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2269-30

Workshop on New Materials for Renewable Energy

17 - 21 October 2011

Recent progress in dye-sensitized solar cells - Part I

Jun-Ho YUM

Swiss Federal Institute of Technology, EPFL, Lausanne
Switzerland

Strada Costiera 11, 34151 Trieste, Italy - Tel.+39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it

Recent Progress in Dye-Sensitized Solar Cells Part I

Jun-Ho Yum

junho.yum@epfl.ch

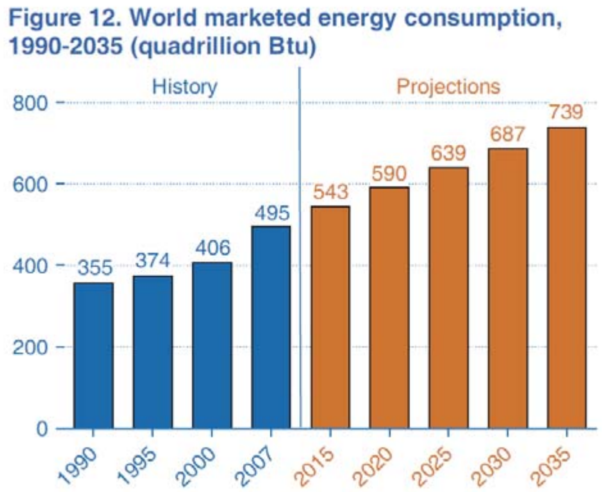
Swiss Federal Institute of Technology Lausanne

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Workshop on New Materials for Renewable Energy, October 19, 2011

Problems

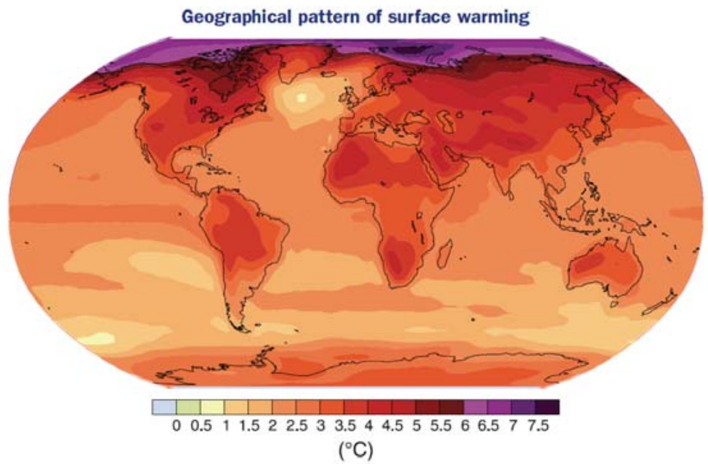
Energy demand



International Energy Outlook, 2010

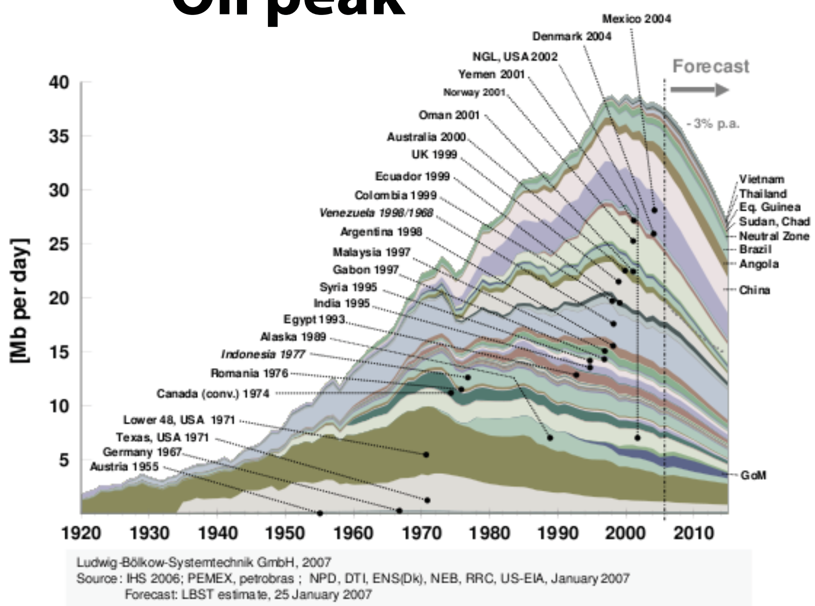
Pollution

Global warming



IPCC, 4th Assessment Report, 2007

Oil peak



Nuclear disaster

Nuclear Disaster

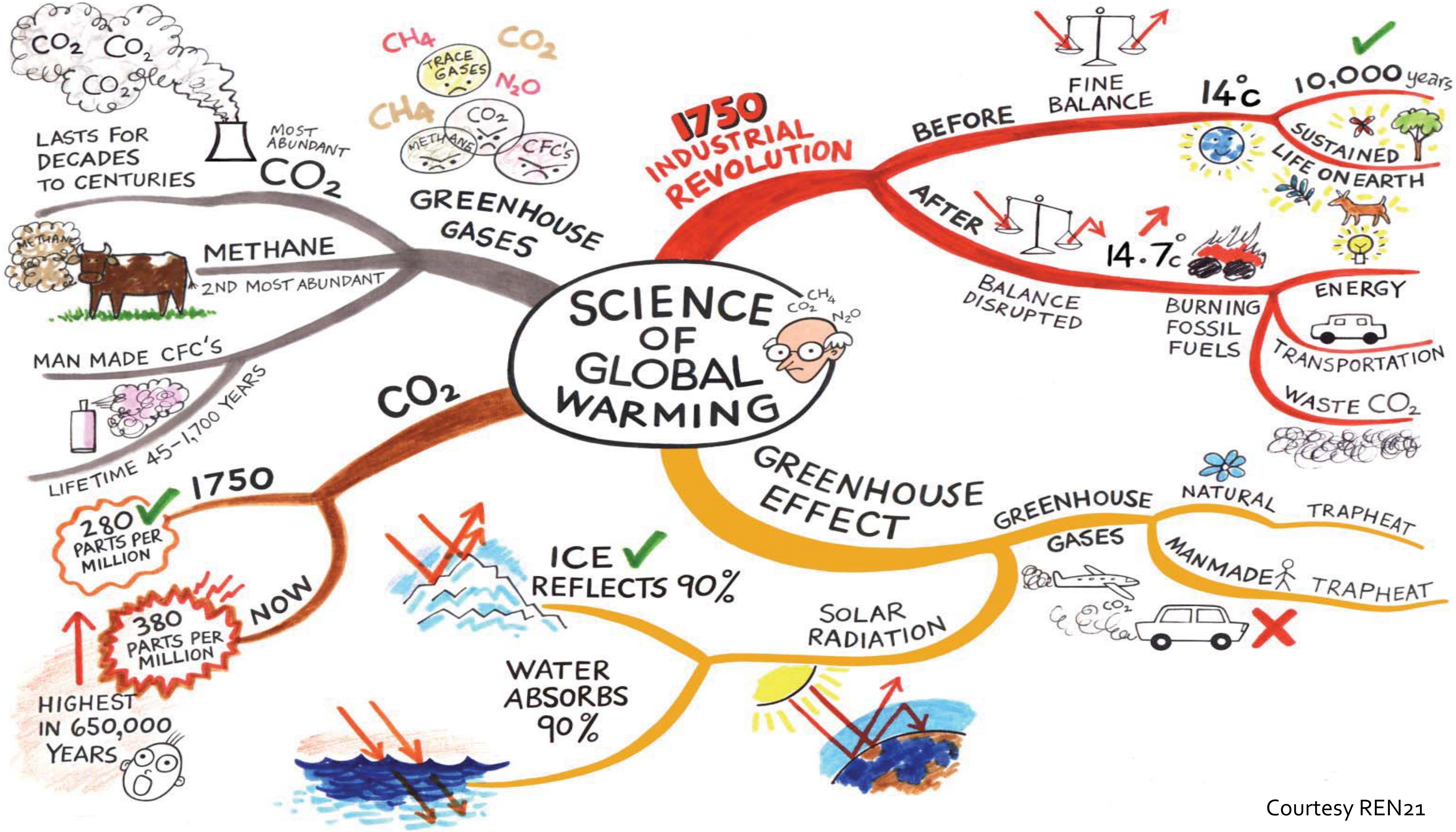
Nuclear Energy is not a Solution

14 June 2011 Italy nuclear: Berlusconi accepts referendum blow. Opposition to nuclear power has grown since Fukushima.

Germany and Switzerland have both announced that they will phase out nuclear power by 2022.

Fukushima reactor March 24, 2011

Why renewable energy sources?



Courtesy REN21

Challenge

- ✓ **Energy Gap in 2050: ~14 TW**
  With a projected global population of 12 billion by 2050 coupled with moderate economic growth, the total world power consumption is estimated to be ~28 TW. Current global use is~14 TW. The power supply gap to be covered by 2050 is expected to be at least 14 terawatt corresponding to a yearly energy deficit of 440 exajoules ! (1 exajoule = 10^{18} joule).

