Electricity from Solar Energy

Photovoltaics

Andriy Zhugayevych

October 13, 2015

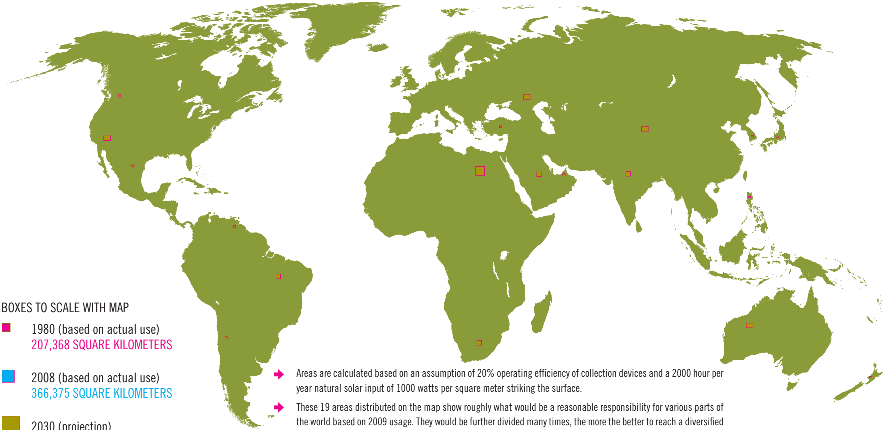
Outline

- Introduction to solar energy
- Photovoltaic effect: how it works
- Power conversion efficiency: theory and practice
- Photovoltaic materials

SURFACE AREA REQUIRED TO POWER THE WORLD

WITH ZERO CARBON EMISSIONS AND WITH SOLAR ALONE

www.landartgenerator.org



BOXES TO SCALE WITH MAP

🟥 1980 (based on actual use)
207,368 SQUARE KILOMETERS

🟦 2008 (based on actual use)
366,375 SQUARE KILOMETERS

🟨 2030 (projection)
496,805 SQUARE KILOMETERS

Required area that would be needed in the year 2030 is shown as one large square in the key above and also as distributed around the world relative to use and available sunlight.

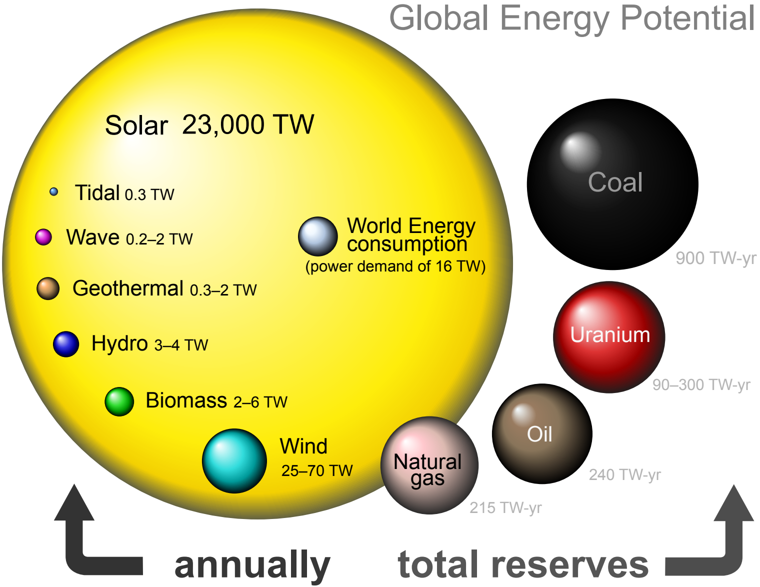
- Areas are calculated based on an assumption of 20% operating efficiency of collection devices and a 2000 hour per year natural solar input of 1000 watts per square meter striking the surface.
- These 19 areas distributed on the map show roughly what would be a reasonable responsibility for various parts of the world based on 2009 usage. They would be further divided many times, the more the better to reach a diversified infrastructure that localizes use as much as possible.
- The large square in the Saharan Desert (1/4 of the overall 2030 required area) would power all of Europe and North Africa. Though very large, it is 18 times less than the total area of that desert.
- The definition of "power" covers the fuel required to run all electrical consumption, all machinery, and all forms of transportation. It is based on the US Department of Energy statistics of worldwide Btu consumption and estimates the 2030 usage (678 quadrillion Btu) to be 44% greater than that of 2008.
- Area calculations do not include magenta border lines.

