COLOURS AND MATERIALS IN OUR ENERGY FUTURE

Shri C.J. Bhumkar Memorial Lecture, The Colour Society

Mumbai, March 18, 2016

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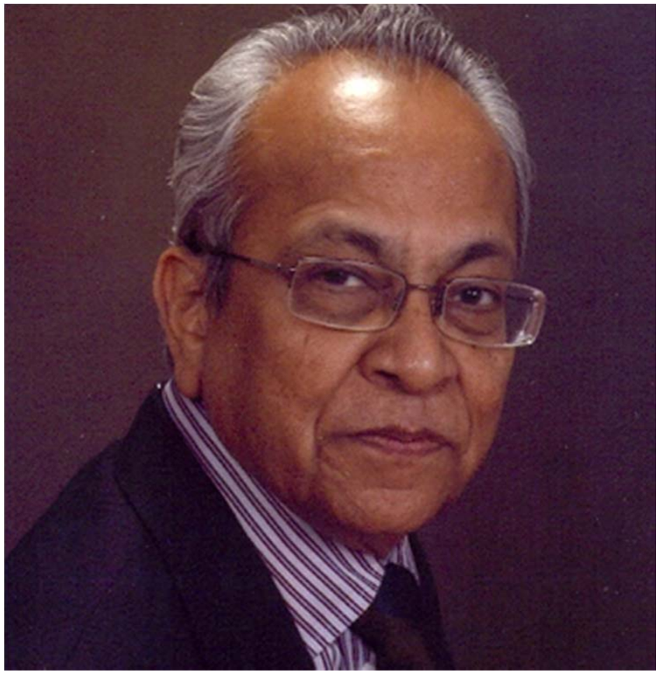
A Tribute to the Legendary Shri C.J. Bhumkar

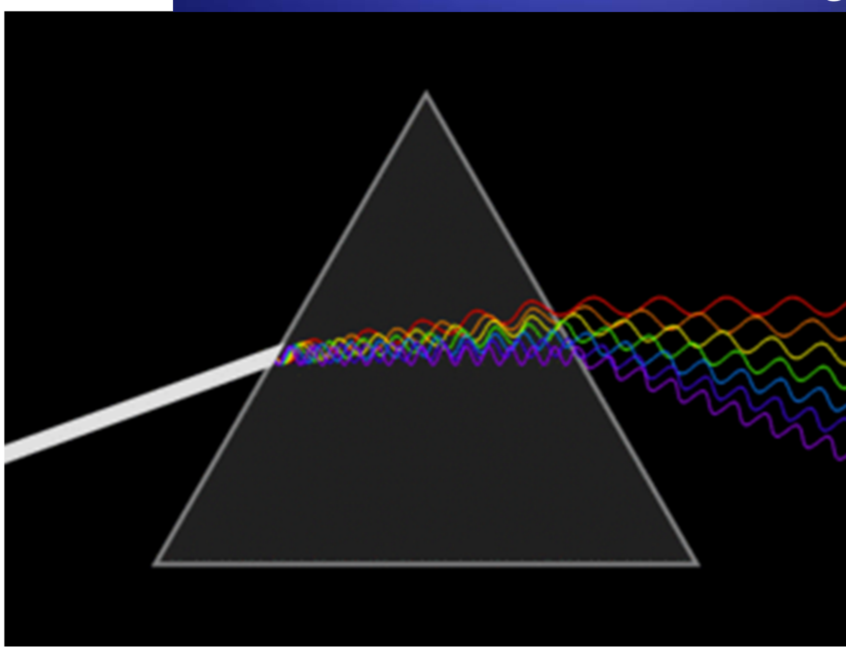


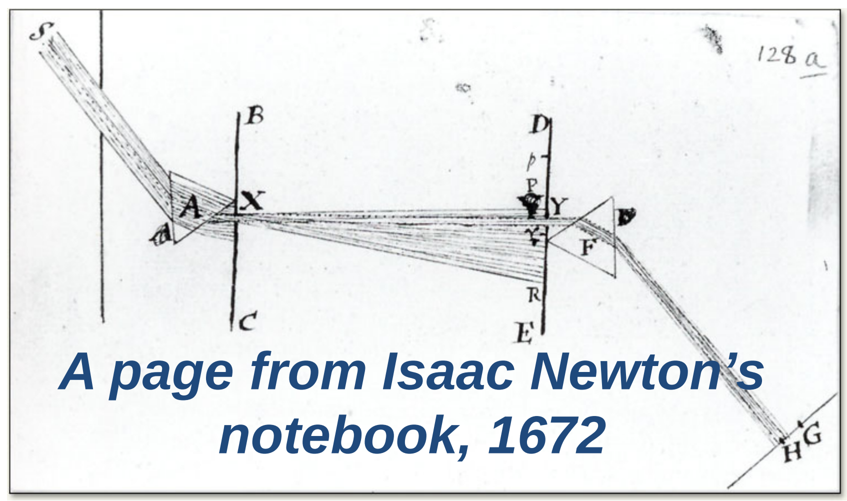
1935-2009

An inventor, technologist, technical professional and entrepreneur, *par excellence*

"Small companies with specialized technologies working in partnership with large companies can complement the larger enterprises"

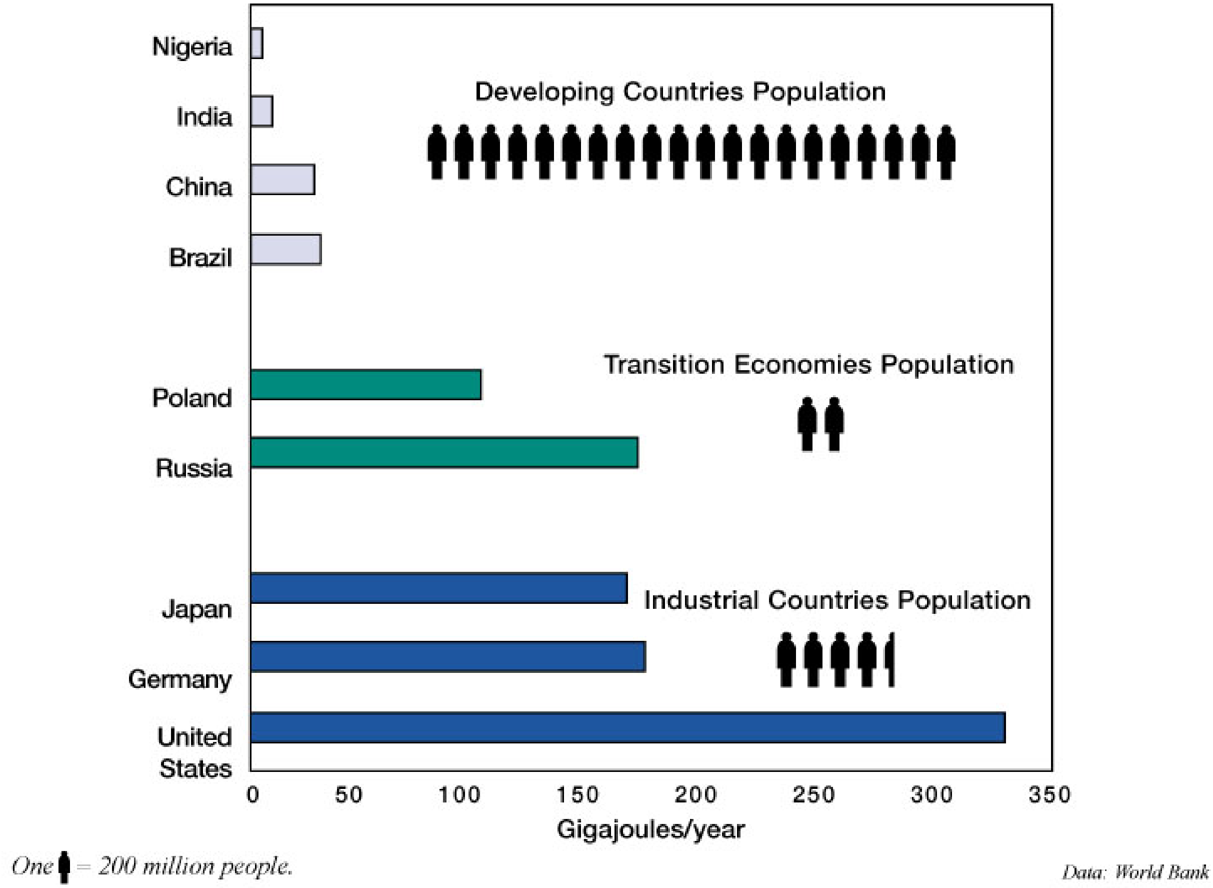
The existence of small, medium and large enterprises must be seen as an interdependent ecosystem, not as predators and preys or merely as part of an efficient supply chain