- ✓ **To cap CO_2 at 550 ppm* (twice the pre-industrial level):** most of this additional energy needs to come from carbon-free sources.
  - ***350 ppm should ideally be targeted !**

- ✓ **Solar energy is the largest non-carbon-based energy source (120 PW).**

- ✓ However, it has to be converted at **cost low** enough to be competitive with conventional resources

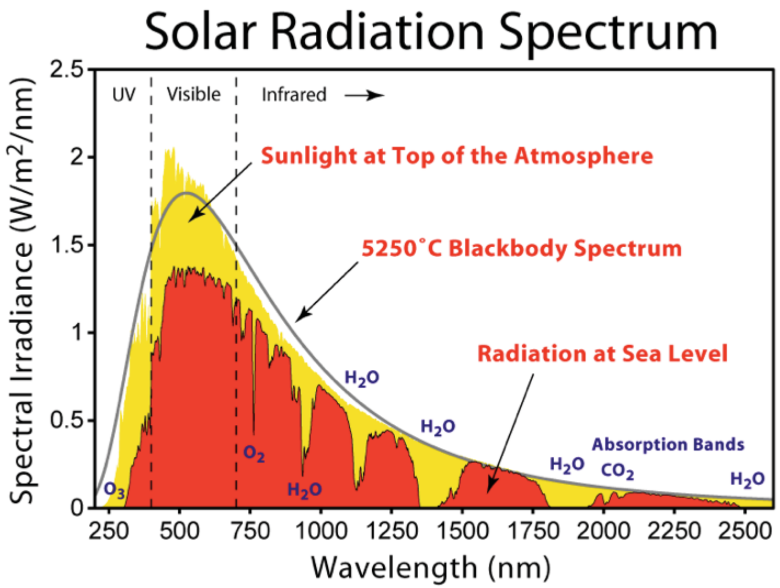
Challenge

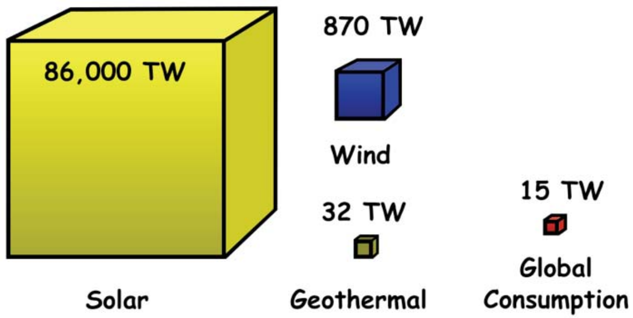
Incoming Solar Radiation =
170 PW (1 PW = 10^{15} W)

Reflection to the space = 30%

Solar Energy into the Earth = **120 PW**

E/1 hr = 432 ExaWatt ≈
E Needs for entire world for a year





7th Century B.C.

Magnifying glass used to concentrate sun's rays to make fire and to burn ants.

3rd Century B.C.

Greeks and Romans use burning mirrors to light torches for religious purposes.

2nd Century B.C.

As early as 212 BC, the Greek scientist, Archimedes, used the reflective properties of bronze shields to focus sunlight and to set fire to wooden ships from the Roman Empire which were besieging Syracuse.

1st to 4th Century A.D.

The famous Roman bathhouses in the first to fourth centuries A.D. had large south facing windows to let in the sun's warmth.

www1.eere.energy.gov/solar/pdfs/solar_timeline.pdf

History of Solar Power Technology

1865- The first solar powered engine

1913- The first solar thermal power station

1954- The first practical solar panel

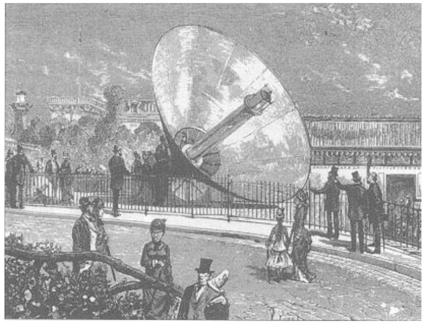
1958- The first solar powered satellite

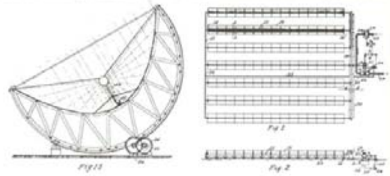
1960- The first solar powered car

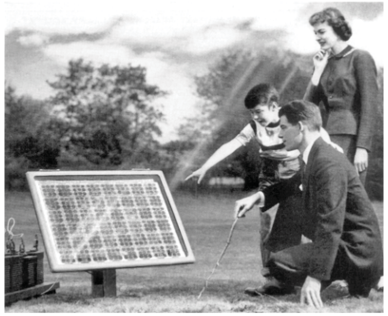
1997- The first solar powered mobile phone

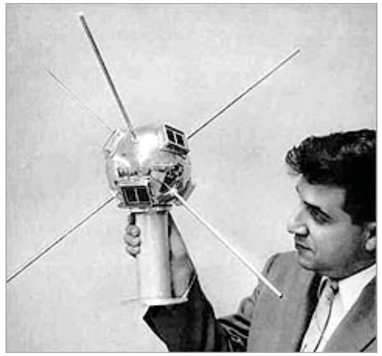
2010- The first solar powered spacecraft

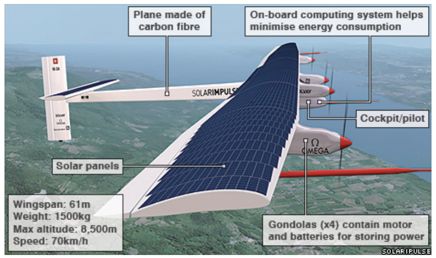
2011- The solar powered flight (Solar Impulse)

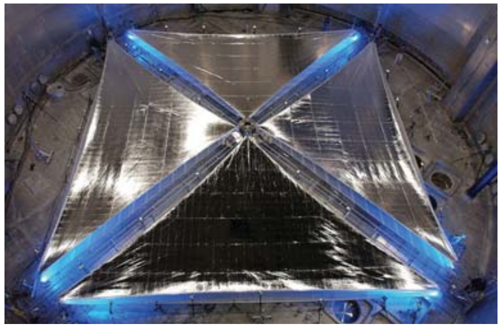






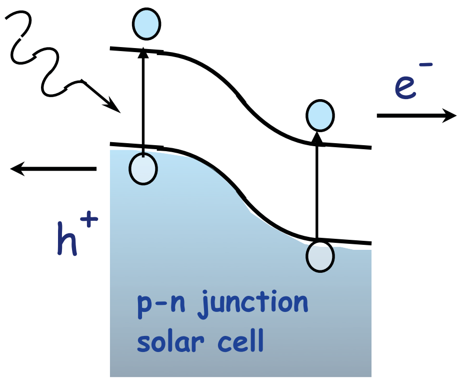


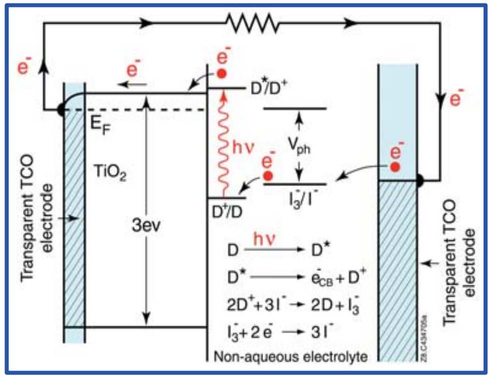




http://solarcharging.nokia.com/2011/08/a-pictorial-history-of-solar-powered-technology/
http://www.solarimpulse.com/