land art generator initiative

$\Longrightarrow$ Complete ecological solution of our power demands

No other energy source compares to solar energy

(even at mediocre photovoltaic efficiency)



Global Energy Potential

Solar 23,000 TW

Tidal 0.3 TW

Wave 0.2–2 TW

Geothermal 0.3–2 TW

Hydro 3–4 TW

Biomass 2–6 TW

Wind 25–70 TW

World Energy consumption
(power demand of 16 TW)

Coal 900 TW-yr

Uranium 90–300 TW-yr

Oil 240 TW-yr

Natural gas 215 TW-yr

annually

total reserves

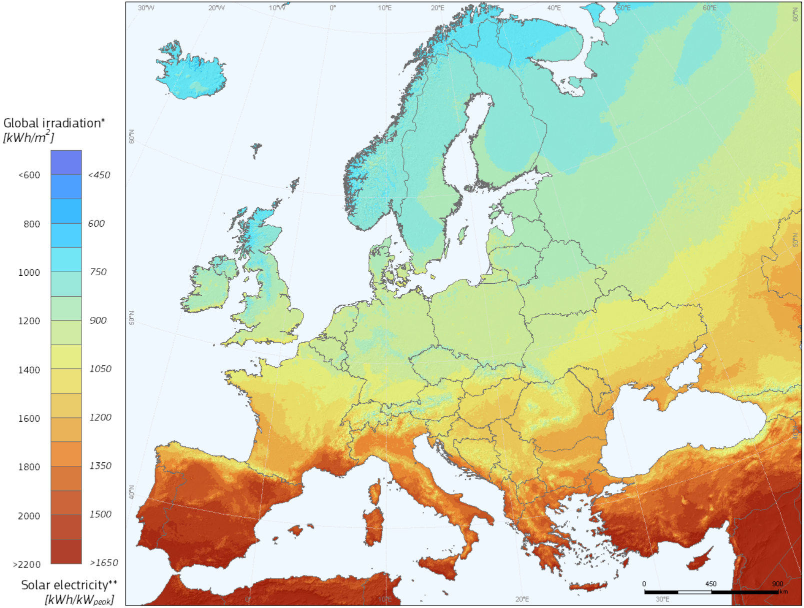
Solar power estimates

- 1.35 kW/m^2 out of atmosphere
- 1 kW/m^2 at surface
- Sun is moving on the sky $\implies$ factor of 1/3
- Sun is not in zenith $\implies$ factor of 4/5 for New Mexico
- Clouds $\implies$ factor of 3/4 for New Mexico

On average 200 W/m^2 $\implies$

- Small house can be powered by roof-size solar cell
- Person can be powered by umbrella-size solar cell
- Impractical for mechanical power (vehicles)

Photovoltaic Solar Electricity Potential in European Countries



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

***Yearly sum of solar electricity generated by optimally-inclined 1kW$_p$ system with a performance ratio of 0.75*

PVGIS http://re.jrc.ec.europa.eu/pvgis/

Authors: Thomas Huld, Irene Pinedo-Pascua
EC • Joint Research Centre
In collaboration with: CM SAF, *www.cmsaf.eu*

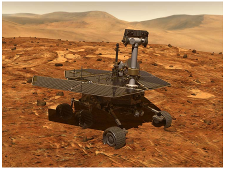
Basic rules of photovoltaics

- It is a high technology
  (mechanical, electrical, optical, materials, nano-engineering)
- Trade-off between cost and power conversion efficiency
  (always)
- Lifetime is an issue
  (absorbed photon has enough energy to break a bond)
- Energy must be stored in-place
  (highly variable energy source)
- Use hybrid devices to utilize more solar energy
  (practical efficiency limit for simple cells is currently 20%)

