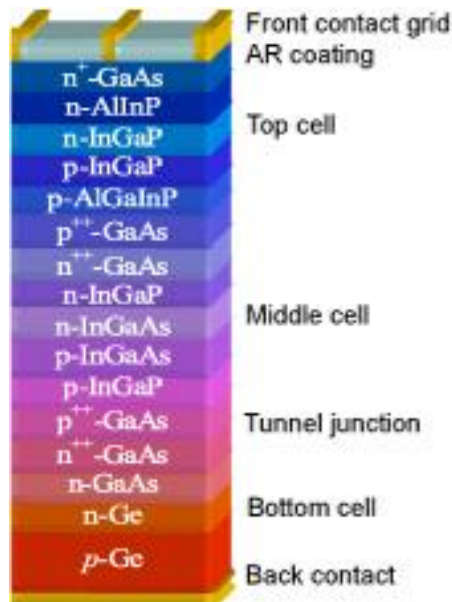


Monolithic Approach

- First tandem solar cell (1987)



- 3 junction solar cell

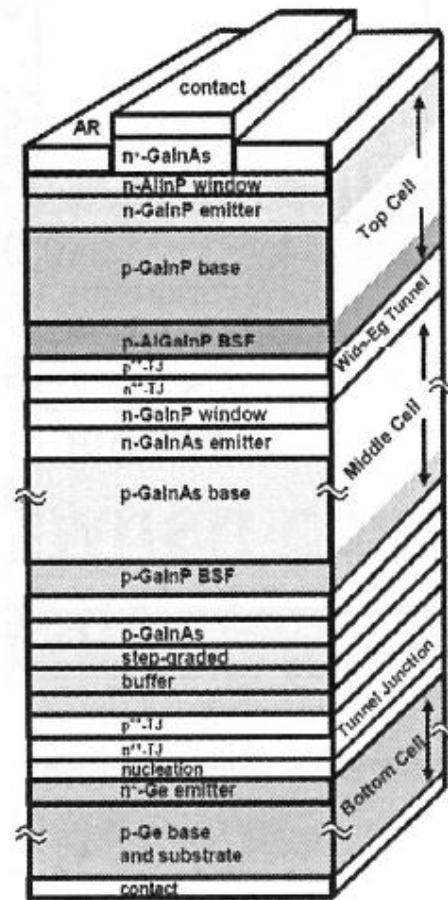
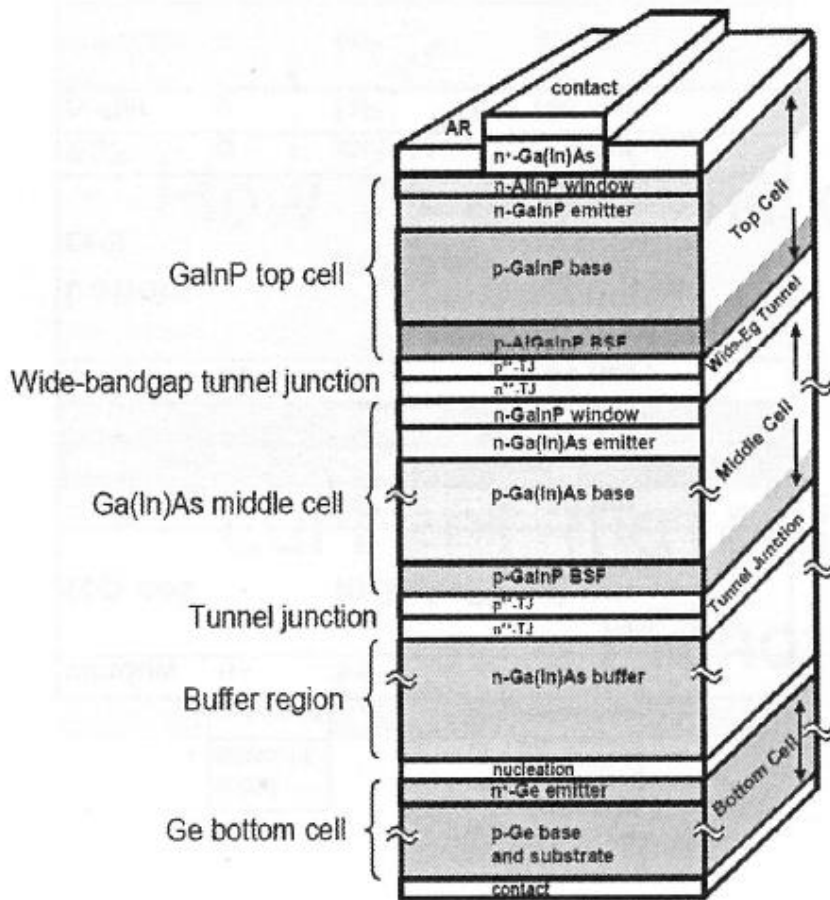