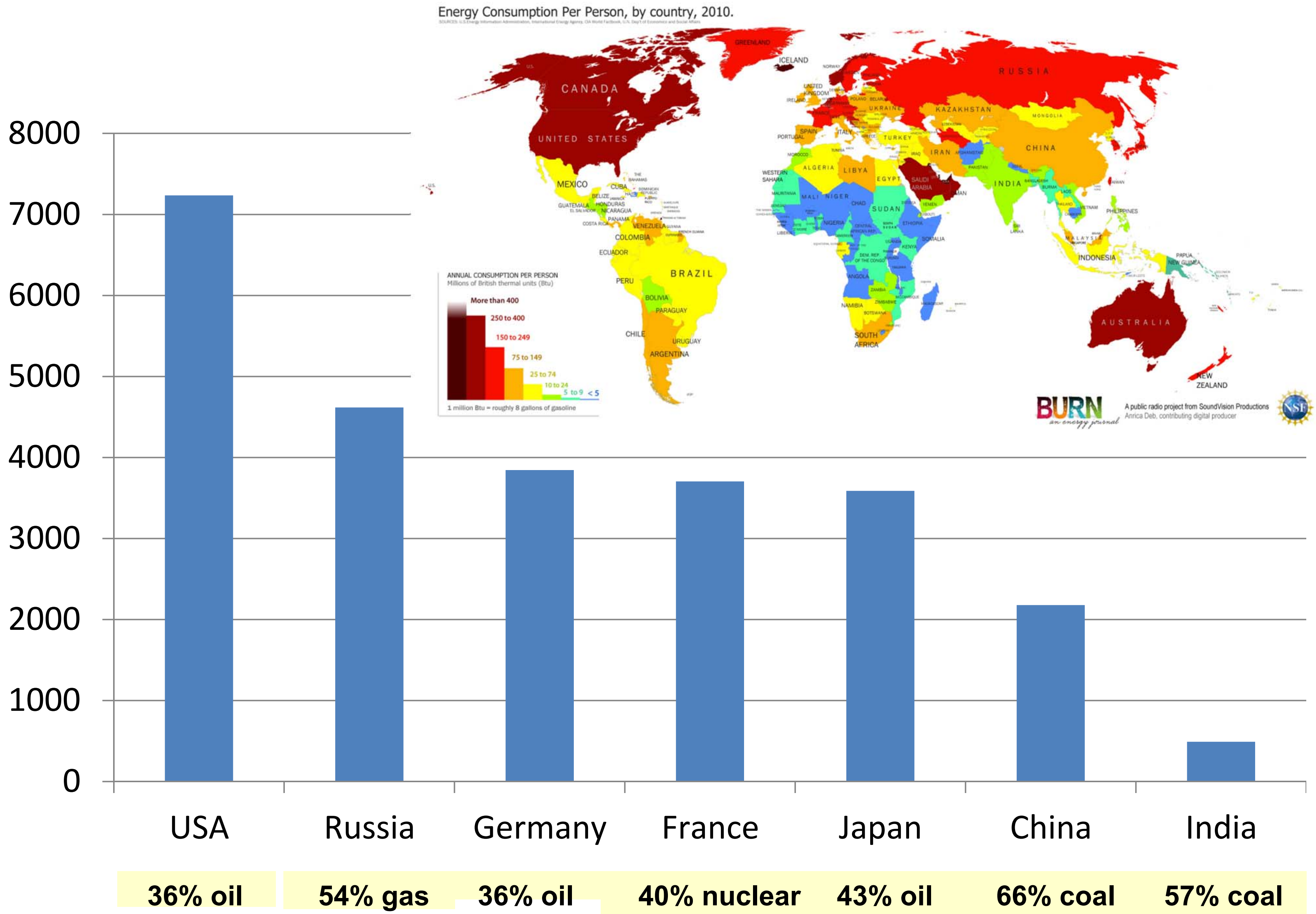
A page from Isaac Newton’s notebook, 1672

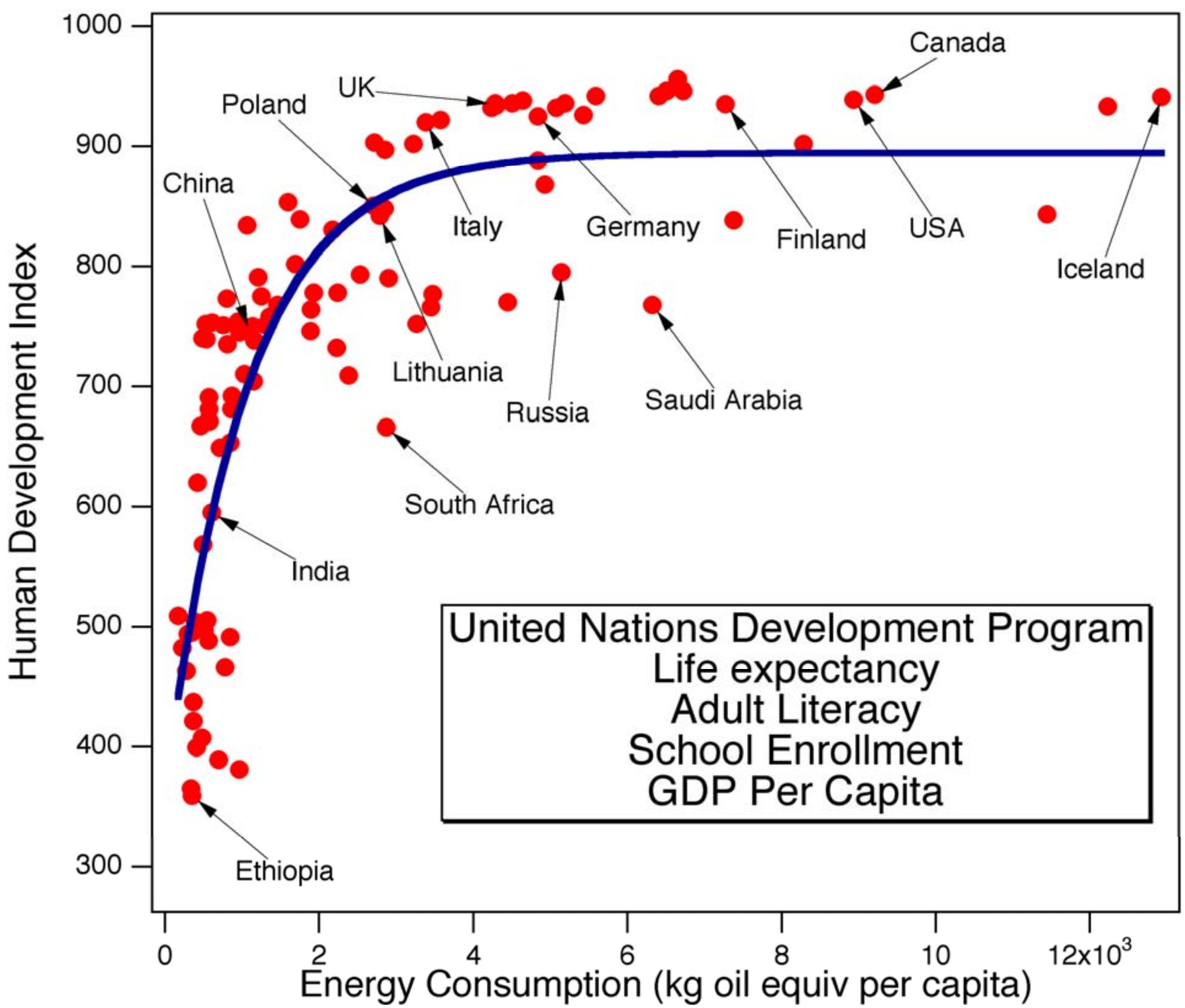
THE ENERGY ASSYMETRY



Half the world's population subsists on agrarian or lower levels of energy access. Their population density generally exceeds the carrying capacity of their environment

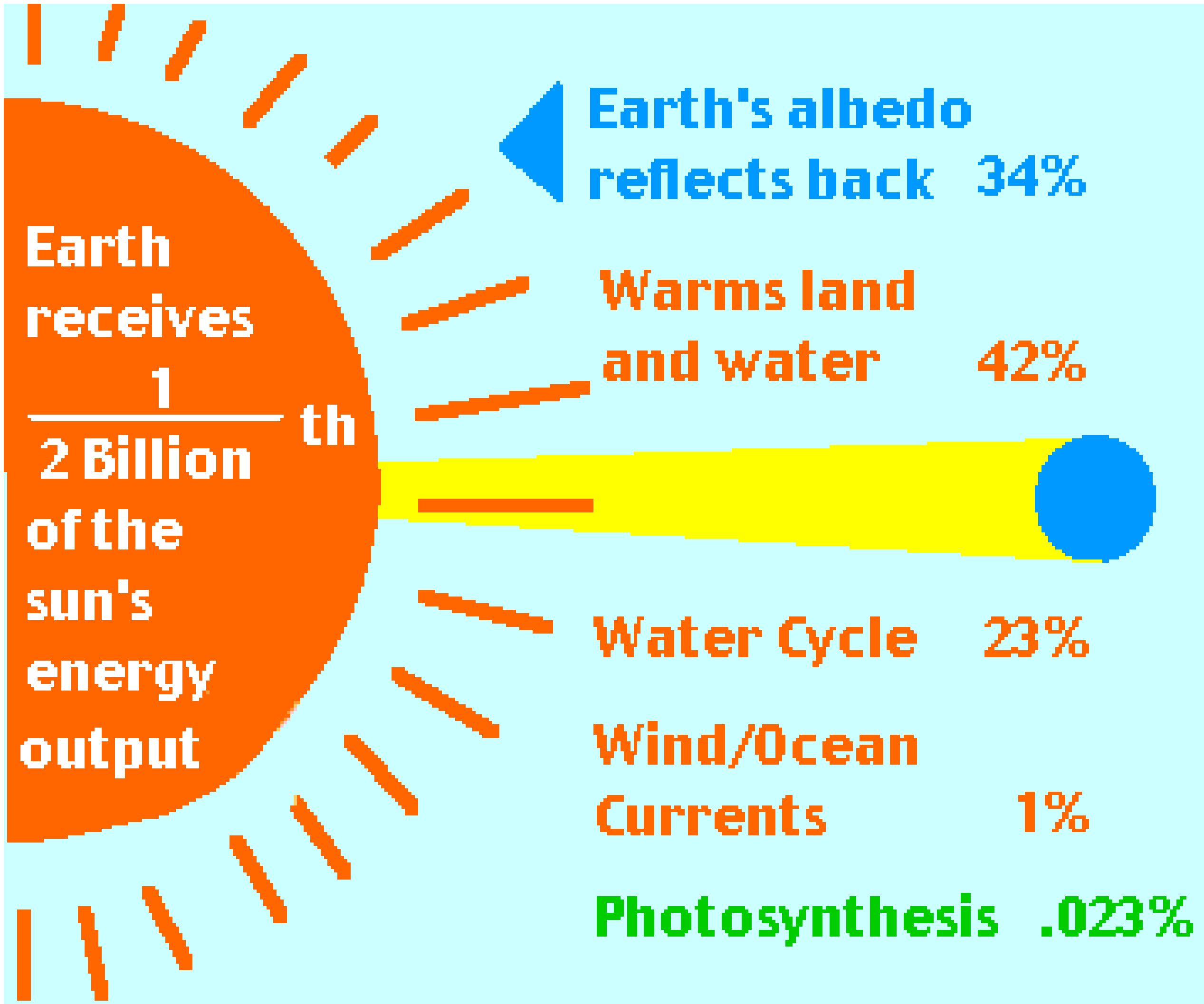
PRIMARY ENERGY CONSUMPTION, KG OF OIL EQUIVALENT, PER CAPITA, 2014





Is there a model of growth which deviates from the above relationship ?