Application areas

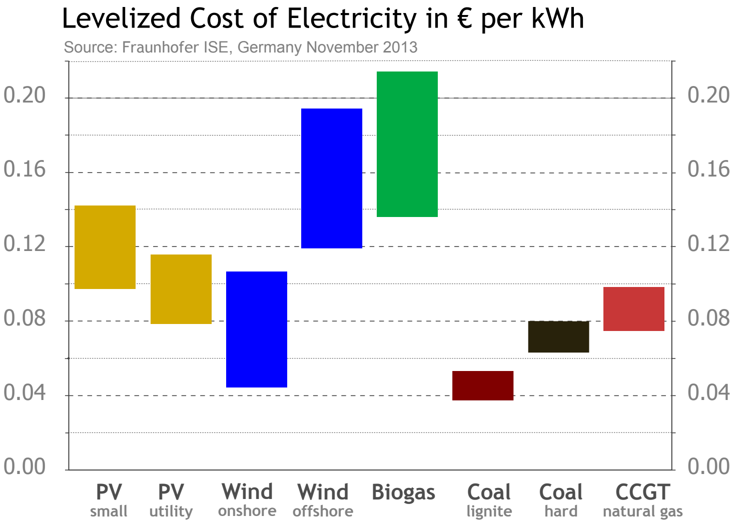
- Electricity generation (solar power plants, roof/wall solar cels)
  (Solar Star 2015 – 600 MW = 1/10 of power of the largest plants)


- The only energy source (space, remote locations)
  (Boeing Spectrolab – 400 W/kg or m^2; GoalZero – 250 W × 1250 Wh)

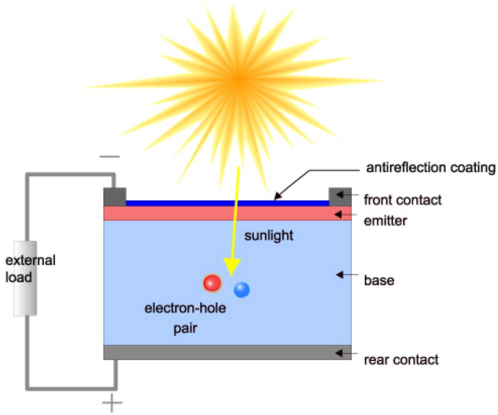


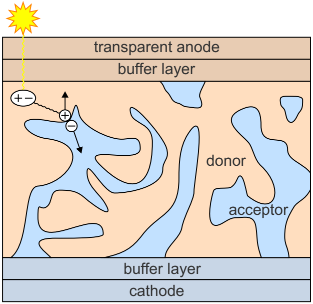

- Green energy (renewable, free of charge)

Electricity cost: photovoltaics steadily moves down



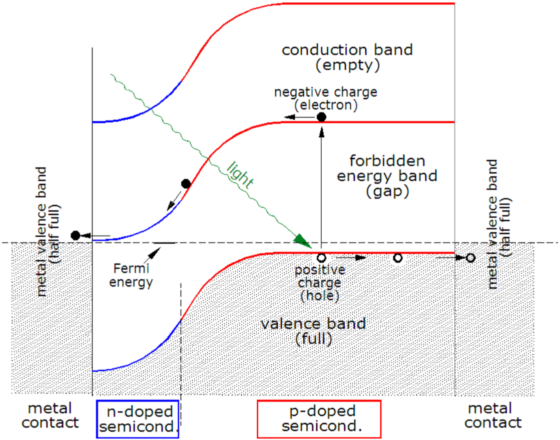
Photovoltaic effect

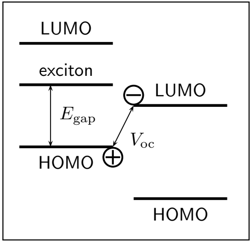




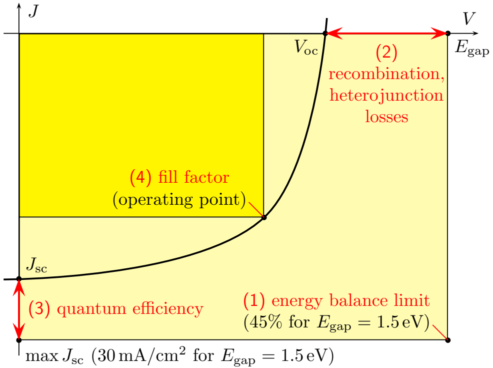
Challenge:
Efficient charge separation at full light absorption and high voltage

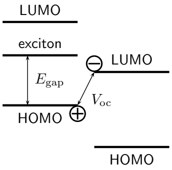
Photovoltaic effect: p-n junction and heterojunction