Record Multi-Junction Solar Cells



Lattice-matched 41.6%

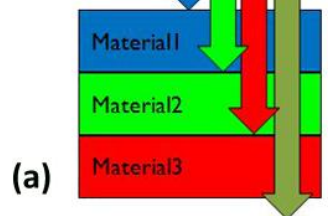
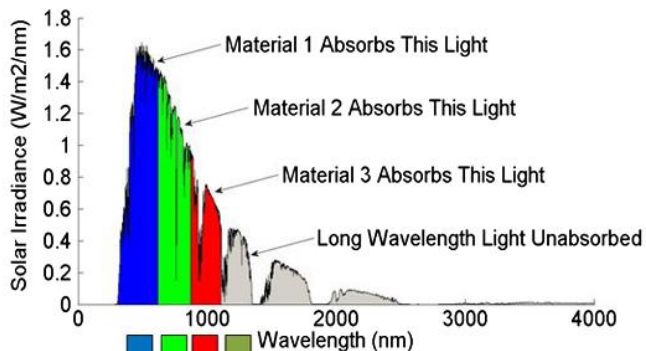
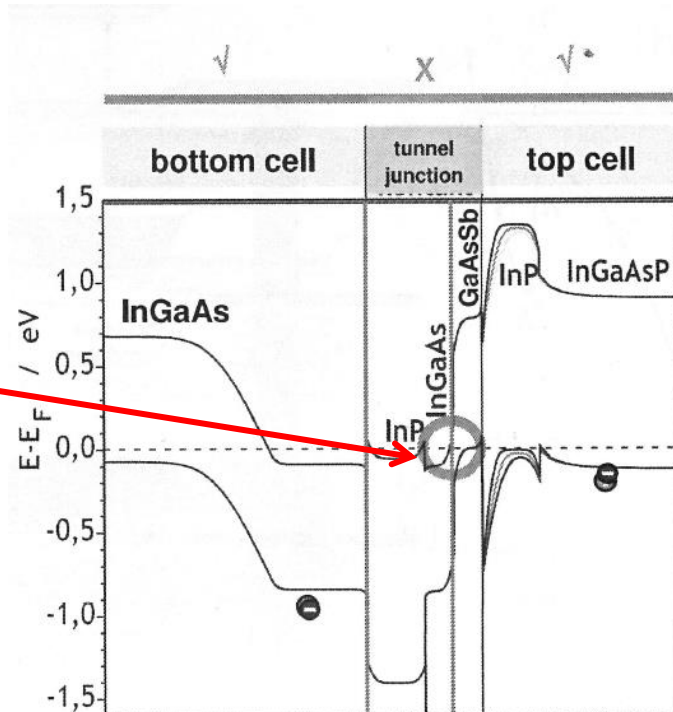
Lattice-mismatched (metamorphic) 41.1%