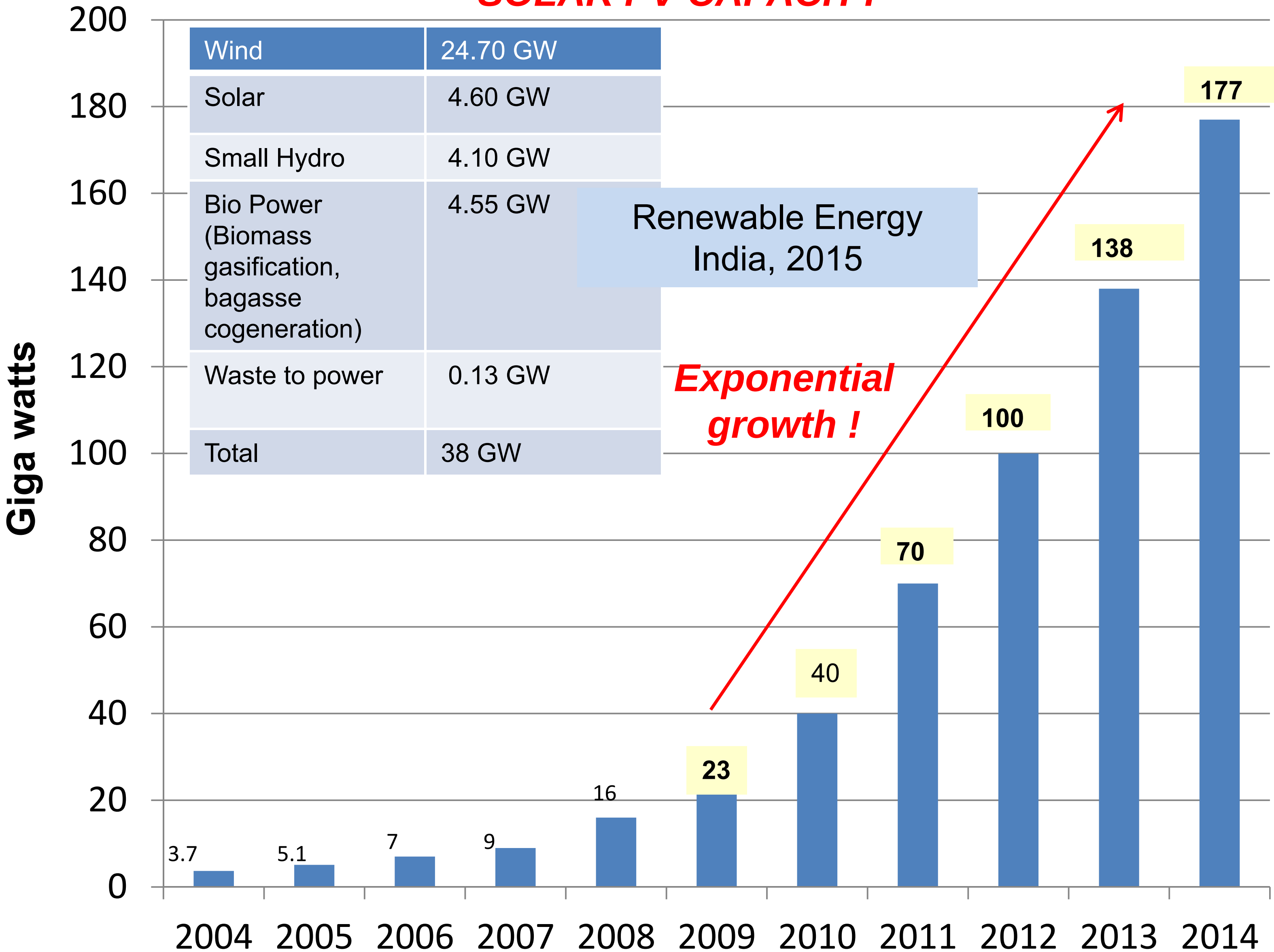
ENERGY FROM SUN



Frugal
and
Parsimonious

- 26000 TW energy
- More energy from the sun strikes earth in one hour than all of the energy consumed by humans in one year

RENEWABLE ENERGY :GLOBAL SOLAR PV CAPACITY



Wind	24.70 GW
Solar	4.60 GW
Small Hydro	4.10 GW
Bio Power (Biomass gasification, bagasse cogeneration)	4.55 GW
Waste to power	0.13 GW
Total	38 GW

SOLAR ENERGY SCENE IN INDIA

- 100 GW by 2022; 60% utility scale and balance roof top; 4 GW actual capacity in 2015

- If achieved 25 % of total electricity capacity by 2020

- Capital investment needed $ 160 billion

- One of the top three markets in the world

- 500 mW project by Sun Edison at Ghani Solar Park, Kurnool, AP at Rs 4.63 per kWh (Reverse Auction, 3 November 2015, Economic Times)

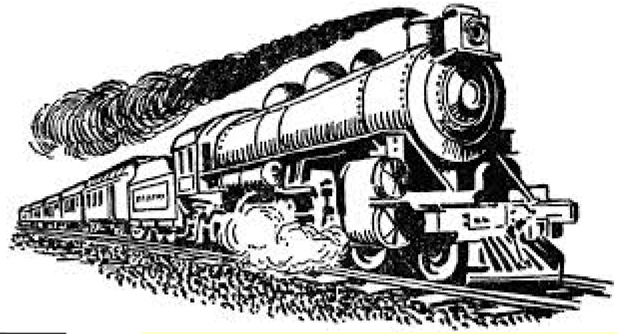
LAG BETWEEN DISCOVERY AND ITS MATERIAL IMPACT

- Thomas Edison illuminated the office of J. P. Morgan in Manhattan in 1882 with an incandescent bulb. However, electricity displaced steam power only in the mid thirties. The reason for this slow diffusion was the design of the factories. They had been built vertically to accommodate the pulley system used with steam power and electric motor could not be accommodated within this structure. The factories had to be ultimately destroyed before they could be electrified
- Discovery of photoelectric effect was in 1880; On 25 April 1954, Chapin, Fuller and Pearson in Bell Labs demonstrated that electricity can be produced from sunlight using a diffused silicon crystal. It was a serendipitous discovery. Silicon solar cells were a technical success, but a financial failure ! It would have cost an average homeowner in the US $ 1.5 million to power his house in 1956. Until 2000, the installed solar energy capacity in the world was only 1 GW !

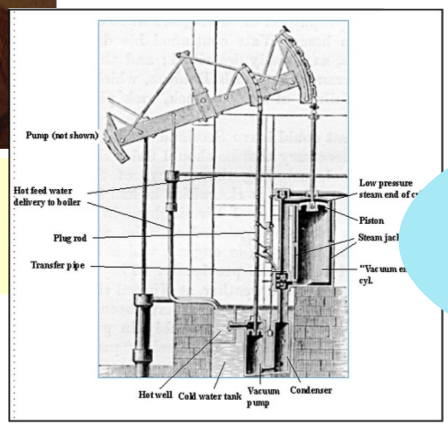
The lag is a result of inherent physical and psychological limits to quick acceptance of new ideas as well as the need for a multidimensional and coordinated approach to bring technology to markets

James Watt, 1763

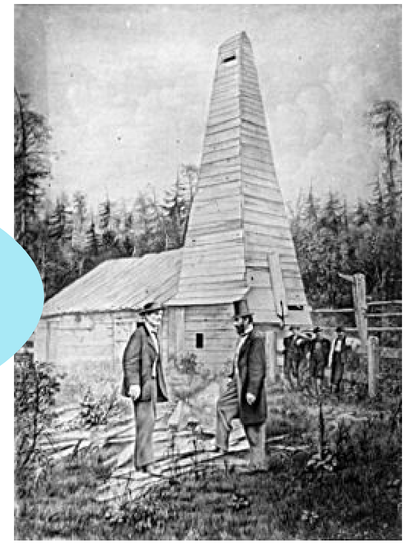
Industrial Revolution



Steam Engine, 1820



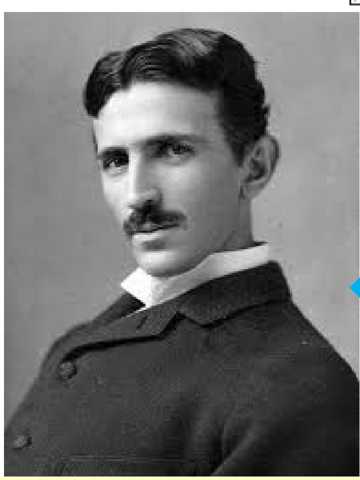
Energy transition in society is painfully slow !



First Petroleum well, 1859

Nikolaus Otta, ICE, 1861

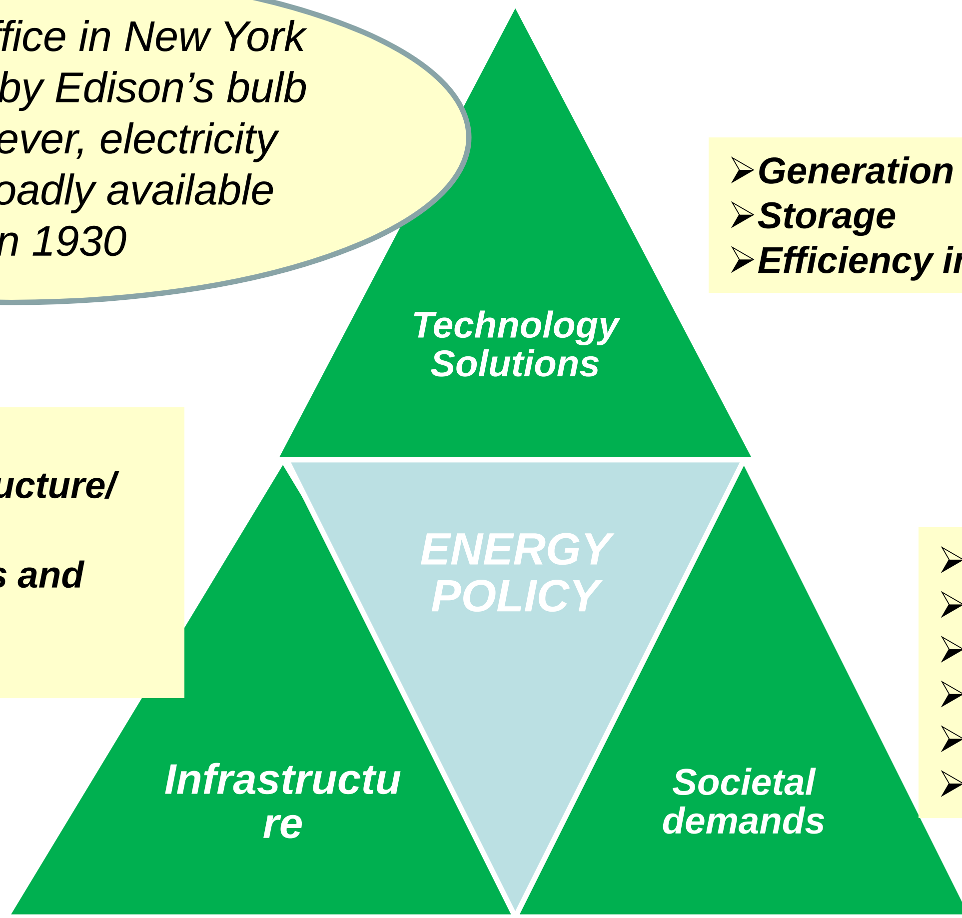
1879



Nicola Tesla, Turbine and AC,1893

EMBEDDED ENERGY INFRASTRUCTURE : DIFFICULTY IN PREDICTING ITS FUTURE ARCHITECTURE

JP Morgan's office in New York was electrified by Edison's bulb in 1882; However, electricity was made broadly available only in 1930