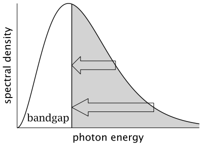




Power conversion efficiency (PCE): main factors



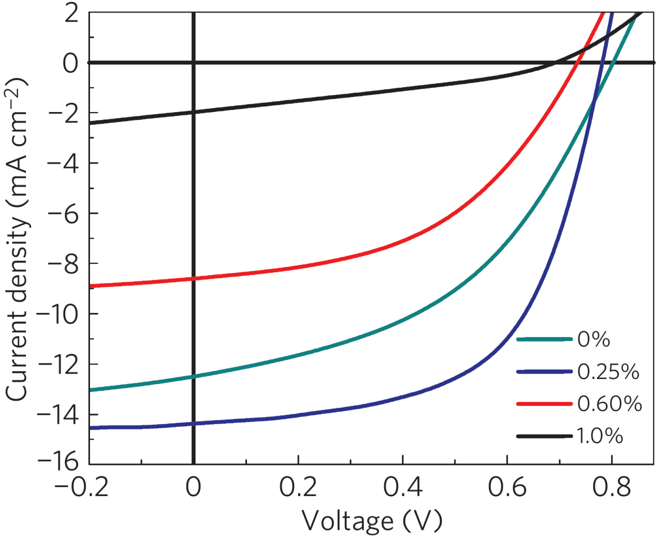




$$\eta = \frac{J_{\rm sc} \times V_{\rm oc} \times {\rm FF}}{P_{\rm in}} \equiv \eta_{\rm abs}(E_{\rm g}) \times \frac{eV_{\rm oc}}{E_{\rm g}} \times \frac{J_{\rm sc}}{J_{\rm sc}^{\rm max}(E_{\rm g})} \times {\rm FF}$$

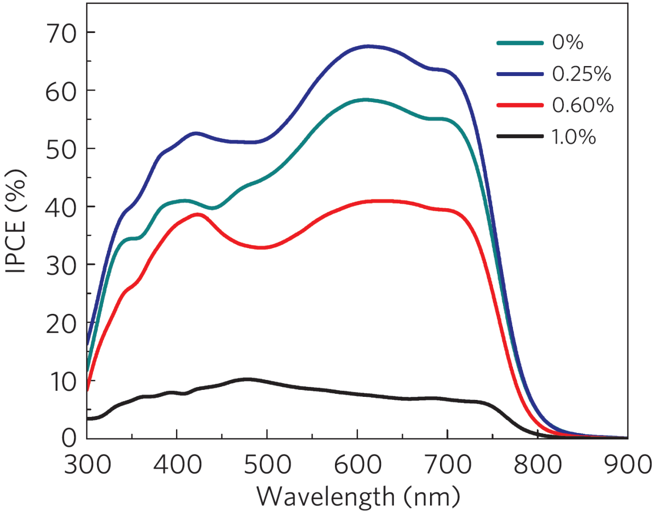
$V_{\rm oc}$ – open-circuit voltage, $J_{\rm sc}$ – short-circuit current, $E_{\rm g}$ – bandgap

Power conversion efficiency: Fill factor



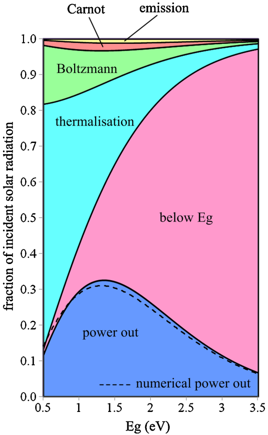
Nature Mater 11, 44 (2012)

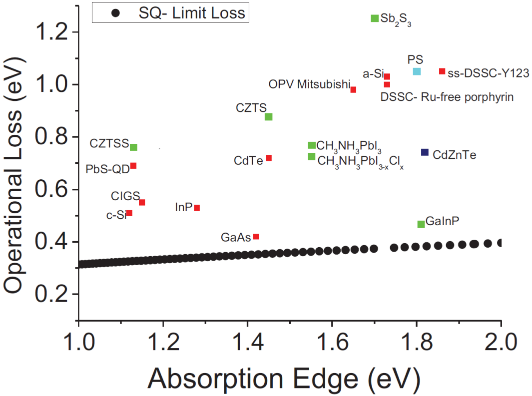
Power conversion efficiency: Quantum efficiency