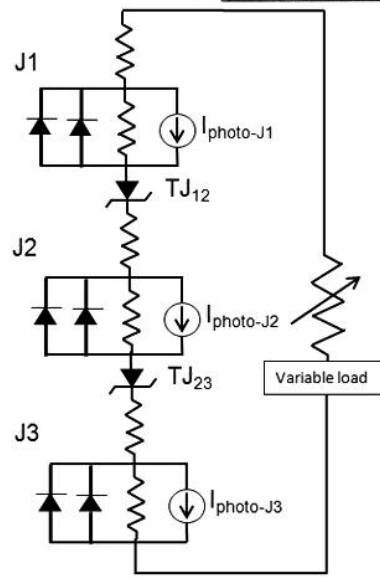
Structure of Tandem Cell



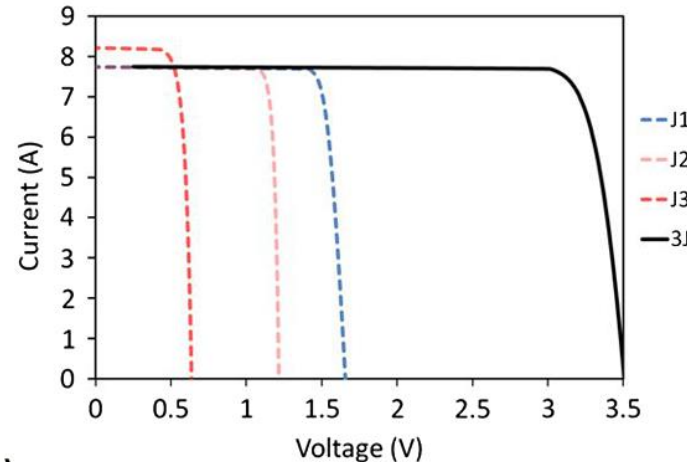
- Band gap diagram
 - Avoid non-desirable recombination!!!



(a)



(b)

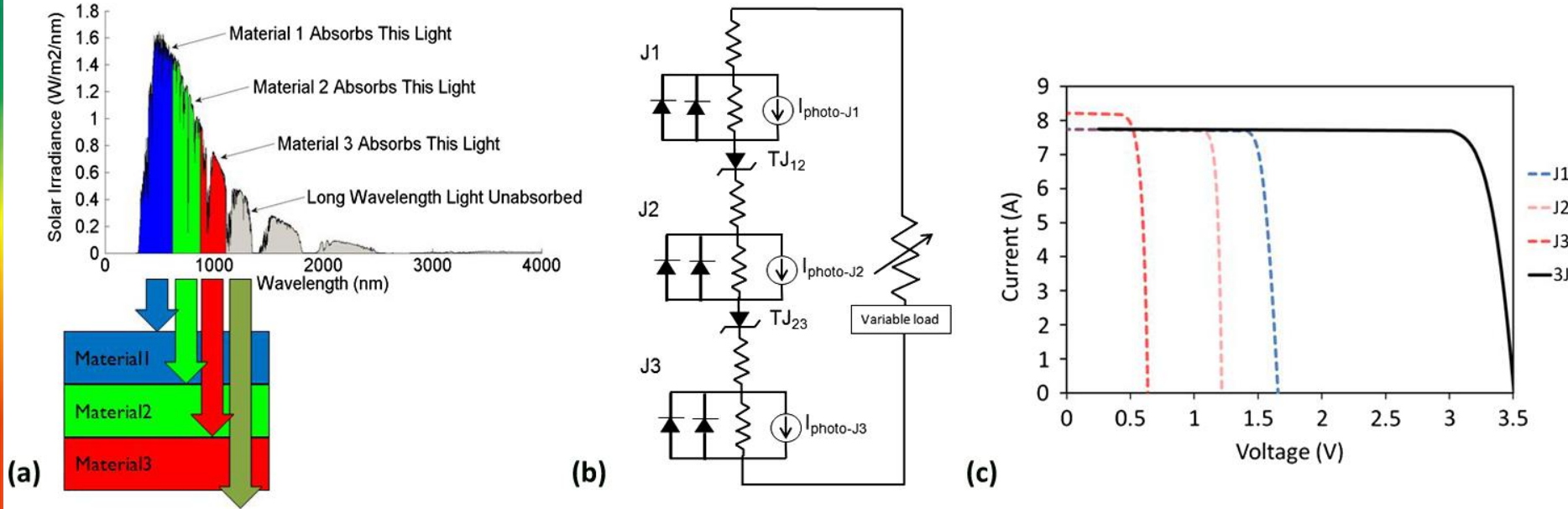


(c)