- ***Generation***
- ***Storage***
- ***Efficiency in use***

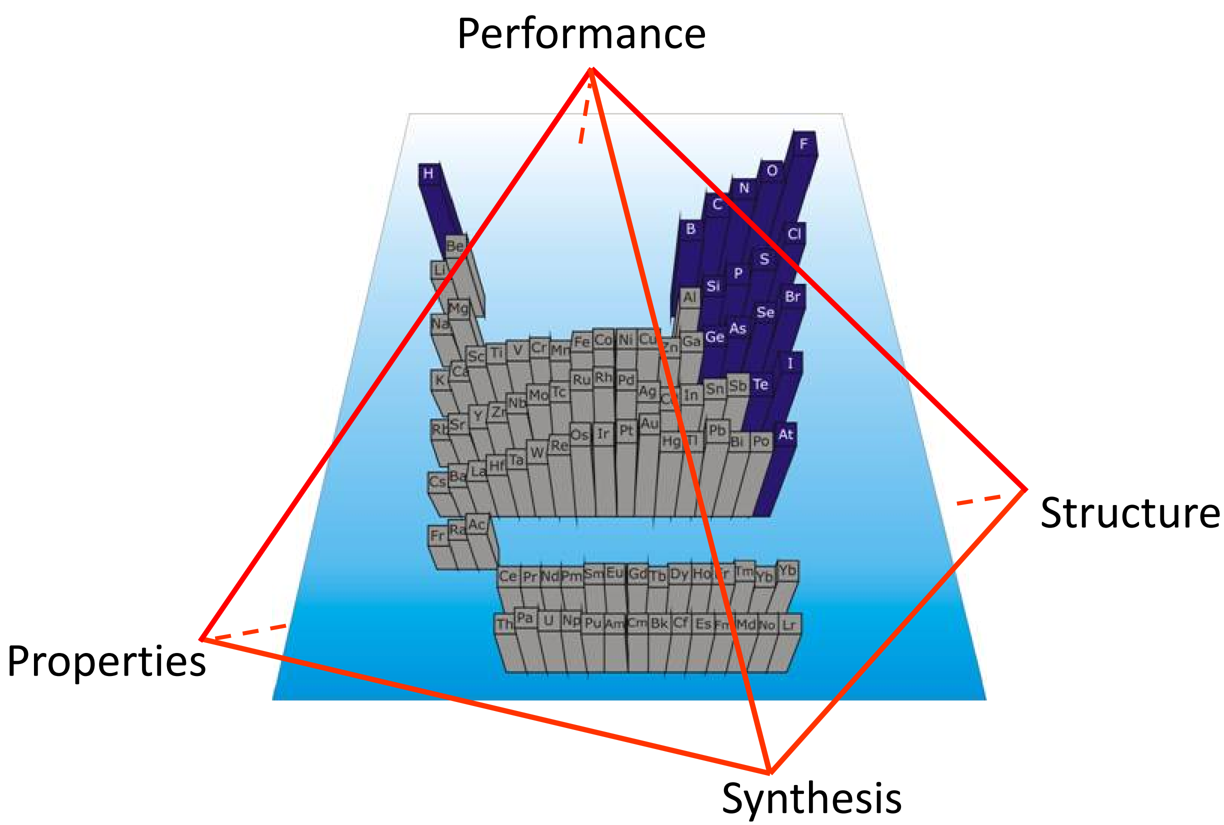
- ***Replacement cost***
- ***Embedded infrastructure/ systems / capital***
- ***Pricing, tariff, taxes and subsidies***

- ***Consumption pattern***
- ***Cost to consumer***
- ***Pay as you use***
- ***Reliability***
- ***Empowerment***
- ***Environmental impact***

Radical changes are possible only when technology and infrastructure gets locked in synergistic embrace

The Science of Materials:

Four Basic Elements



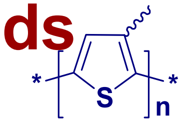
and The Periodic Table of Materials

(M.C. Flemings: *Annu. Rev. Mat. Sci.*, 1999)

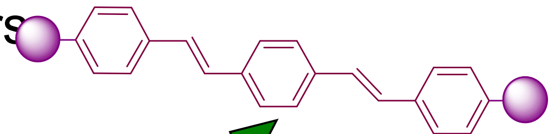
ELEMENTS OF THE 21ST CENTURY

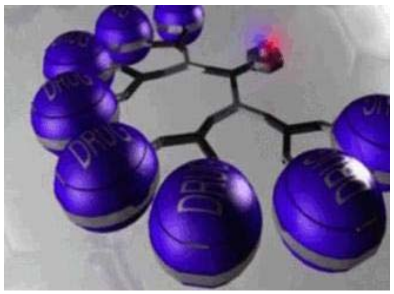
Solar Energy	Silicon, cadmium, tellurium, indium, gallium, selenium, silver, germanium
Wind Energy	Dysprosium, neodymium, samarium, cobalt, rhenium
Batteries	Lead, lithium, sulfur, cobalt, lanthanum
Fuel cells	Platinum, palladium
Nuclear energy	Uranium, thorium, helium
Solid state lighting	Gallium, indium

Organic compounds



- Conducting polymers
- Small light harvesting dye molecules
- Oligomers
- Dendrimers
- Polymers

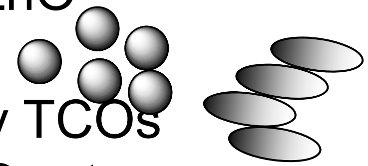


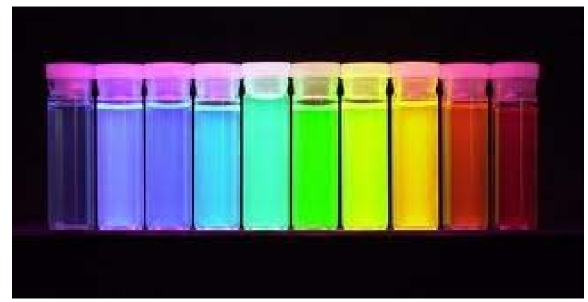


Materials

Inorganic compounds

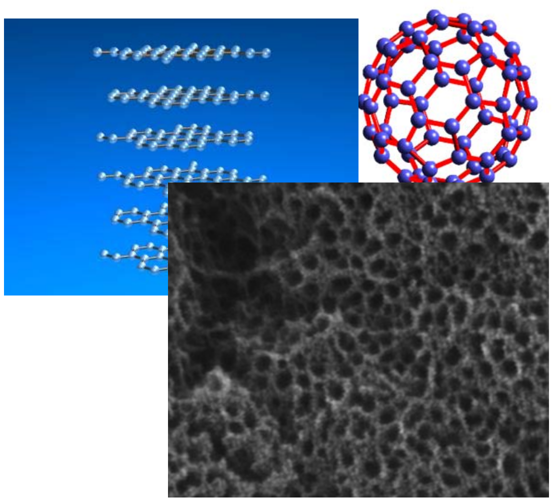
- TiO_2, ZnO
- SiO_2
- Ternary TCOs
- Zn_2SnO_4 etc.
- Other metal oxides
- Metal sulfides
- Quantum dots

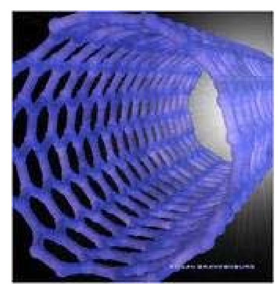


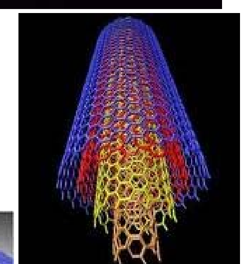


Carbon Family

- SWCNT
- MWCNT
- Graphene
- Fullerene
- Amorphous carbon



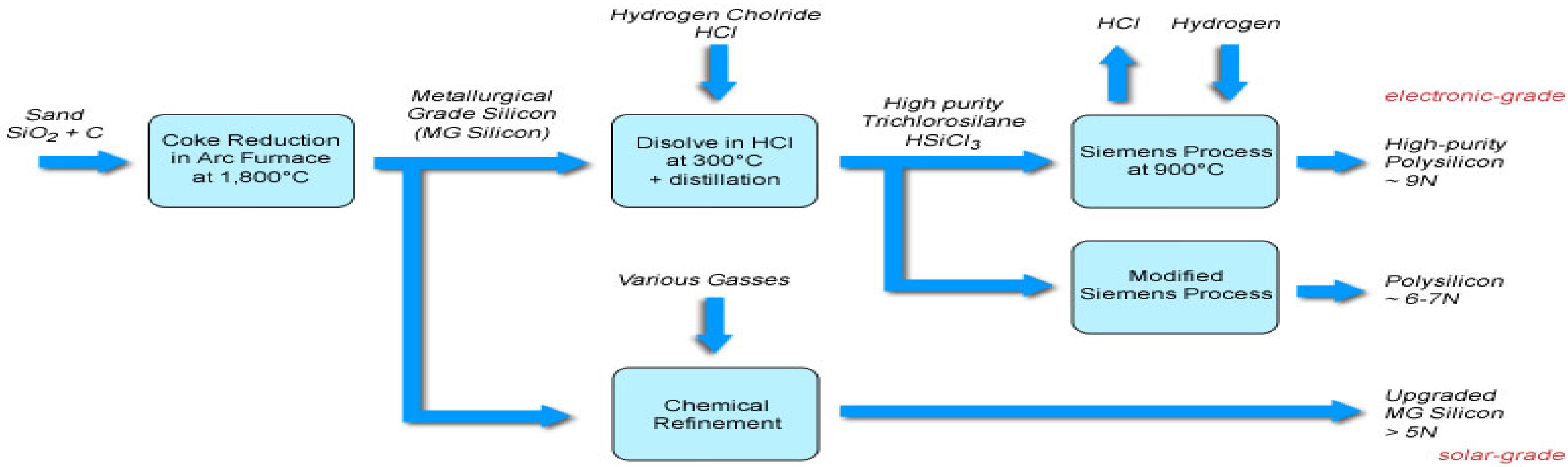




IS SILICON PV GREEN ENERGY ?