Nature Mater 11, 44 (2012)

Power conversion efficiency: Shockley–Queisser limit





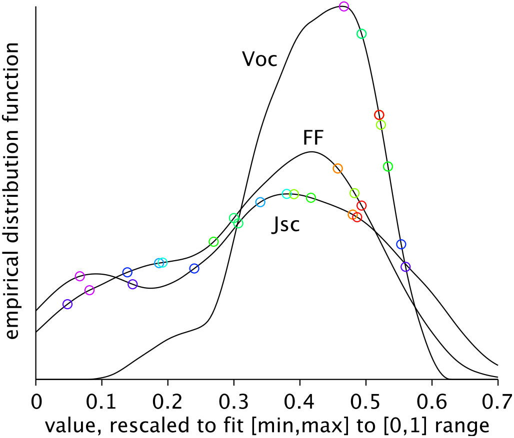
$$\boxed{eV_{\mathrm{oc}} = E_{\mathrm{g}}\left(1 - \frac{T}{T_{\mathrm{in}}}\right) - kT\ln\frac{\Omega_{\mathrm{out}}}{\Omega_{\mathrm{in}}} + kT\ln\frac{\gamma(E_{\mathrm{g}},T_{\mathrm{in}})}{\gamma(E_{\mathrm{g}},T)} + kT\ln\eta_{\mathrm{lum}}}$$

Ref.: J App Phys 32, 510 (1961), Adv Mater 26, 1622 (2014), Prog Photovolt Res Appl 19, 286 (2011)

Power conversion efficiency: examples

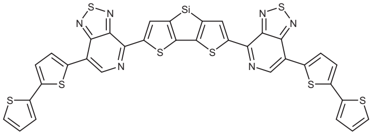
		OPV	Si	GaAs
Energy balance limit, $\eta_{\mathrm{abs}}(E_{\mathrm{g}})$		0.5	0.49	0.45
Recombination losses, $eV_{\mathrm{oc}}/E_{\mathrm{g}}$	$\times$	0.6	0.63	0.79
Quantum efficiency, $J_{\mathrm{sc}}/J_{\mathrm{sc}}^{\mathrm{max}}(E_{\mathrm{g}})$	$\times$	0.6	0.97	0.93
Fill Factor, $\max JV/J_{\mathrm{sc}}V_{\mathrm{oc}}$	$\times$	0.8	0.83	0.87
Power conversion efficiency	$=$	14%	25%	29%

Distribution of V_{oc}, J_{sc}, FF

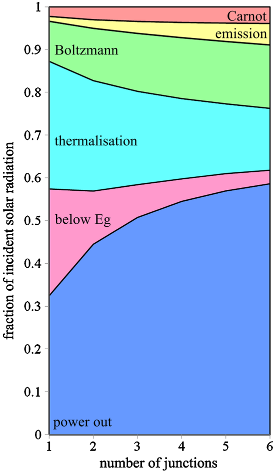


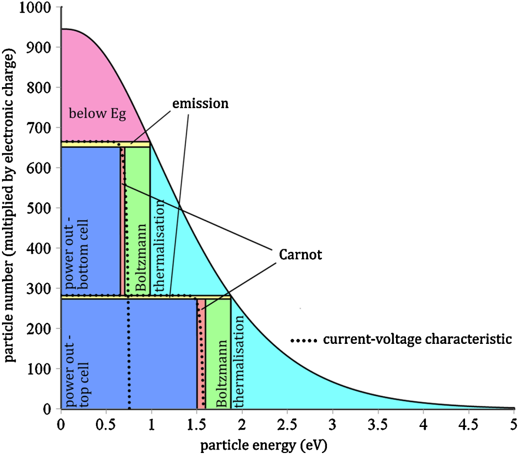
– Empirical distribution over 67 OPVs is provided by J. McClean (Clean Energy Project) http://cleanenergy.harvard.edu

◦ Dots correspond to refinement of one system, up to 7% PCE (Nature Mater 11, 44 (2012) JACS 134, 16597 (2012))