Characterization of Tandem Cell



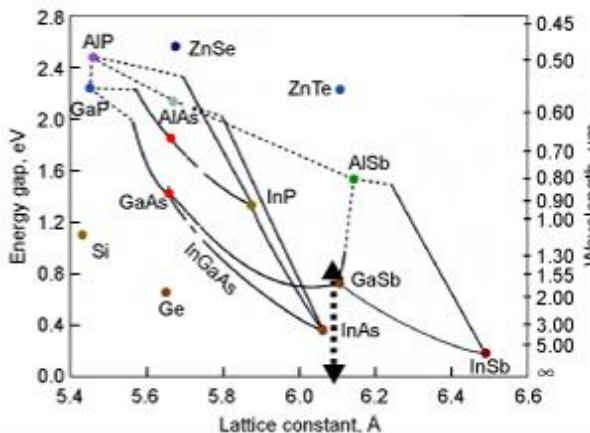
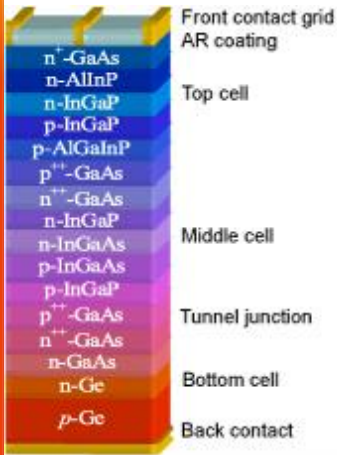
- Light sources with appropriate wavelength



Elements for These Structures



- Alloys from a-Si, c-Si, Ge
- III-V because
 - Low defect density (recombination in pure material very low)
 - Properties tunable in a wide range (band gap engineering, reproducible preparation on atomic scale)
 - Direct band gaps (high absorption coefficient)