Consider the following facts

- Solar PV manufacturing processes involve converting quartz to metallurgical grade silicon and then to polysilicon ingots which are sliced to form wafers



- Every ton of metallurgical grade silicon production results in 4 tons of silicon tetrachloride; Material utilization efficiency is a mere 30%
- 1 ton of crude silicon production results in 10 t of carbon dioxide; Purification process results in additional 45 t of carbon dioxide

IS SILICON PV GREEN ENERGY ?

- Solar cell fabricated with Siemen's process needs 6 years of operation to recover the energy used to make it
- Silicon production uses sulfur hexafluoride, HF, 1,1,1 trichloroethane and large quantities of strong acids
- Silver that is used for making panels at 5 % of current power demand will consume 50 % of current silver produced
- Little or no recycling of silicon in process waste or end of life panels

Ironic that we consider silicon PV as a clean and sustainable form of energy !

India has no domestic silicon production capacity; all silicon is imported, 70 % from China !

THE CHALLENGE OF SOLAR CELL FABRICATION

- 5 TW of solar power generation

  15% efficiency

  250 w/sq m

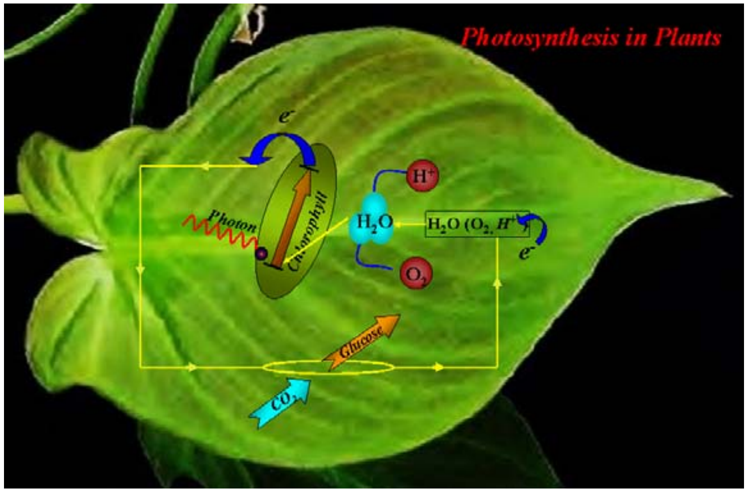
- 250,000 sq km

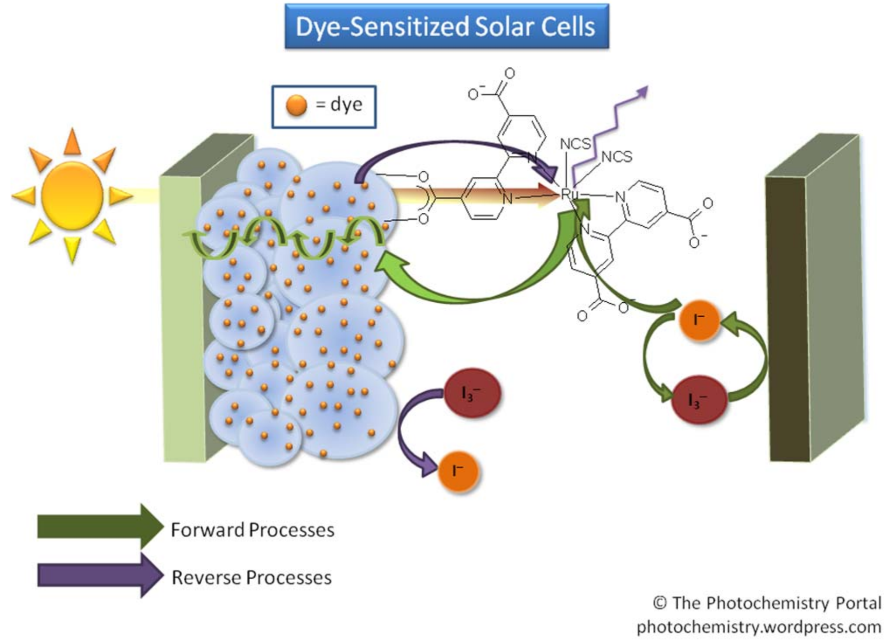
  30 year replacement

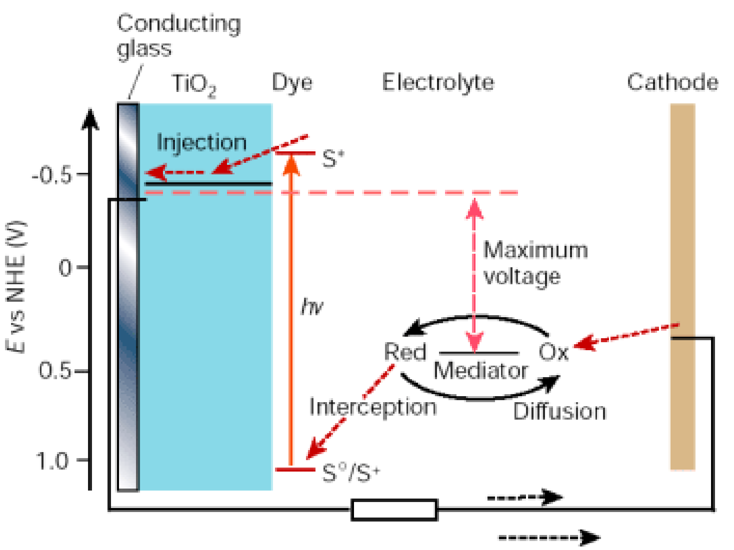
- 25 sq km of cells per day
- 1 billion cells (15x15 cm) each day

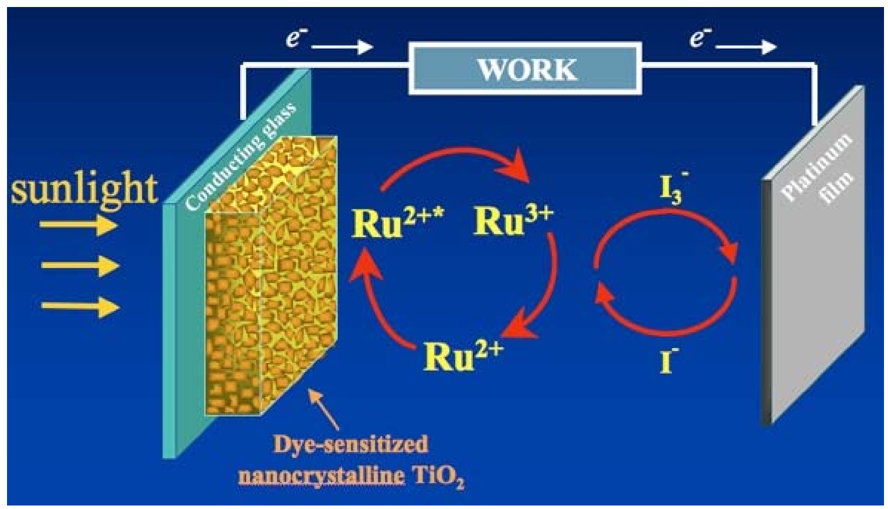
The current method of fabrication of silicon wafers from ingots is incapable of achieving this scale of operation ; clearly, there is a technology gap

DYE SENSITIZED SOLAR CELL : TAKING A LEAF OUT OF NATURE





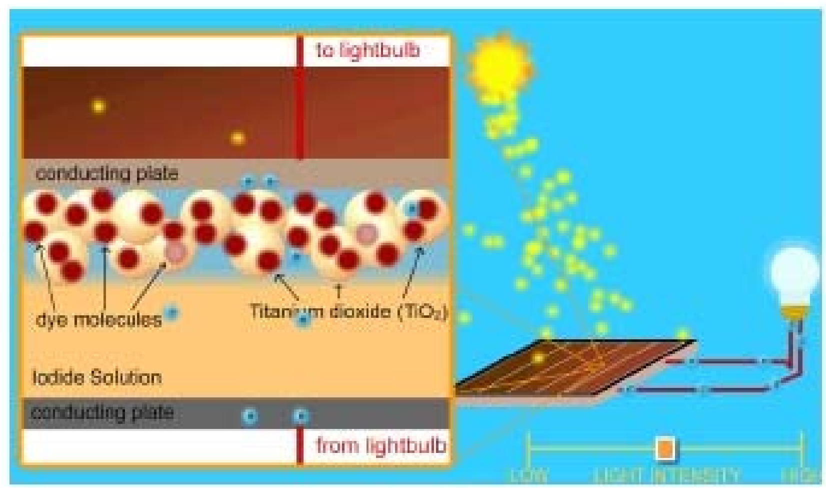




Ref: Grätzel, M. Nature 1991, 414, 338.

How a Dye-Sensitized Cell Works

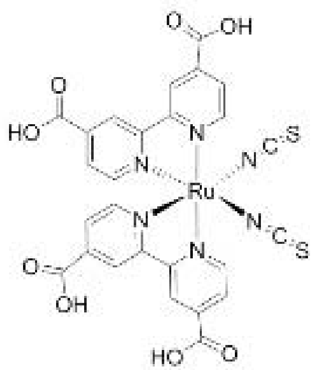
- **Light with high enough energy excites electrons in dye molecules**
- **Excited electrons infused into semiconducting TiO_2, transported out of cell**
- **Positive "holes" left in dye molecules**
- **Separation of excited electrons and "holes" creates a voltage**



Click image to launch animation
(requires web access)