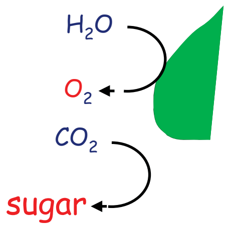
Solar Energy Utilization



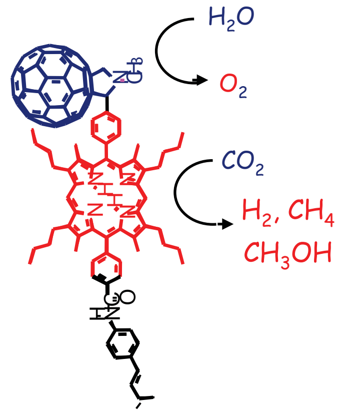


dye sensitized cell and
photoelectrochemical solar cells

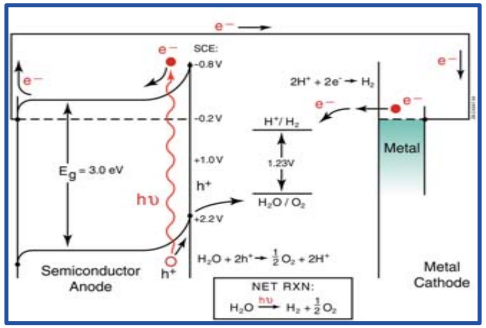
Solar Electric



natural
photosynthesis

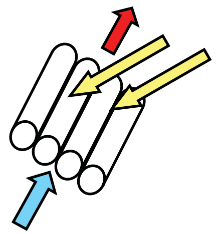


artificial
photosynthesis

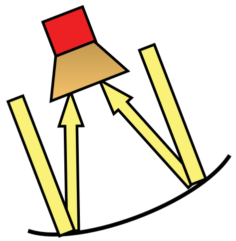


photoelectrolysis/H_2O splitting

Solar Fuels



50 - 200 °C
space, water
heating



500 - 3000 °C
heat engines
electricity generation
process heat

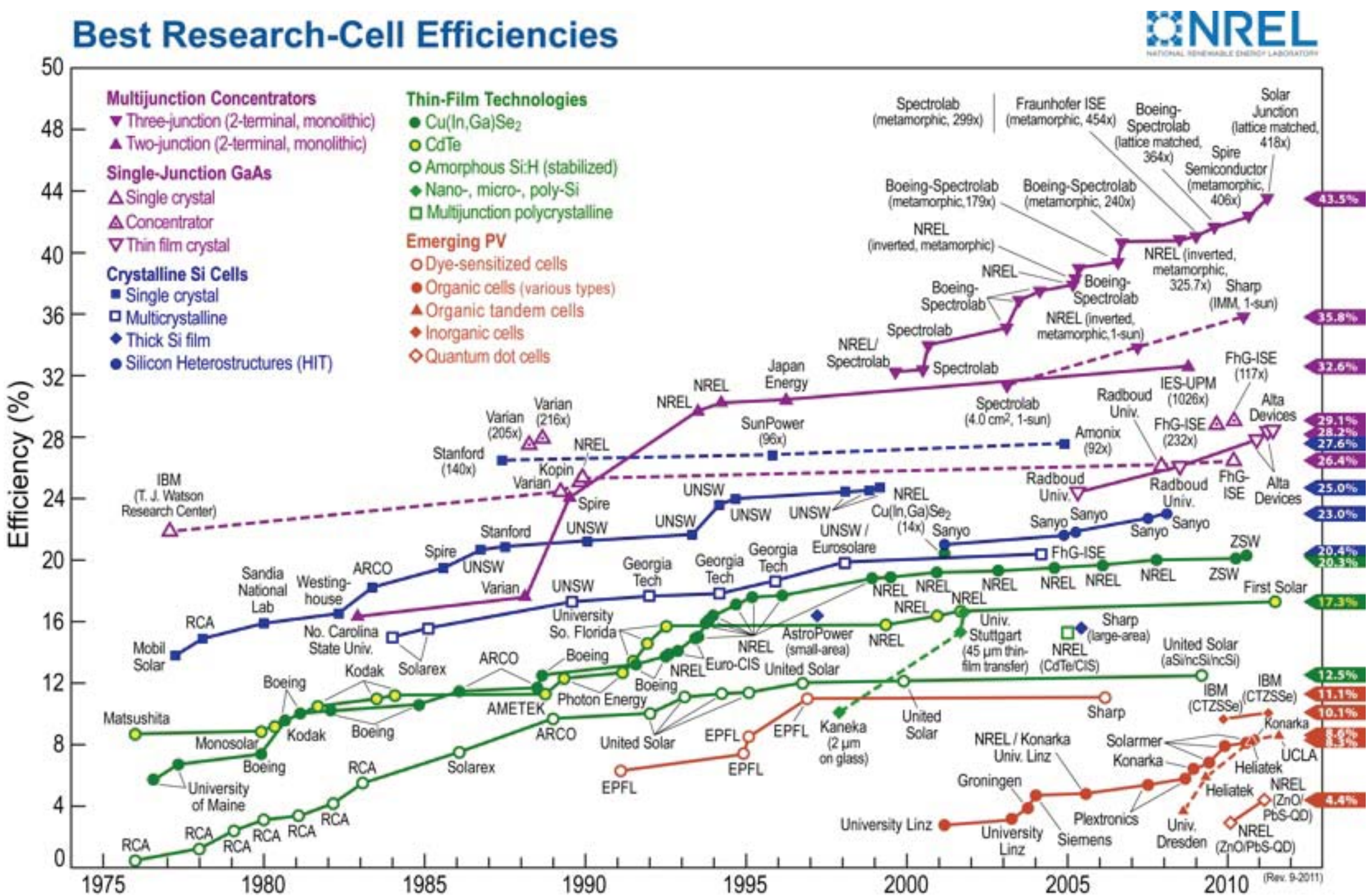
Solar Thermal

from Arthur Nozik

Solar Cell Effect

If 5 kWp solar cell array is installed on a rooftop of a home over a single year, **it would prevent:**

- **3.3 tons of coal from being burned**
- **300 kg of ash from being disposed of landfills**
- **30 kg of SO_2 and 25 kg of NO_x from causing acid rain**
- **8.5 tons of CO_2 from enhancing the greenhouse effect**



Best Research-Cell Efficiencies
NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Efficiency (%)
Multijunction Concentrators
Three-junction (2-terminal, monolithic)
Two-junction (2-terminal, monolithic)
Single-Junction GaAs
Single crystal
Concentrator
Thin film crystal
Crystalline Si Cells
Single crystal
Multicrystalline
Thick Si film
Silicon Heterostructures (HIT)
Thin-Film Technologies
Cu(In,Ga)Se2
CdTe
Amorphous Si:H (stabilized)
Nano-, micro-, poly-Si
Multijunction polycrystalline
Emerging PV
Dye-sensitized cells
Organic cells (various types)
Organic tandem cells
Inorganic cells
Quantum dot cells
Spectrolab (metamorphic, 299x)
Fraunhofer ISE (metamorphic, 454x)
Boeing-Spectrolab (lattice matched, 364x)
Solar Junction (lattice matched, 418x)
Spire Semiconductor (metamorphic, 406x)
Boeing-Spectrolab (metamorphic, 179x)
Boeing-Spectrolab (metamorphic, 240x)
NREL (inverted, metamorphic)
NREL (inverted, metamorphic, 325.7x)
Sharp (IMM, 1-sun)
NREL (inverted, metamorphic, 1-sun)
Spectrolab (4.0 cm², 1-sun)
IBM (T. J. Watson Research Center)
Stanford (140x)
Varian (205x)
Varian (216x)
SunPower (96x)
Amonix (92x)
FhG-ISE (117x)
IES-UPM (1026x)
FhG-ISE (232x)
Radboud Univ.
Alta Devices
Japan Energy
NREL/ Spectrolab
Kopin
Spire
UNSW
Sanyo
Stanford
ARCO
Sandia National Lab
Westing-house
RCA
Mobil Solar
No. Carolina State Univ.
Solarex
Kodak
Boeing
Matsushita
Monosolar
University of Maine
AMETEK
Photon Energy
University So. Florida
Georgia Tech
Euro-CIS
United Solar
AstroPower (small-area)
Univ. Stuttgart (45 µm thin-film transfer)
NREL (CdTe/CIS)
Sharp (large-area)
United Solar (aSi/ncSi/ncSi)
First Solar
ZSW
FhG-ISE
UNSW / Eurosolare
NREL Cu(In,Ga)Se2 (14x)
EPFL
Kaneka (2 µm on glass)
IBM (CTZSSe)
Konarka
UCLA
Heliatek
NREL (ZnO/PbS-QD)
Solarmer
NREL / Konarka Univ. Linz
Groningen
University Linz
Plextronics
Siemens
Univ. Dresden
43.5%
35.8%
32.6%
29.1%
28.2%
27.6%
26.4%
25.0%
23.0%
20.4%
20.3%
17.3%
12.5%
11.1%
10.1%
8.6%
8.3%
4.4%
50
48
44
40
36
32
28
24
20
16
12
8
4
0
1975
1980
1985
1990
1995
2000
2005
2010
(Rev. 9-2011)

Solar Cell performance

I_{SC} : Short-circuit current

→ Current value when V=0

V_{OC} : Open-circuit voltage

→ Voltage value when I=0

P : Power output of the cell

P=IV

F.F : Fill factor

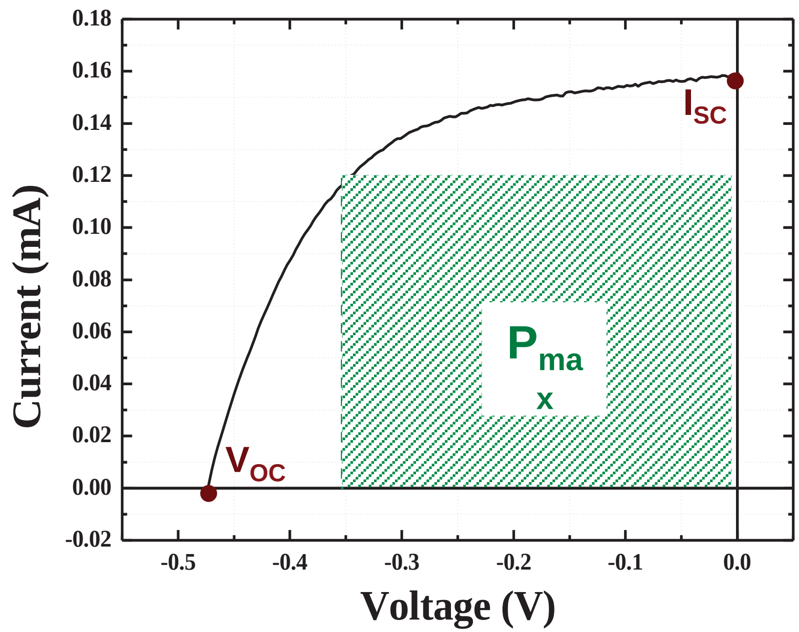
$$F.F = \frac{P_{max}}{I_{SC}V_{OC}} = \frac{I_m V_m}{I_{SC}V_{OC}}$$

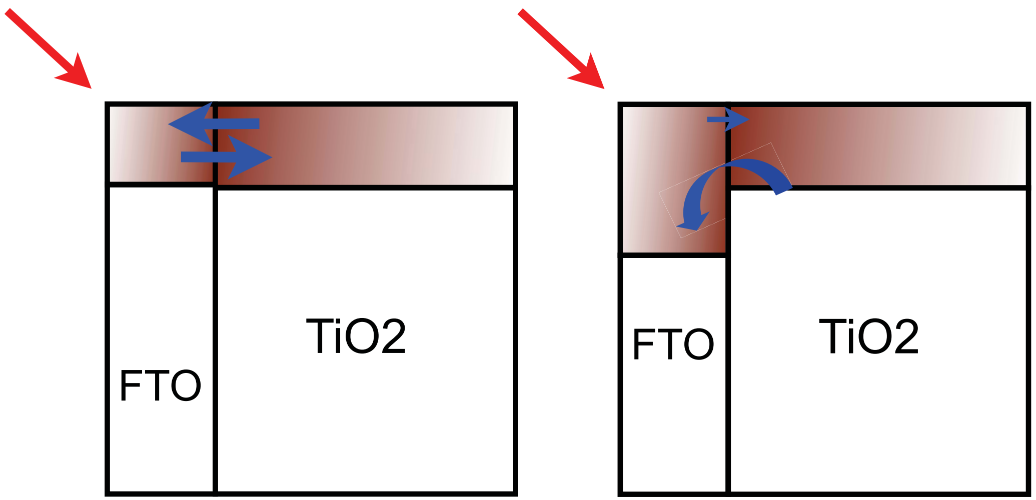
The overall efficiency

$$\eta = \frac{P_{max}}{P_r} = \frac{F.F\ I_{SC}V_{OC}}{P_r}$$

(P_r : Radient power input)