Periodic Table of Elements

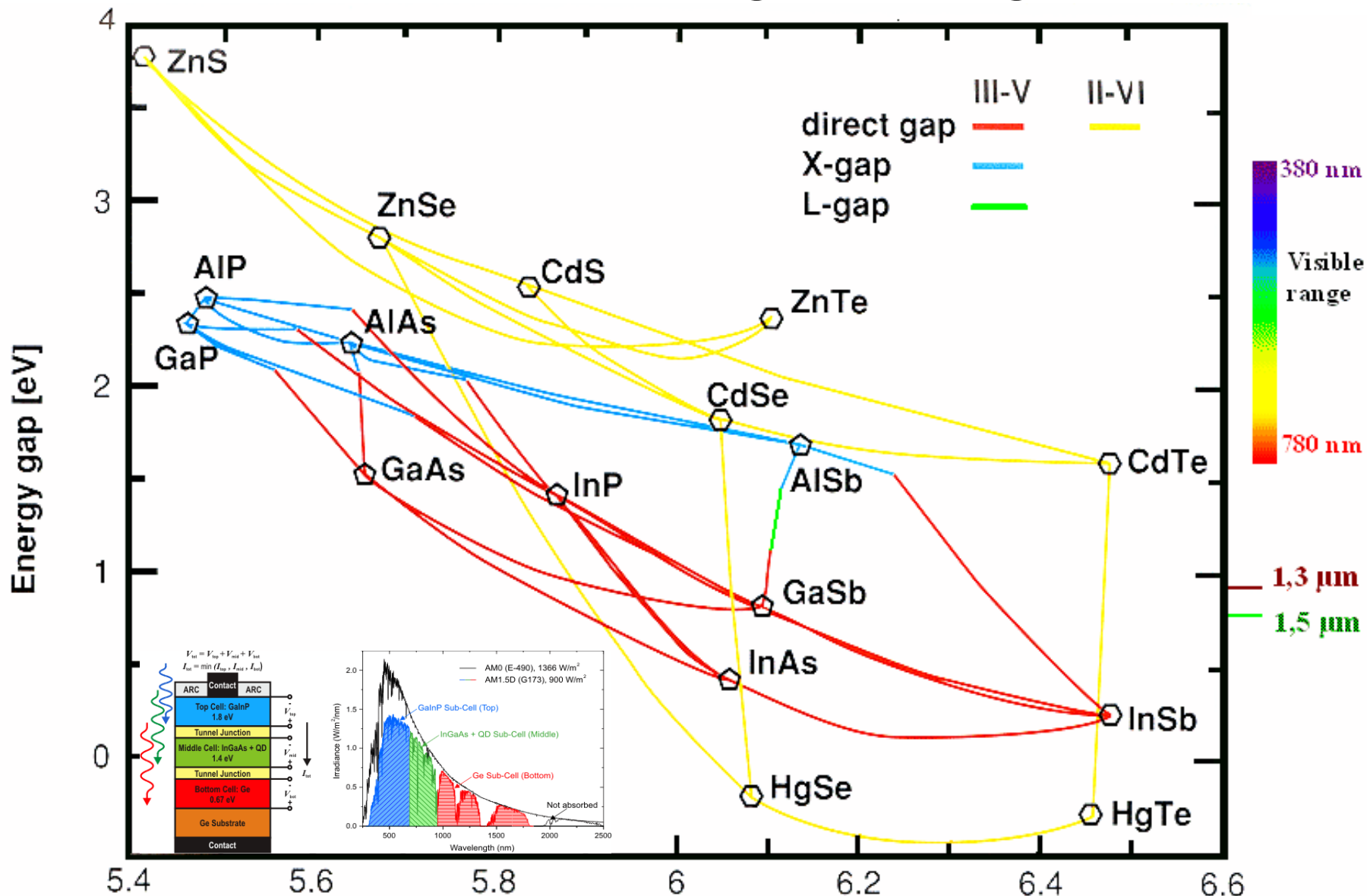
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18		
1 H Hydrogen (1.00794)	2 He Helium (4.002602)											3 Li Lithium (6.941)	4 Be Beryllium (9.012182)	5 B Boron (10.811)	6 C Carbon (12.011)	7 N Nitrogen (14.00643)	8 O Oxygen (15.999)	9 F Fluorine (18.9984032)	10 Ne Neon (20.1797)
11 Na Sodium (22.98976928)	12 Mg Magnesium (24.304)											13 Al Aluminum (26.9815385)	14 Si Silicon (28.0855)	15 P Phosphorus (30.973761998)	16 S Sulfur (32.06)	17 Cl Chlorine (35.45)	18 Ar Argon (39.948)		
19 K Potassium (39.0983)	20 Ca Calcium (40.078)	21 Sc Scandium (44.955912)	22 Ti Titanium (47.88)	23 V Vanadium (50.9415)	24 Cr Chromium (51.9961)	25 Mn Manganese (54.938045)	26 Fe Iron (55.845)	27 Co Cobalt (58.933195)	28 Ni Nickel (58.6934)	29 Cu Copper (63.546)	30 Zn Zinc (65.38)	31 Ga Gallium (69.723)	32 Ge Germanium (72.64)	33 As Arsenic (74.9216)	34 Se Selenium (78.96)	35 Br Bromine (79.904)	36 Kr Krypton (83.798)		
37 Rb Rubidium (85.4678)	38 Sr Strontium (87.62)	39 Y Yttrium (88.90584)	40 Zr Zirconium (91.224)	41 Nb Niobium (92.90638)	42 Mo Molybdenum (95.94)	43 Tc Technetium (98.9062)	44 Ru Ruthenium (101.07)	45 Rh Rhodium (102.9055)	46 Pd Palladium (106.42)	47 Ag Silver (107.8682)	48 Cd Cadmium (112.411)	49 In Indium (114.818)	50 Sn Tin (118.710)	51 Sb Antimony (121.757)	52 Te Tellurium (127.6)	53 I Iodine (126.905)	54 Xe Xenon (131.29)		
55 Cs Cesium (132.90545196)	56 Ba Barium (137.327)	57-71 Lanthanoids	72 Hf Hafnium (178.49)	73 Ta Tantalum (180.94788)	74 W Tungsten (183.84)	75 Re Rhenium (186.207)	76 Os Osmium (190.23)	77 Ir Iridium (192.222)	78 Pt Platinum (195.084)	79 Au Gold (196.966569)	80 Hg Mercury (200.59)	81 Tl Thallium (204.3833)	82 Pb Lead (207.2)	83 Bi Bismuth (208.9804)	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)		
87 Fr Francium (223)	88 Ra Radium (226)	89-103 Actinoids	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (264)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 Ds Darmstadtium (267)	111 Rg Roentgenium (268)	112 Uub Ununbium (269)	113 Uut Ununtrium (270)	114 Uuq Ununquadium (271)	115 Uup Ununpentium (272)	116 Uuh Ununhexium (273)	117 Uus Ununseptium (274)	118 Uuo Ununoctium (276)		

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

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Band Gap Engineering





SOLAR ENERGY APPLICATION SYSTEMS

Prof. Ing. Vitezslav Benda, CSc.

Place: T2:B3-142

E-mail: benda@fel.cvut.cz

Ing. Peter Pikna

Place: T2:E1-101

E-mail: piknapet@fel.cvut.cz