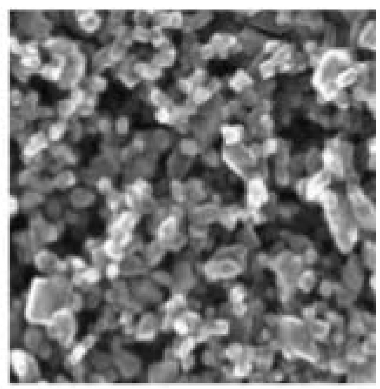
Dye-Sensitized Solar Cell Components

Sensitizing Dye



Chemical Structure of N3 Dye

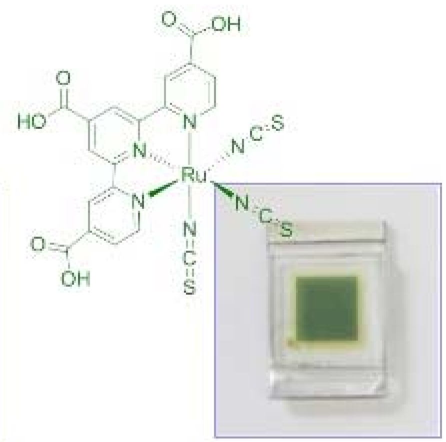
Titania Nanoparticles

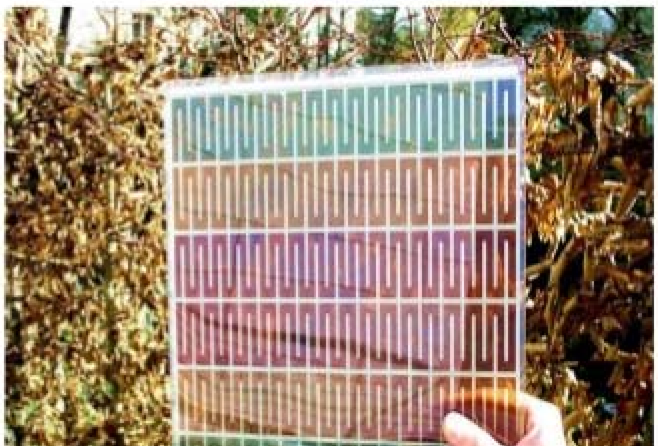


20 nm Titania nanoparticles

Electrolyte

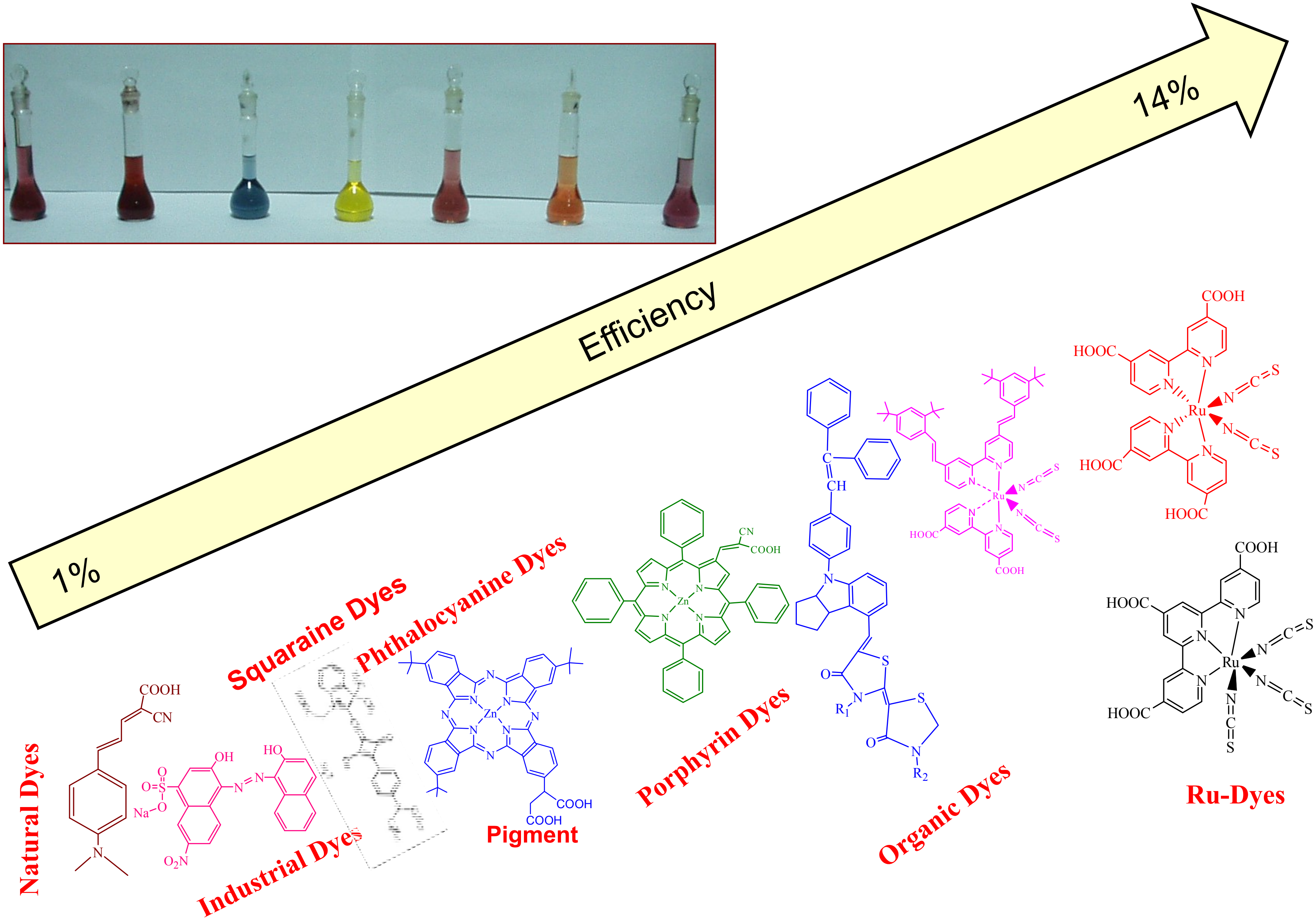
Iodide/Tri-iodide
Redox Couple





Various colors in a series-connected dye solar cell module courtesy Dr. Andreas Hinsch, FHI, ISE Freiburg Germany.

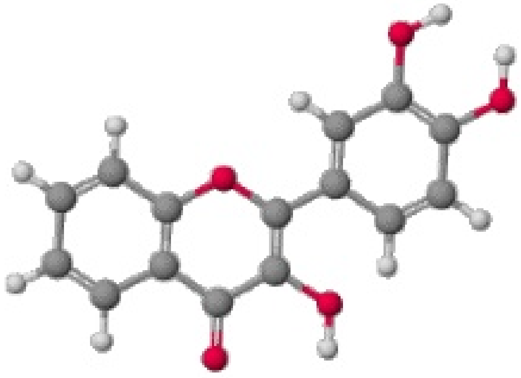
Leaf-shaped transparent DSC with four colors courtesy AISIN SEIKI CO.,LTD.



14%
Efficiency
1%
Natural Dyes
Industrial Dyes
Squaraine Dyes
Phthalocyanine Dyes
Pigment
Porphyrin Dyes
Organic Dyes
Ru-Dyes

High School Students make their own solar cell

anthocyanine dye from blackberries



Dye-Sensitized Solar Cells are 12% Efficient. What can we do to make them better?

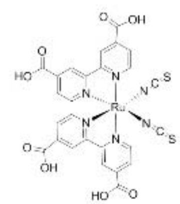
- **Develop dyes to absorb more photons**
- **Create new electrolytes that provide higher voltages.**
- **Develop Dye-Sensitized Solar Cells that can last for 30 years**

Design Near-Infrared Absorbing Dyes

- Can increase power conversion efficiency from 12% to 14% by absorbing light out to 900 nm.
- Probably can't make DSCs >14% using liquid electrolytes.

Stanford/EPFL collaboration through the Center for Advanced Molecular Photovoltaics (CAMP)

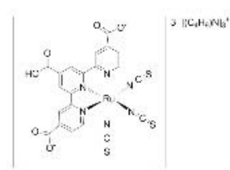
Design dyes that broadly absorb light



N3

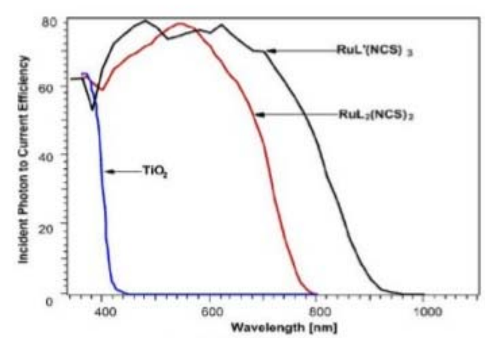
cis-Ru(SCN)$_2$L$_2$

(L = 2,2-bipyridyl-4,4-dicarboxylate)



N749

tri(cyanato)-2.22-terpyridyl-4,44-tricarboxylate)Ru(II)



M.K. Nazeeruddin et al., *J. Am. Chem.Soc.* 123, 1613, (2001)

Applications of DSSC

(a) 200 m² of DSSC panels installed in Newcastle (Australia)– the first commercial DSSC module

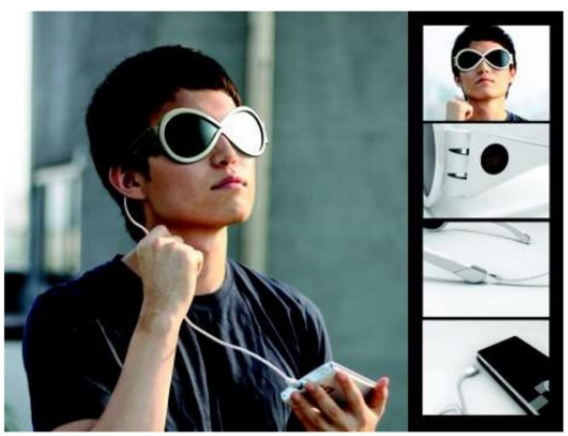
- Flexible
- Wearable
- Paintable
- Can harvest diffuse light

(c) flexible DSSC-based solar module developed by Dyesol (http://www.dyesol.com)

(d) jacket commercialized by G24i (http://www.g24i.com).

Solar Powered Solar Panel Sun Glasses

The SIG, or "Self-Energy Converting Sunglasses" are quite simple. The lenses of the glasses have **dye solar cells,** collecting energy and making it able to power your small devices through the power jack at the back of the frame. "Infinite Energy: SIG"



Courtesy: Sony Corp.