Power curve (I-V curve)

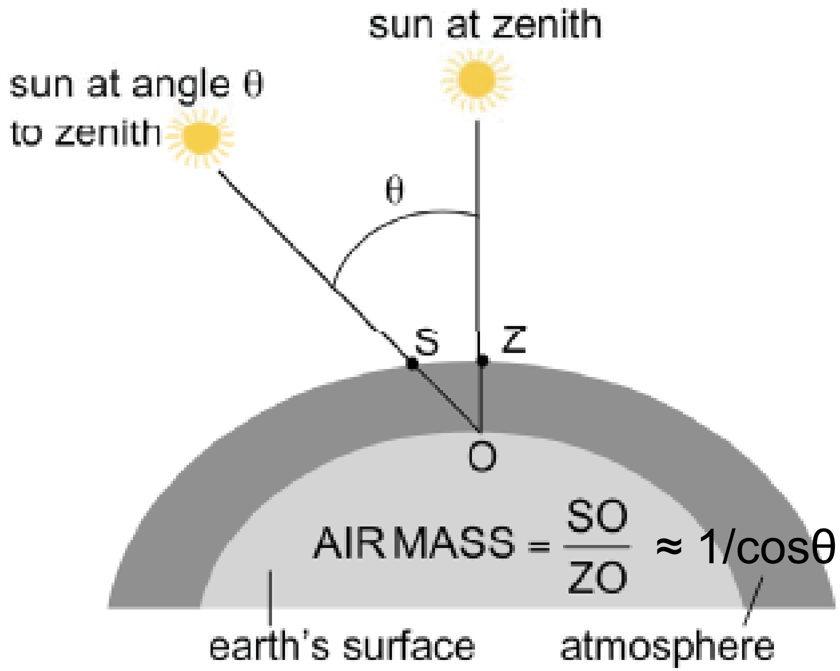




Solar Cell performance

Characterisation Standard:

- intensity of 1000 W/m^2
- spectral power distribution corresponding to AM1.5 ≡ 1Sun
- temperature 298 K

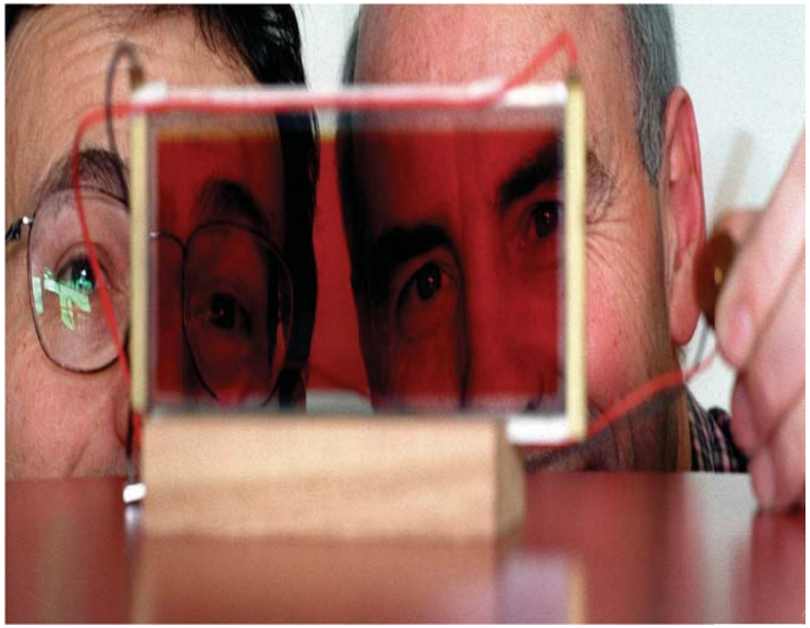


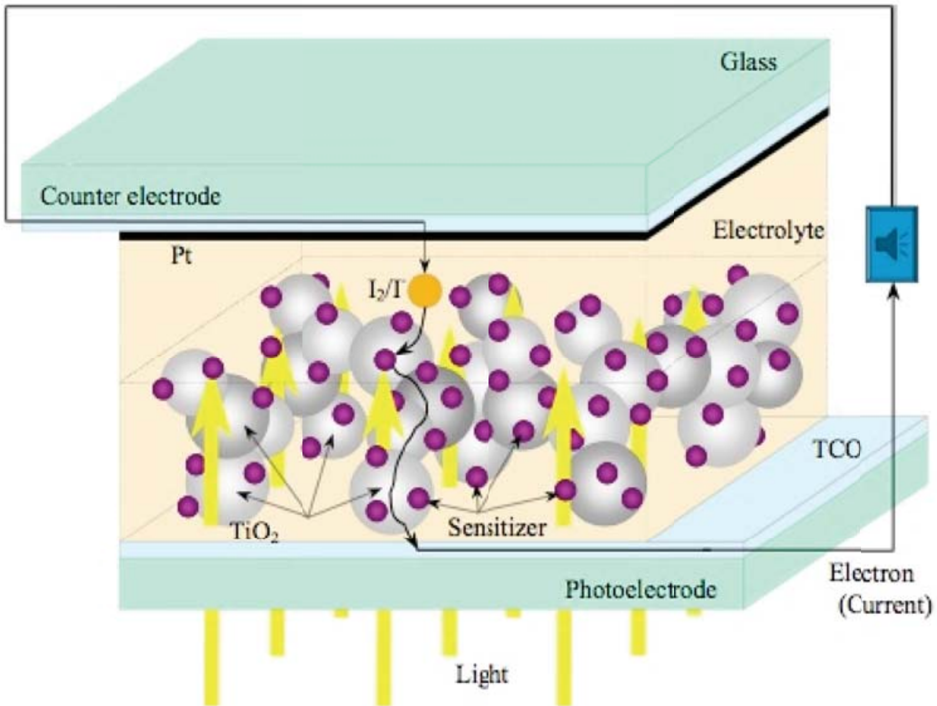
AM0: The spectrum outside the atmosphere, the 5,800 K black body = 1367 W/m^2

AM1: The spectrum after traveling through the atmosphere to sea level with the sun directly overhead, in equatorial region = 1040 W/m^2

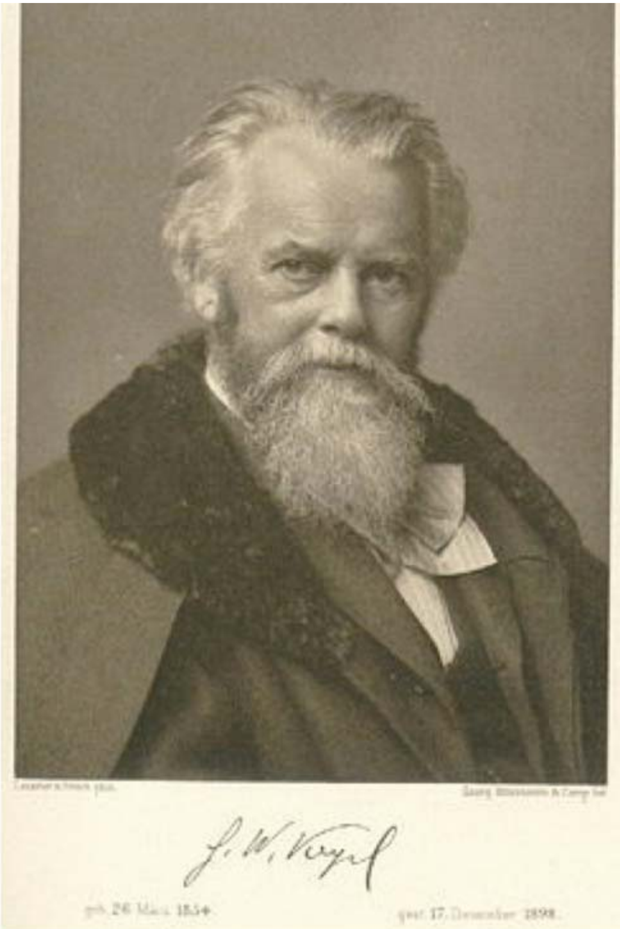
AM1.5: $\theta = 48.2^o$, standard testing of terrestrial solar panels = 1000 W/m^2

A new paradigme, mesoscopic solar cells
Dye-Sensitized Solar Cells





Sensitization goes back to the use of dyes by Vogel in photography (1873)



Hermann W. Vogel was professor of photochemistry, spectroscopy and photography at the Königliche Technische Hochschule, Berlin, from 1879 until his death in 1898. From 1873 he investigated the sensitization of silver halide emulsions with dyes, particularly aniline-based compounds, finding the photoresponse significantly extended towards the red, and later even infrared, making possible the "panchromatic" broad-spectrum black and white film, and more recently, infrared and color photography.