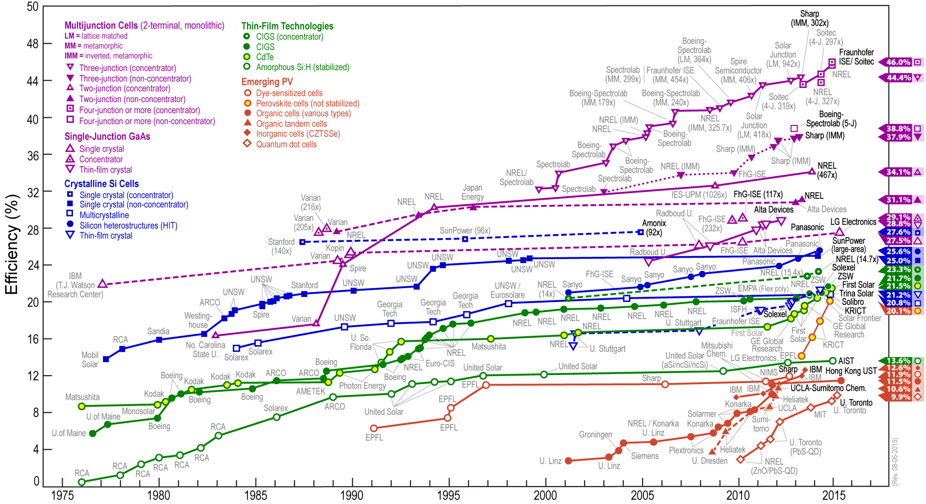


Multijunction cells





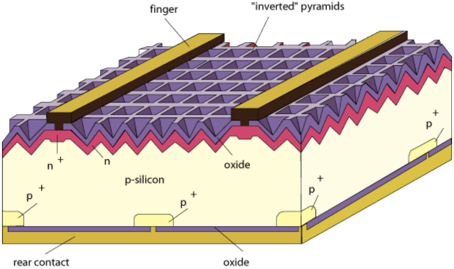
Best Research-Cell Efficiencies

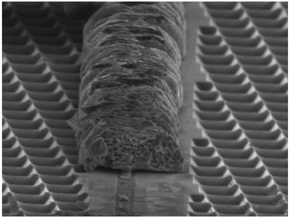


p-n junction cells

75-year evolution of Si solar cells: from 0 to 25%

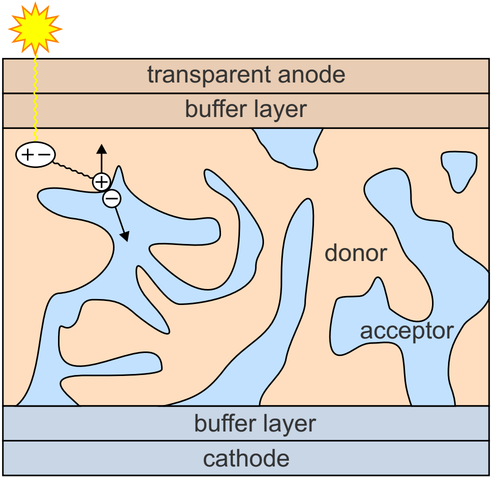
PERL – passivated emitter with rear locally diffused cell:





Reference: pveducation.org

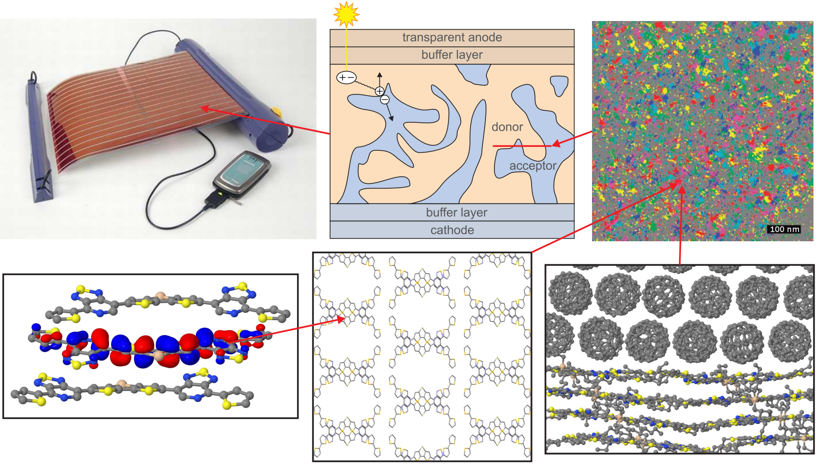
Bulk-heterojunction cells



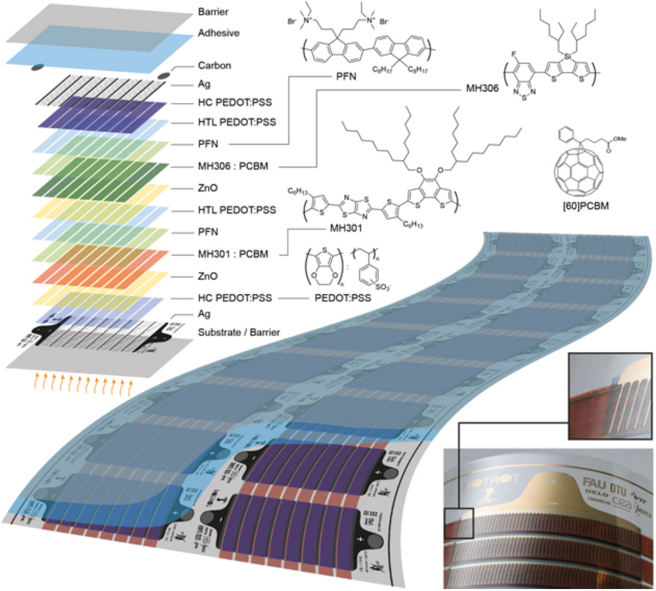
Optimize performance:

- Donor material
- Acceptor material
- Interface
- Morphology
- Contacts
- Light absorption
- Aging
- . . .

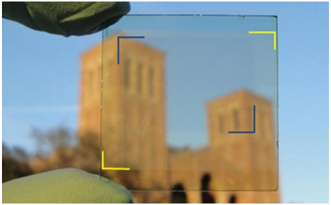
Multiscale complexity

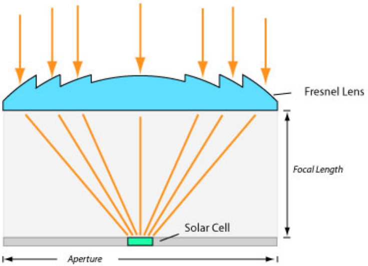


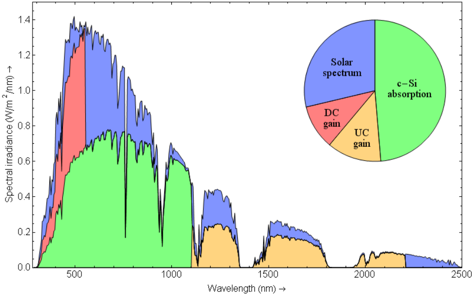
Printed electronics design

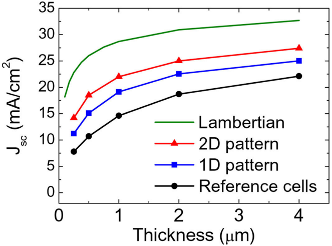


Technology: other tricks

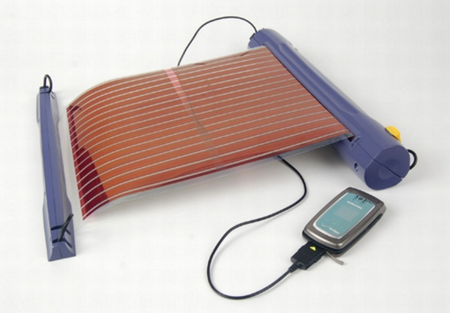








Examples



- Konarka Power Plastic®
- $
- 1% efficiency
- 1 sheet = 1 W = 1 cell phone

Increase efficiency and life time

- Los Alamos Solar Power Project
- $$$
- 15% efficiency
- 1 tray = 2.5 kW = 1 home

Decrease cost

Resources

- Wikipedia
- List of references
- A Zhugayevych, S Tretiak, Theoretical Description of Structural and Electronic Properties of Organic Photovoltaic Materials, Annu Rev Phys Chem 66, 305 (2015) pdf
- Textbooks
- CEE CREI website
- Research: photovoltaic materials and device modeling