67

61

Solar Cell Efficiencies

Silicon Solar Cell Efficiencies:

Theoretical Maximum: 26%

Best in Lab: 25% (Green, UNSW)

Modules: 15-22%

Thin Film Solar Cell Efficiencies:

Theoretical Maximum: >22%

Best in Lab: 20% (Noufi, NREL)

Modules: 9-12%

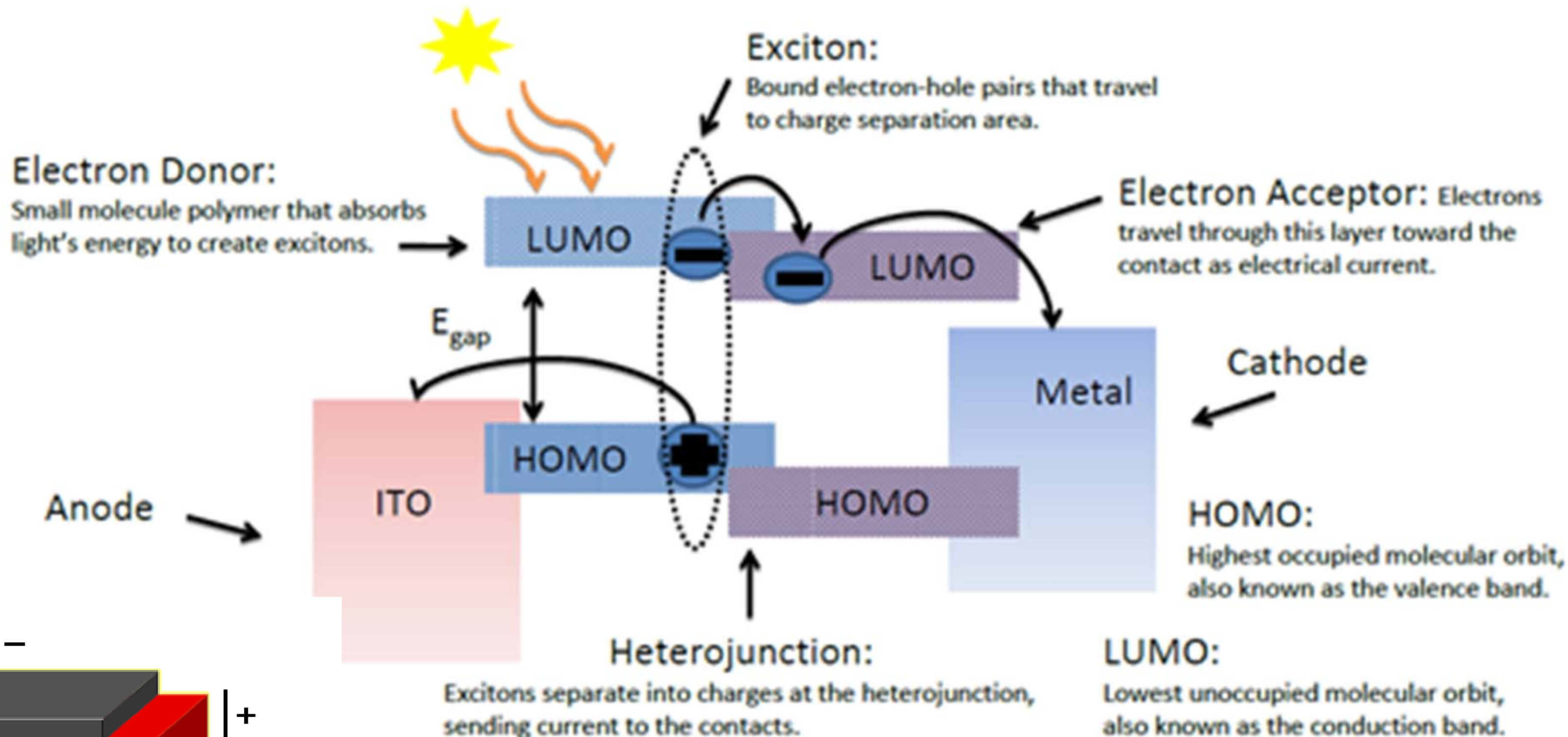
Dye-Sensitized Solar Cell Efficiencies:

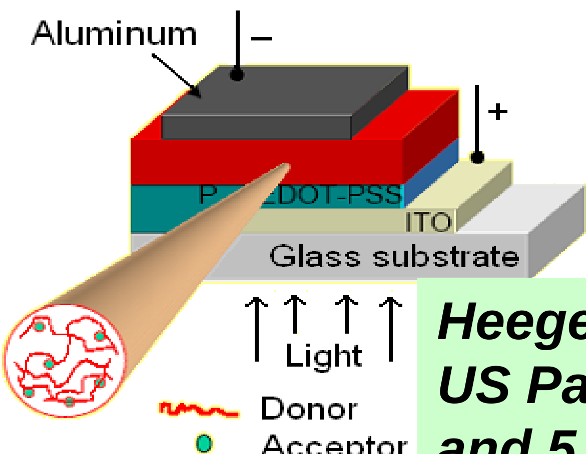
Theoretical Maximum: 14-20%

Best in Lab: 12% (Grätzel, EPFL)

Modules: 6-9%

Operation of Organic Solar Cell



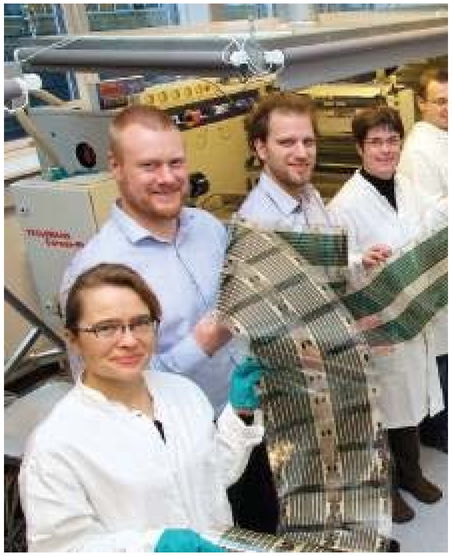


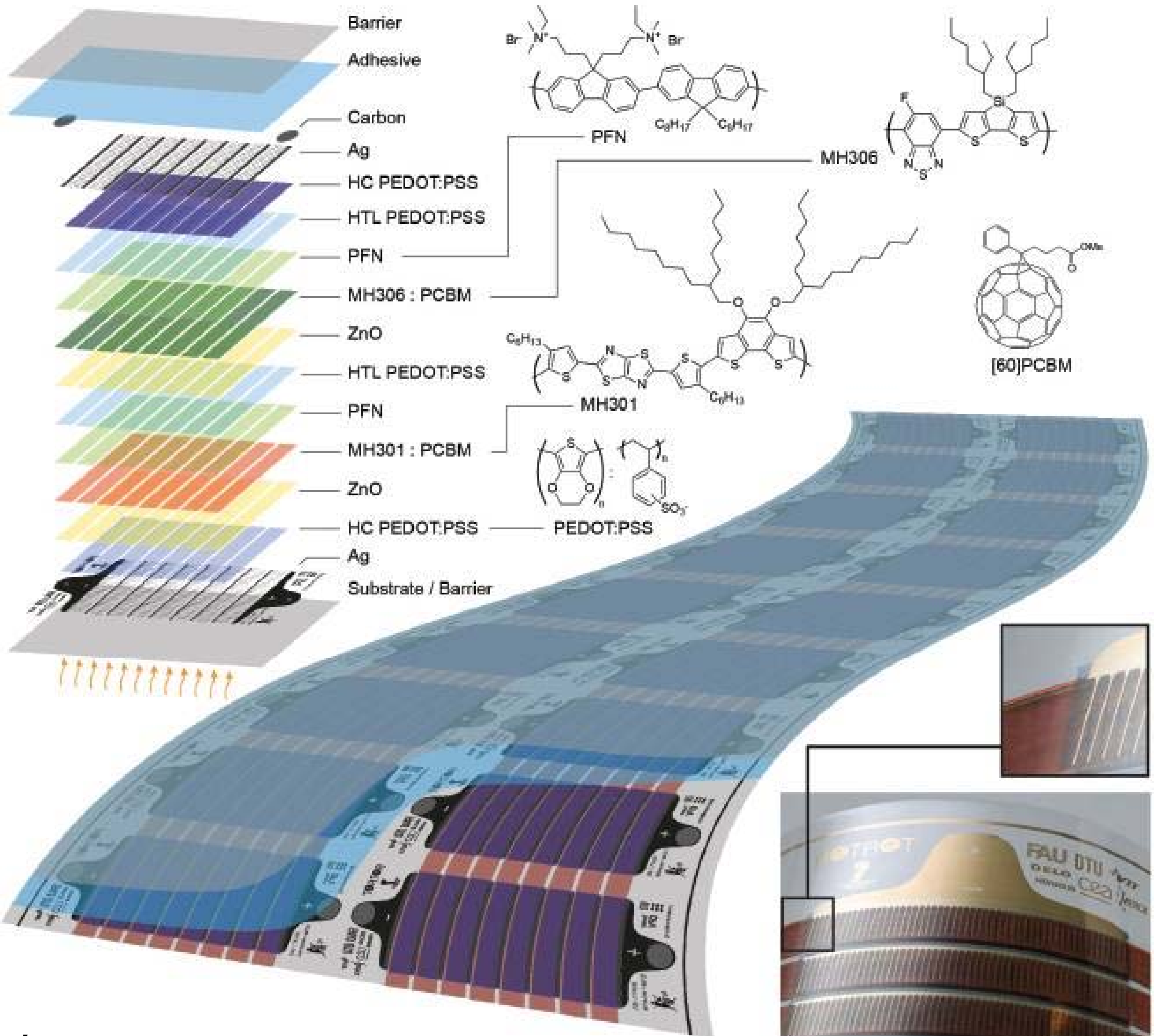
Heeger and Saricifti
US Patents 5,331, 183 and 5,454, 880; Science, 258, 1474, 1992

Components of the device:

1. ITO coated Glass or flexible substrate (Anode)
2. Hole Transport Layer (HTL) of PEDOT:PSS /MoO3 or PFN
3. Donor and Acceptor Layer (DAL) of Polymer : PC60BM/PC70BM
4. Electron Transport Layer (ETL)
5. Cathode Electrode of Al/Ag

ORGANIC PHOTOVOLATAICS





Maximum certified efficiency : 11.5 %

Konarka, USA
Heliatec, Germany
Solarmer
819, UK
Infinity PV(Denmark)
Plextronics(Solvay) : inks