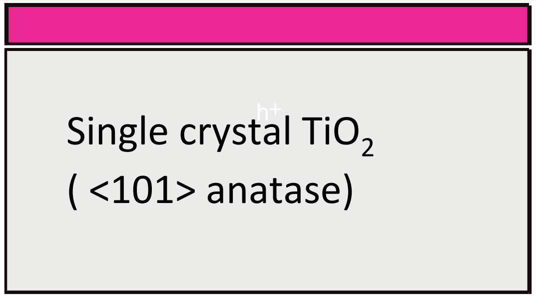
J M Eder introduced the use of the red dye erythrosine in 1884

Courtesy Dr. A. McEvoy

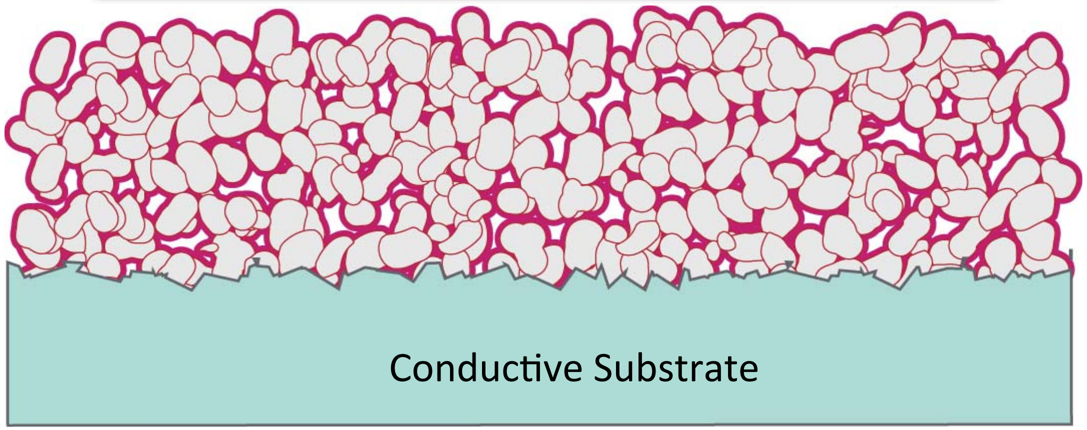
Mesoscopic structure improves photocurrent output > 1000 times

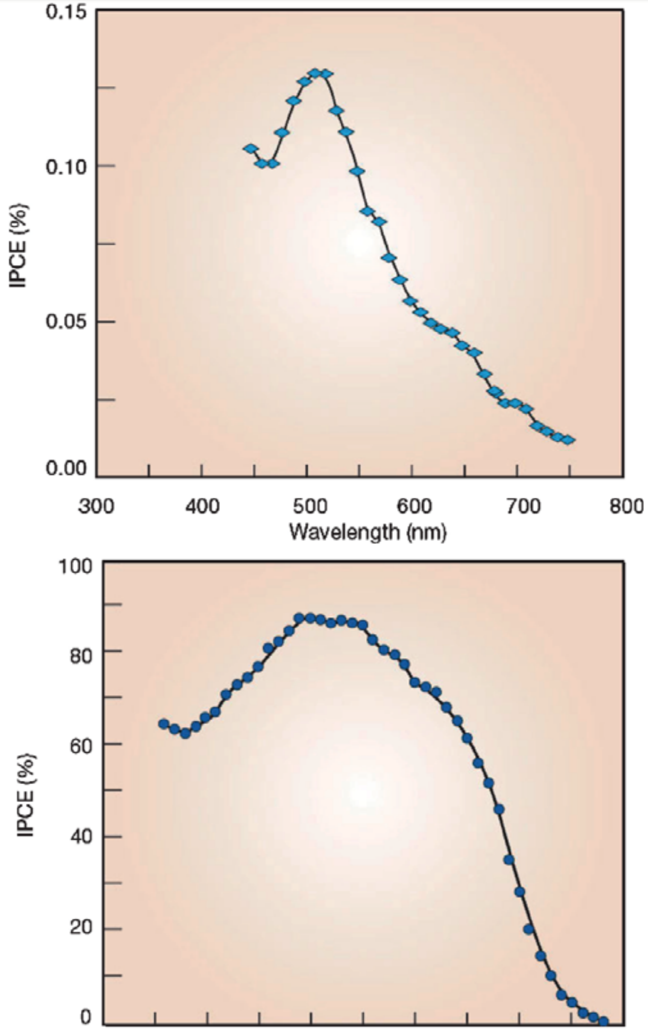
Incident photon to current conversion efficiency (IPCE) increases from 0.12 to 90 %

Dye monolayer on flat surface



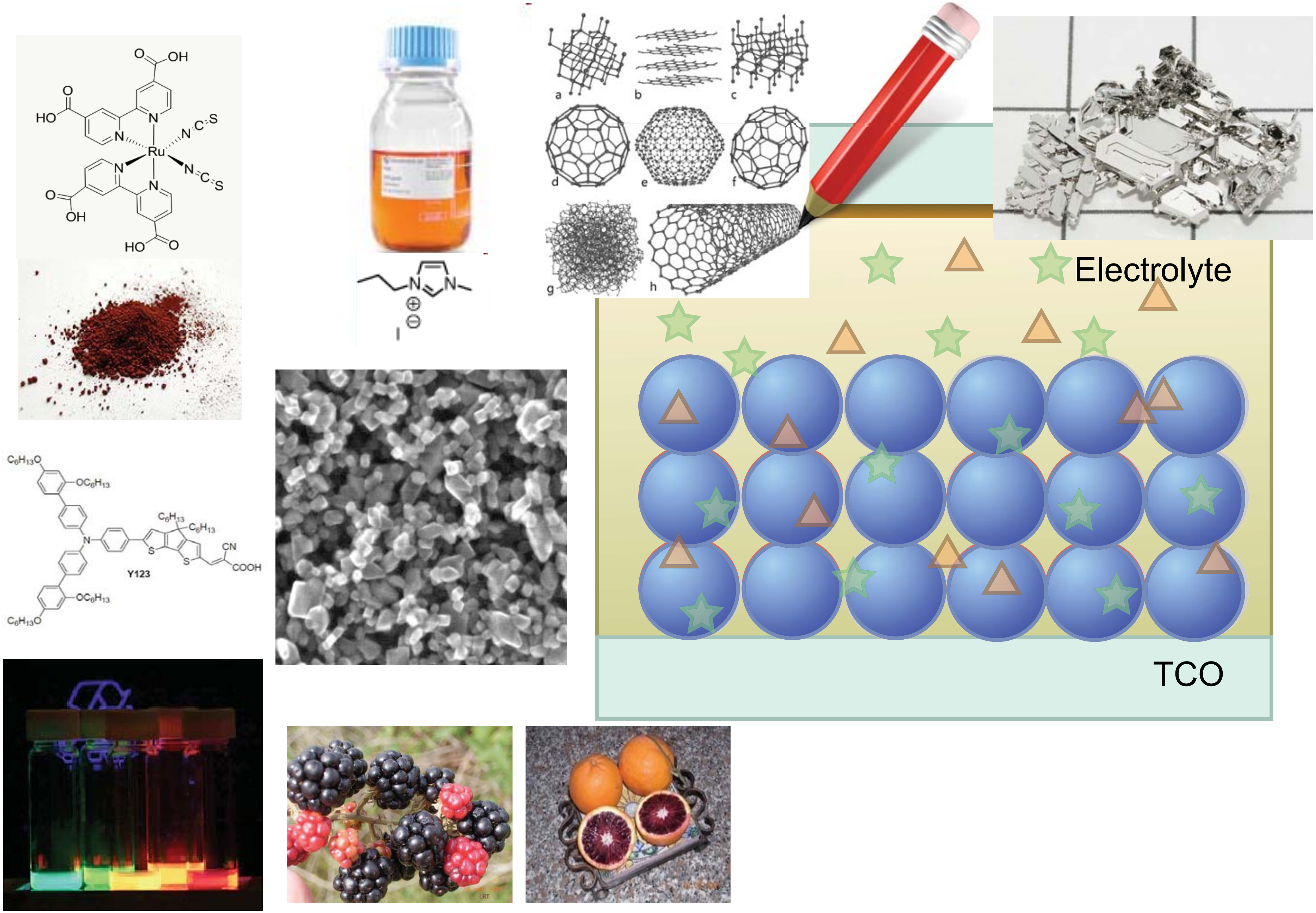
Dye sensitized nanocrystalline TiO_2 film

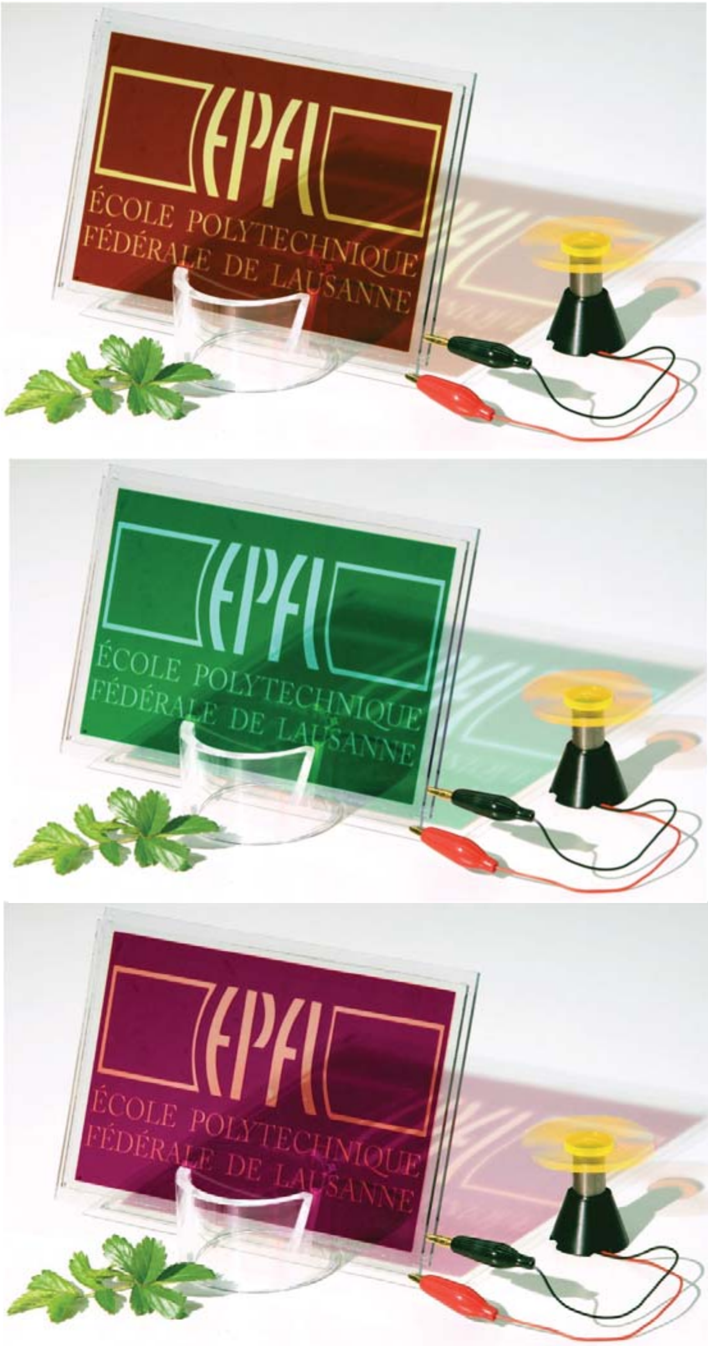


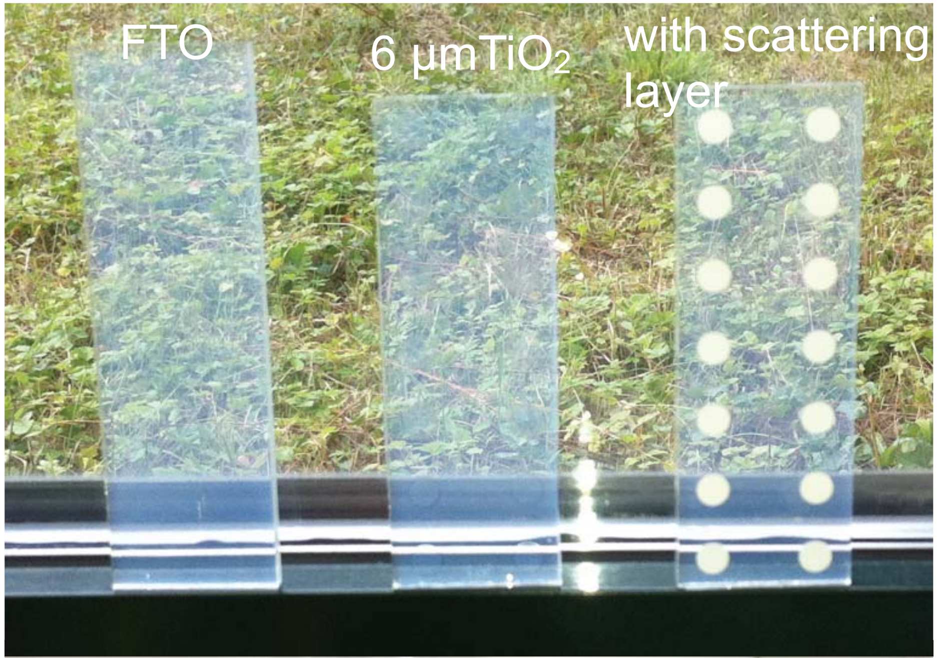


B.O'Regan and M.Grätzel "A Low Cost, High Efficiency Solar Cell based on the Sensitization of Colloidal Titanium Dioxide" ***Nature,*** **1991, 353, 7377-7380. Cited 6500 times.**

Dye-Sensitized Solar Cells Architecture





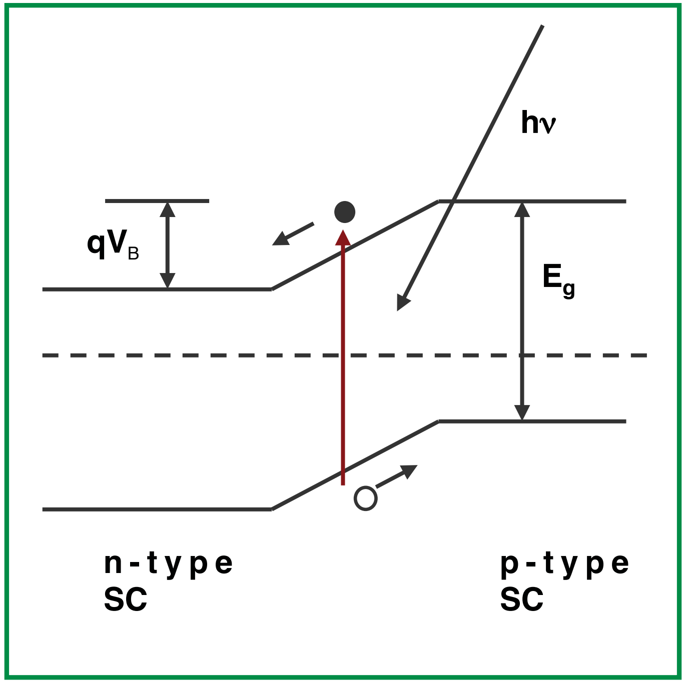


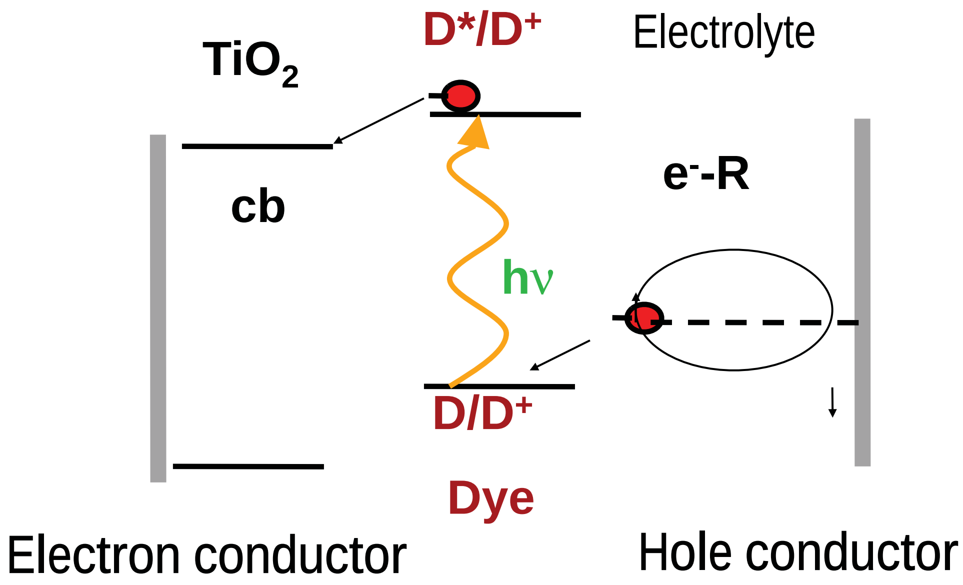
Spontaneous uptake of N3 sensitizer by a nanocrystalline TiO_2 film supported on conducting glass