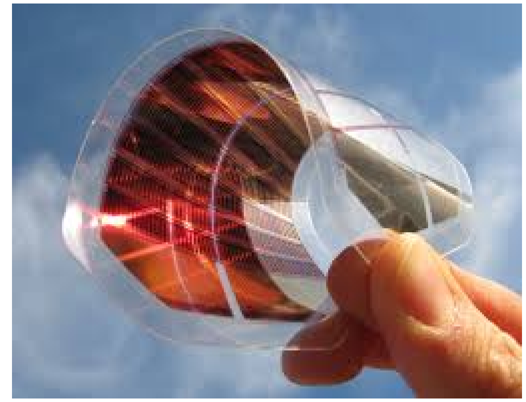
Chemistry World, August 2014, p.24

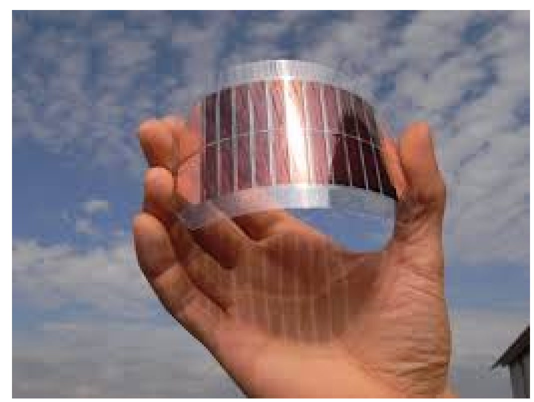
- Theoretical Limit   20%
- 10%, Lifetime 10> Years,
- Konarka Corporation ~ 3%, 2000 hours certified
- 1c/Wp possible

Deposition Techniques and Scaling Up : Roll-to-roll deposition

- Materials

  - Inks and slolvents (olymers and mall molecules)
  - Substrates (glass, plastics, aluminum)
  - Electrodes (ITO, alternative TCOs)





Organic Photovoltaics: Technology and Manufacturing

Y. Galagan and R. Adriessen, TNO, Netherlands

www.intechopen.com

SOLAR PARKS FREDERIK KREBS, TECHNICAL UNIVERSITY DENMARK

Installation

ttps://www.youtube.com/watch?v=o425pMjZL1Y

De-Installation

http://www.youtube.com/watch?v=K2REgwwxrac

Manufacture of Polymer Solar cell: 1 m min^{-1}

Installation De-installation: 100 m min^{-1}

Initial efficiency 2% stabilizes at 1.6-1.8%

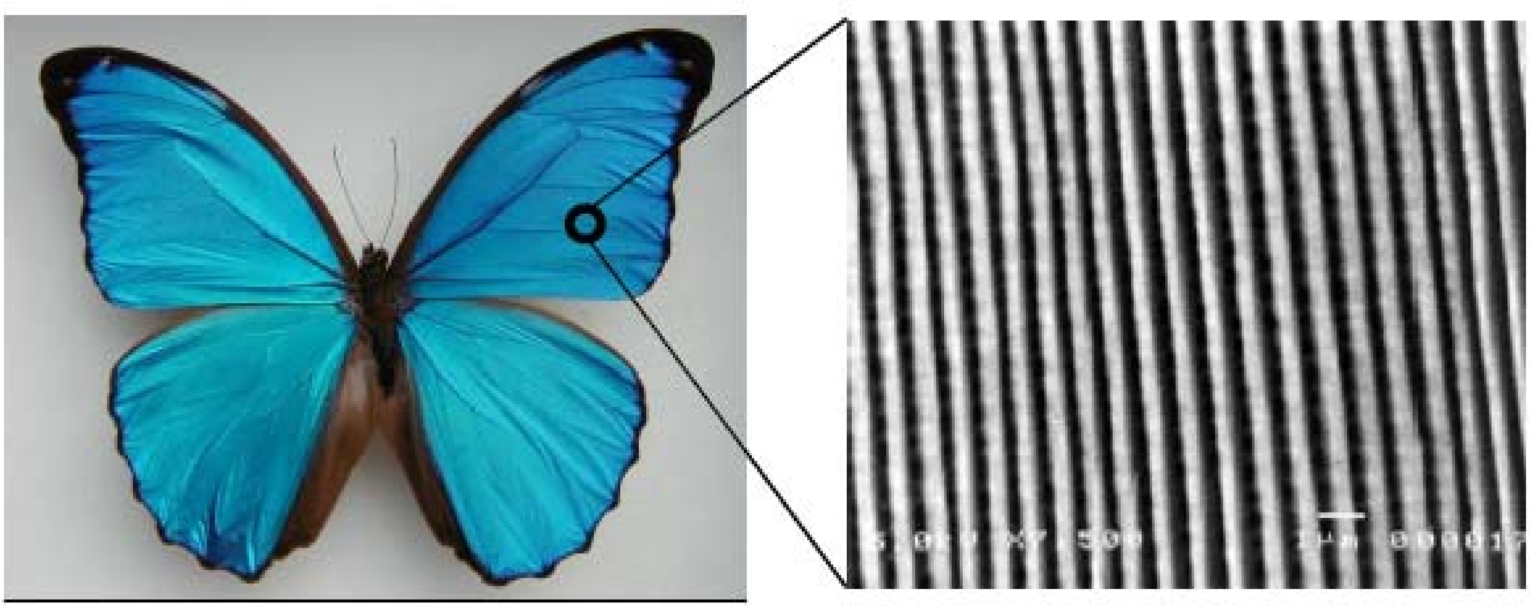
Target : 4% efficiency
10 year stability

Rise to power - OPV based solar parks. Advanced Materials. 2014, 26, 29-39

HOW DOES THE NATURE CREATE THE COLORS OF PEACOCK FEATHERS

Is there a bio-inspired approach to create optical effects in surface coatings?

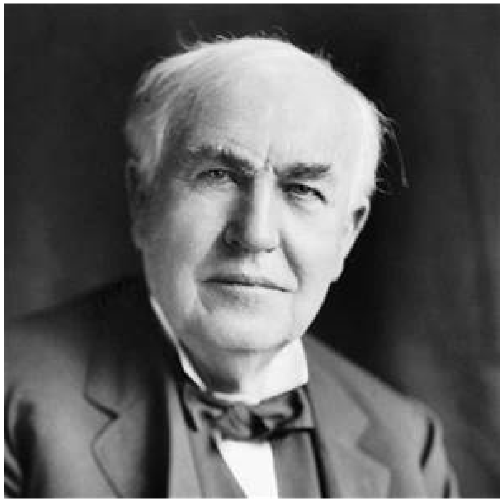
HOW DOES NATURE CREATE THE COLORS OF BUTTERFLY WINGS



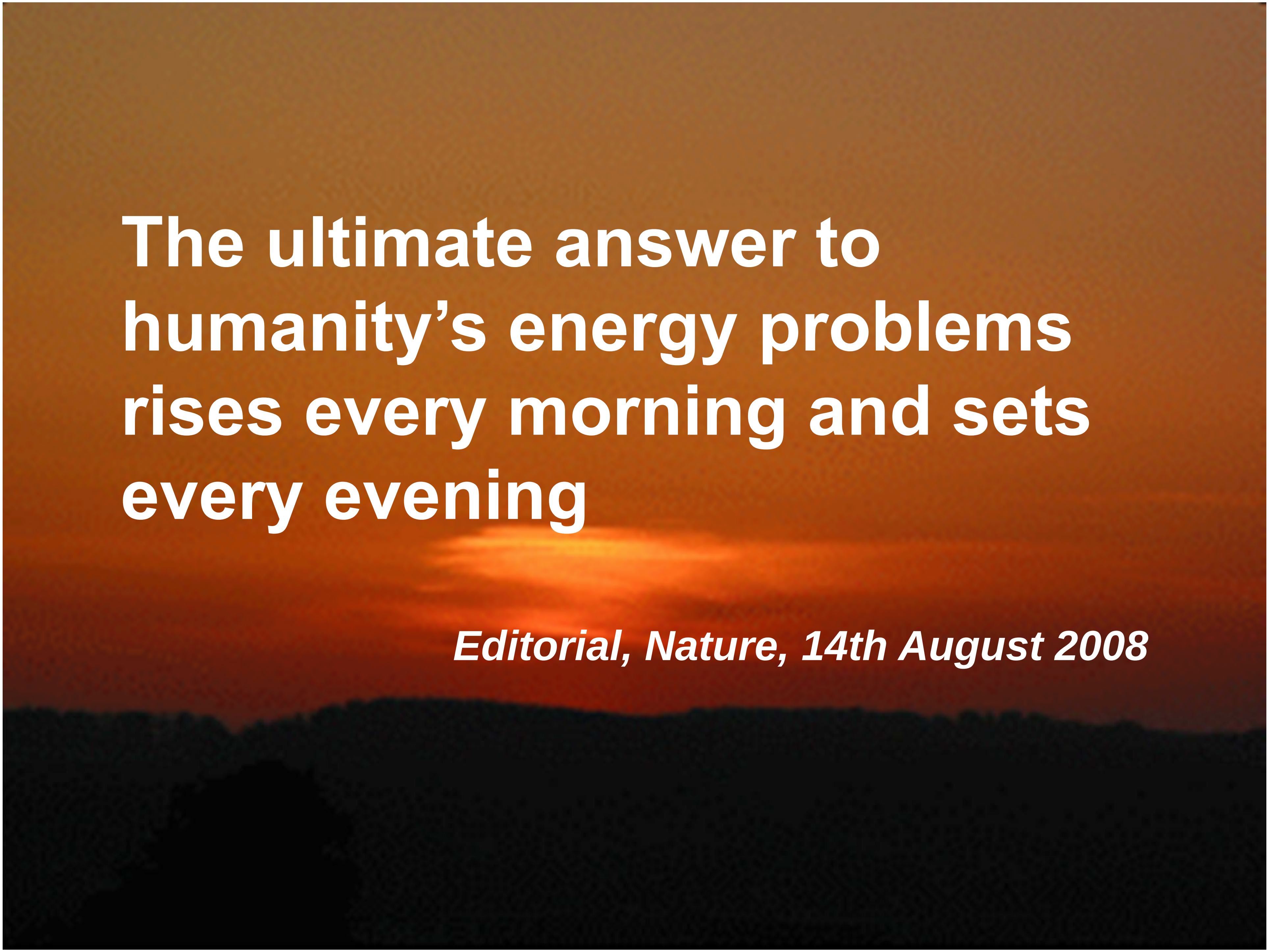
The striking colors of butterfly wings come from light diffracting off the ordered microstructure of their scale. Synthetic surfaces with similar optical effects can be now created in the laboratory

Interaction of light with matter is one of the most profound concepts in science; The colours in our material world , both, nature made and man made is an exquisite manifestation of this science. Our ability to create energy out of light also exploits the same phenomenon.

“ I’d put my money on the sun and solar energy. What a source of power! I hope we don’t have to wait till oil and coal run out before we tackle that ”



Thomas Alva Edison
(1847-1931)


The ultimate answer to humanity’s energy problems rises every morning and sets every evening
Editorial, Nature, 14th August 2008

“ For success it is not enough to be intelligent; it also depends upon how passionate you are about the work you do “

C.J. Bhumkar

Passion, persistence, perseverance and patience are needed for success in securing technology for our energy future

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