DSC vs. Conventional Silicon PV

p-n junction photovoltaic cells

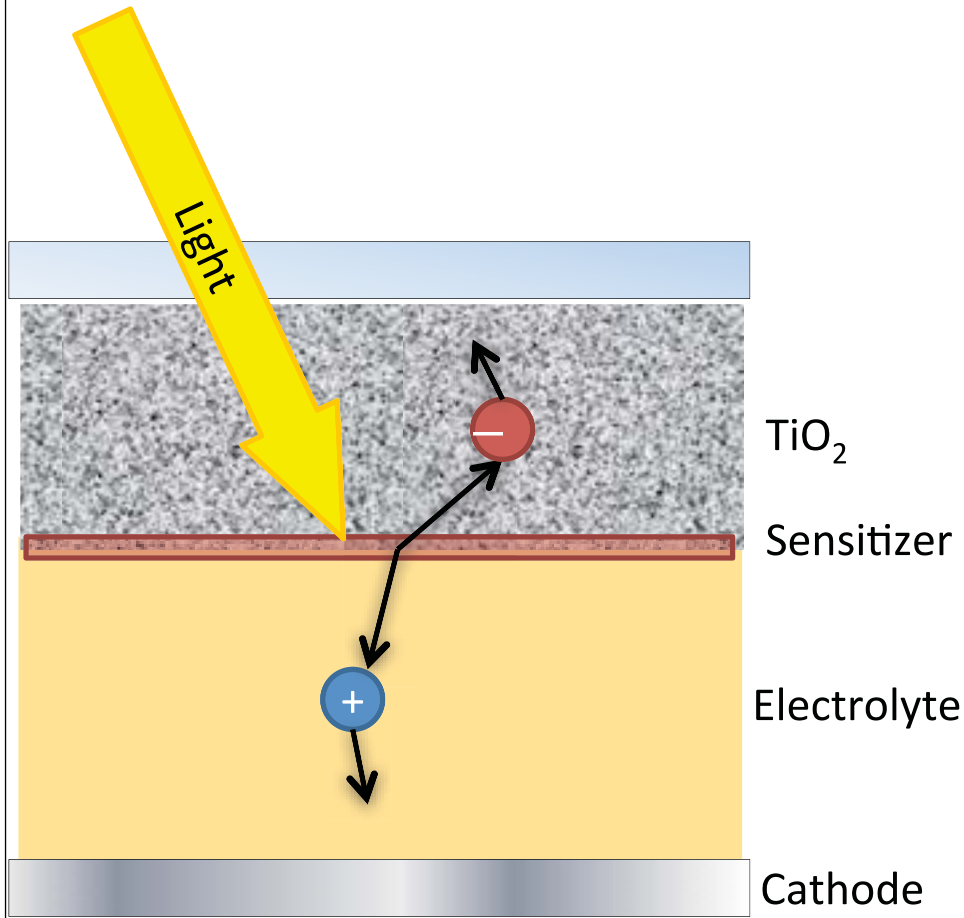
dye sensitized solar cells DSC





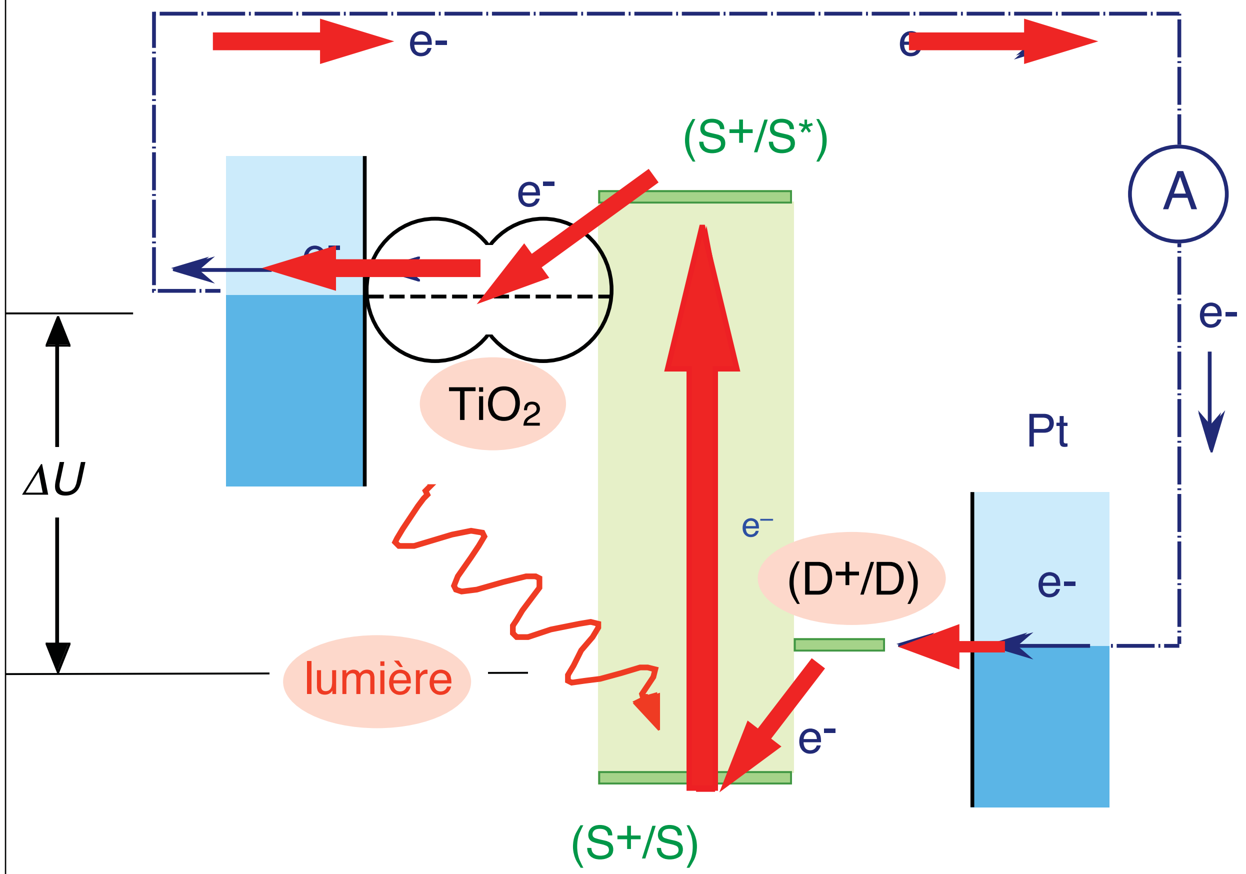
Charge separation by electric field at the p-n junction

Charge separation by kinetic competition as in photosynthesis



- Light absorption and charge transport are **decoupled**
- Relaxed constraints on individual components (each can be separately tuned)
- Only monolayer of dye on TiO_2

Operational principle of a dye sensitized mesoscopic solar cell



1. Incident light results in excited state dye S*
   S ➔ S*

2. Electron transfer from S* to CB
   $S^* \rightarrow S^+ + e^-$

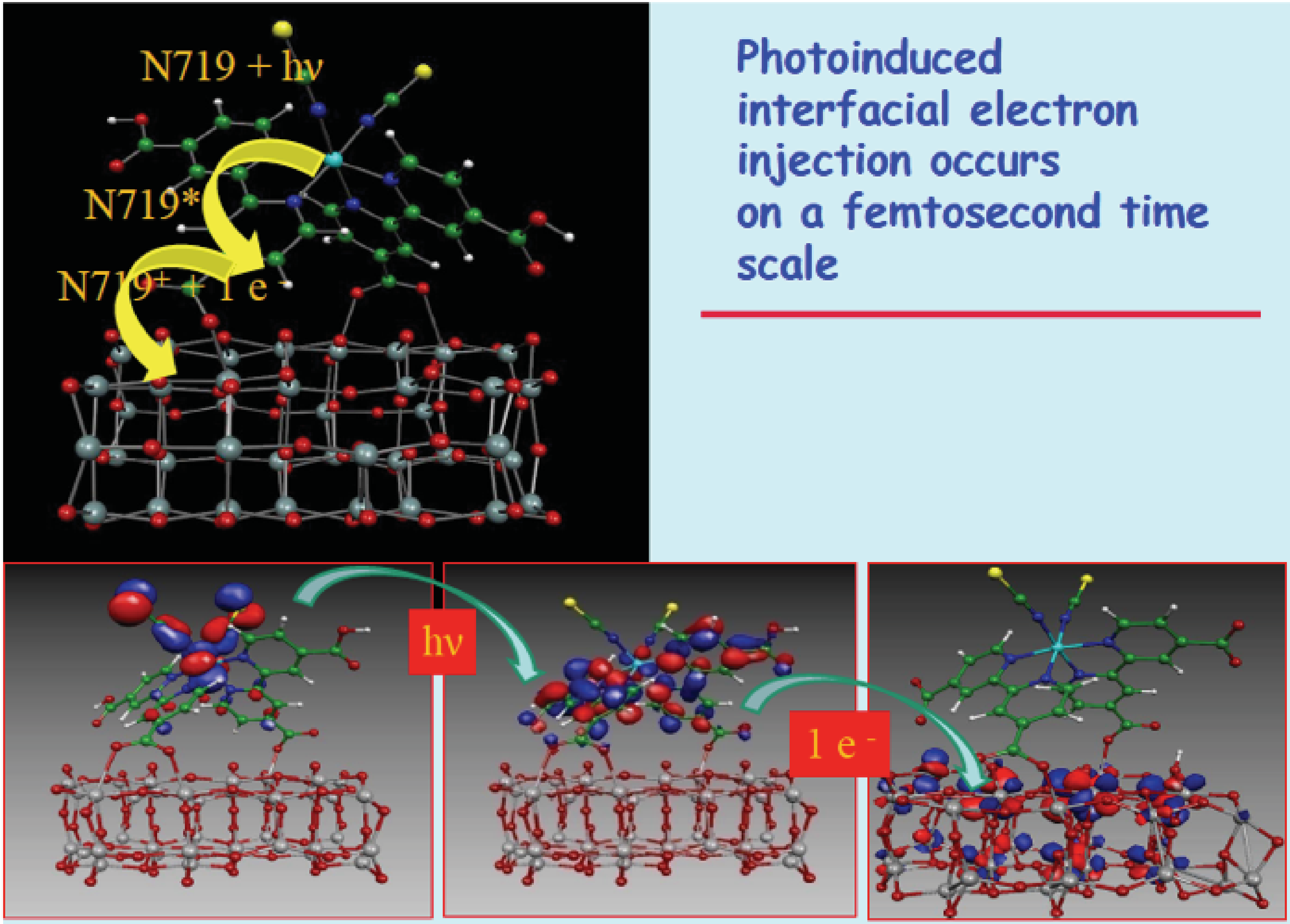
3. Dye regeneration
   $S^+ + R^- \rightarrow S + R$

4. Electrolyte is regenerated

5. Electron diffusion through semiconductor

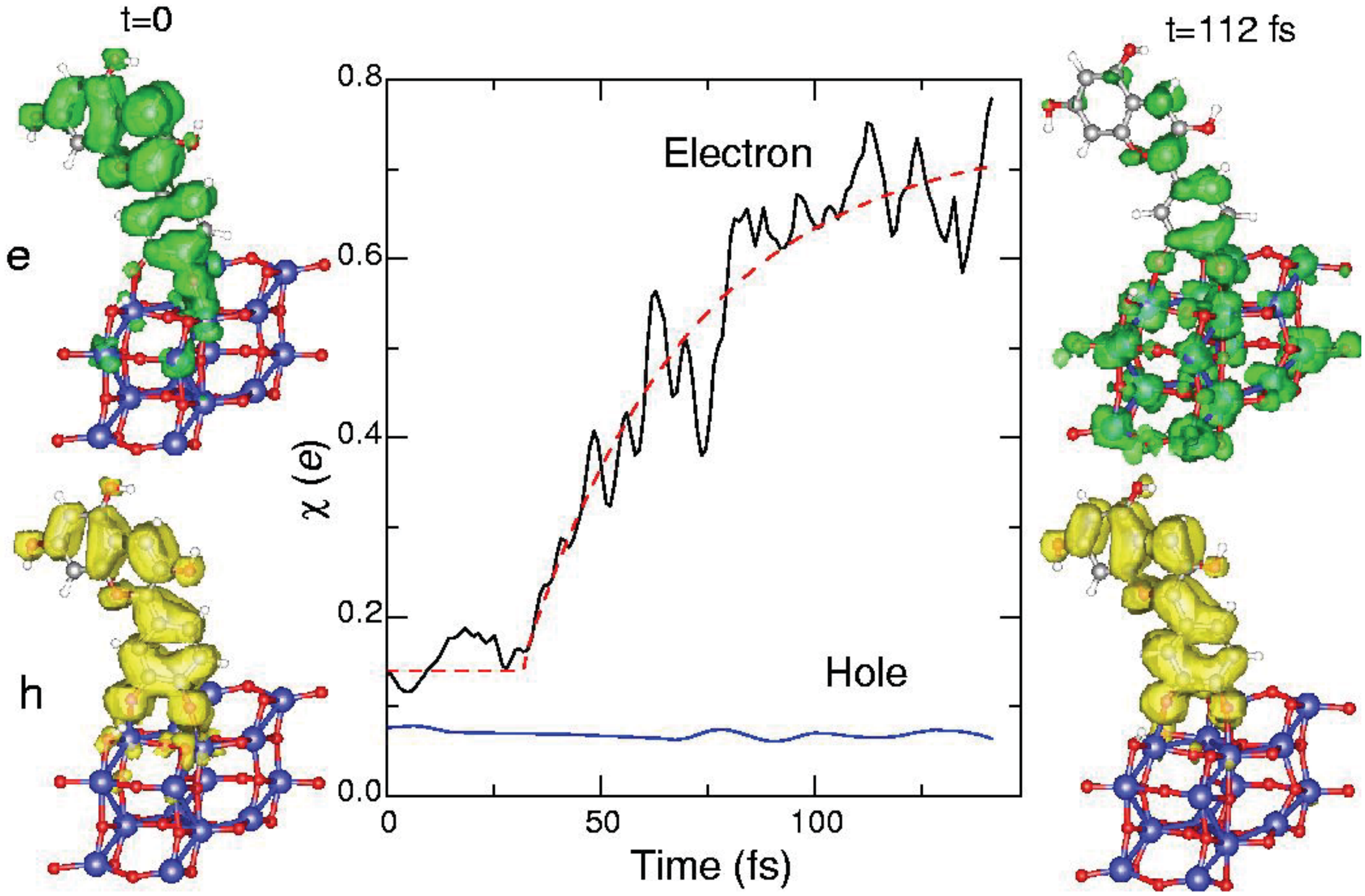
6. Electron passes through circuit

Photoinduced interfacial electron injection occurs on a femtosecond time scale



F. De Angelis, S. Fantacci, A. Selloni, M. Grätzel ***J. Am. Chem. Soc.*** *2007*

Electron and hole dynamics for anthocynanine-sensitized TiO_2 (anatase)



S. Meng and E. Kaxiras, NanoLett. 10, 1238-1247 (2010)

The present status of DSCs

- Power conversion efficiency (PCE) measured under AM 1.5 sunlight (STC):
  laboratory cells: 12.2 % at full sun
  larger modules: 10 % (Sony),
  tandem cells: 16%

- **stability > 20 years outdoors** (DYESOL, DSC-IC Conference Colorado Springs)

- **energy payback time: < 1 year** (3GSolar and ECN, life cycle analysis)

- **Industrial development: October 2009, G24 Innovation (www.g24i.com.) starts roll to roll mass production and commercial sales of light weight flexible cells started in Cardiff Wales.**

- **March 2011: Fujikura announces mass production of black dye modules**

Ongoing and Future Research

- Enhanced light harvesting by advanced meso-structures
- New sensitizers
- New redox mediators
- Solid state heterojunctions
- Quantum dot injection cells
- Tandem devices
- New counter electrodes
- New solid nanocomposite electrolytes

ACS NANO July, 2010

ARTICLE

Dye-Sensitized Solar Cells Employing a Single Film of Mesoporous TiO_2 Beads Achieve Power Conversion Efficiencies Over 10%

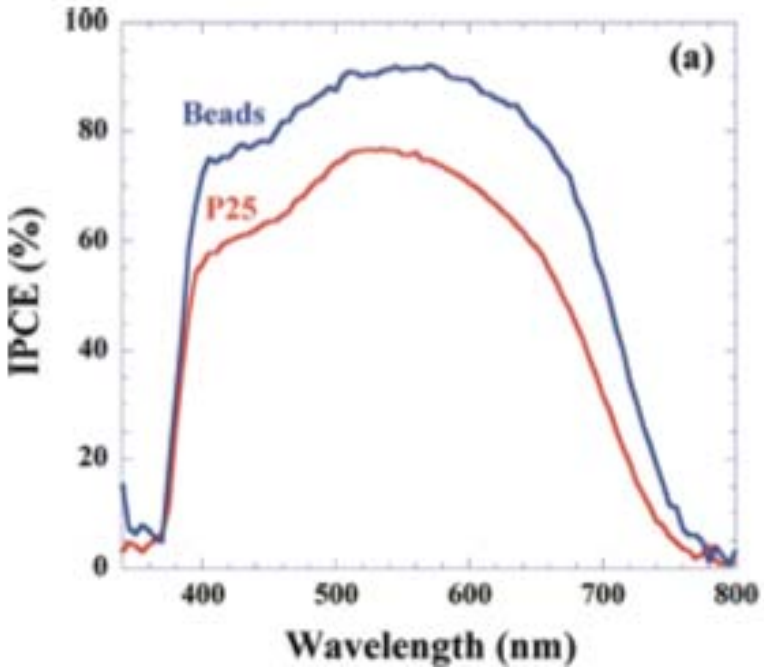
Frédéric Sauvage,[†] Dehong Chen,[‡] Pascal Comte,[†] Fuzhi Huang,[⊥] Leo-Philipp Heiniger,[†] Yi-Bing Cheng,[⊥,*] Rachel A. Caruso,[‡,§,*] and Michael Graetzel[†,*]

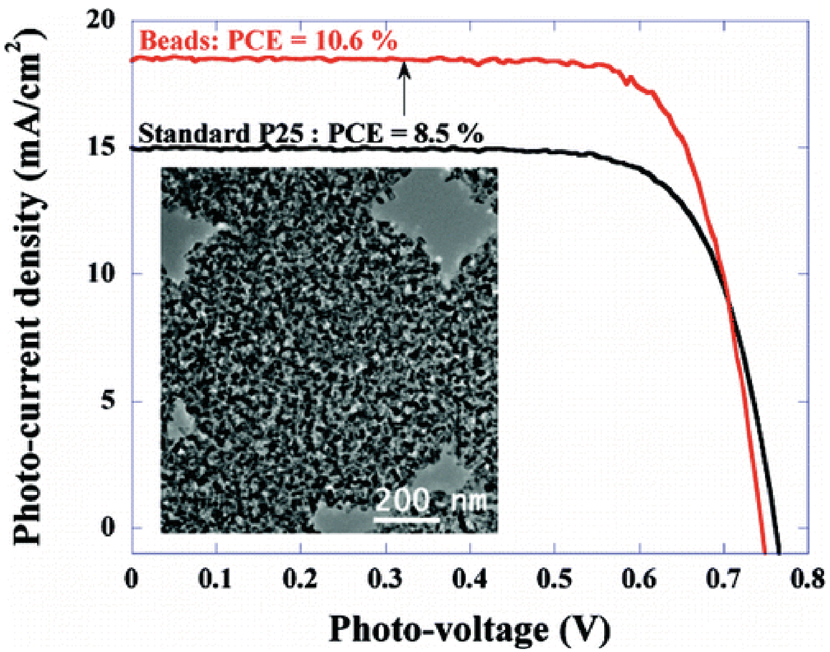
[†]Laboratoire de Photonique et Interfaces, Institut des Sciences et Ingénieurie Chimiques, Ecole Polytechnique Fédérale de Lausanne (EPFL), Station 6, CH-1015, Lausanne, Switzerland, [‡]The University of Melbourne, PFPC, School of Chemistry, 3010 Melbourne, Victoria, Australia, [§]CSIRO Materials Science and Engineering, Private Bag 33, 3169 Clayton South, Victoria, Australia, and [⊥]Monash University, Department of Materials Engineering, 3800 Melbourne, Victoria, Australia

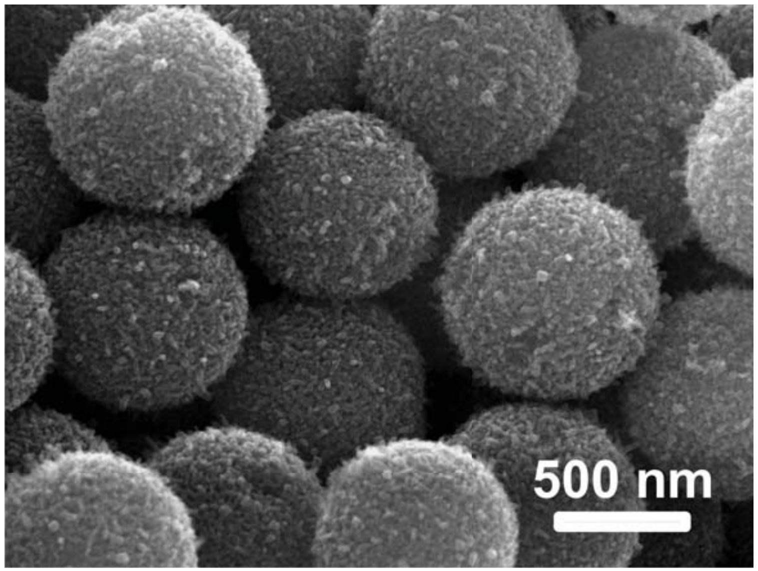
ABSTRACT Dye-sensitized solar cells employing mesoporous TiO_2 beads have demonstrated longer electron diffusion lengths and extended electron lifetimes over Degussa P25 titania electrodes due to the well interconnected, densely packed nanocrystalline TiO_2 particles inside the beads. Careful selection of the dye to match the dye photon absorption characteristics with the light scattering properties of the beads have improved the light harvesting and conversion efficiency of the bead electrode in the dye-sensitized solar cell. This has resulted in a solar to electric power conversion efficiency (PCE) of greater than 10% (10.6% for Ru(II)-based dye C101 and 10.7% using C106) for the first time using a single screen-printed titania layer cell construction (that is, without an additional scattering layer).

KEYWORDS: TiO_2 · beads · C101 dye · dye-sensitized solar cells · DSC

Titanium dioxide is one of the most investigated inorganic semiconductor oxide materials found in today's literature due to its opto-electronic properties which make it appropriate for a variety of applications ranging from photocatalysis,[1] photochromism,[2] Li-ion batteries,[3] and chemical and gas sensors,[4,5] to use as the photoanode for dye-sensitized solar cells (DSC).[6] The DSC is unique in that it is the only photovoltaic device that achieves the separation of light absorption and charge

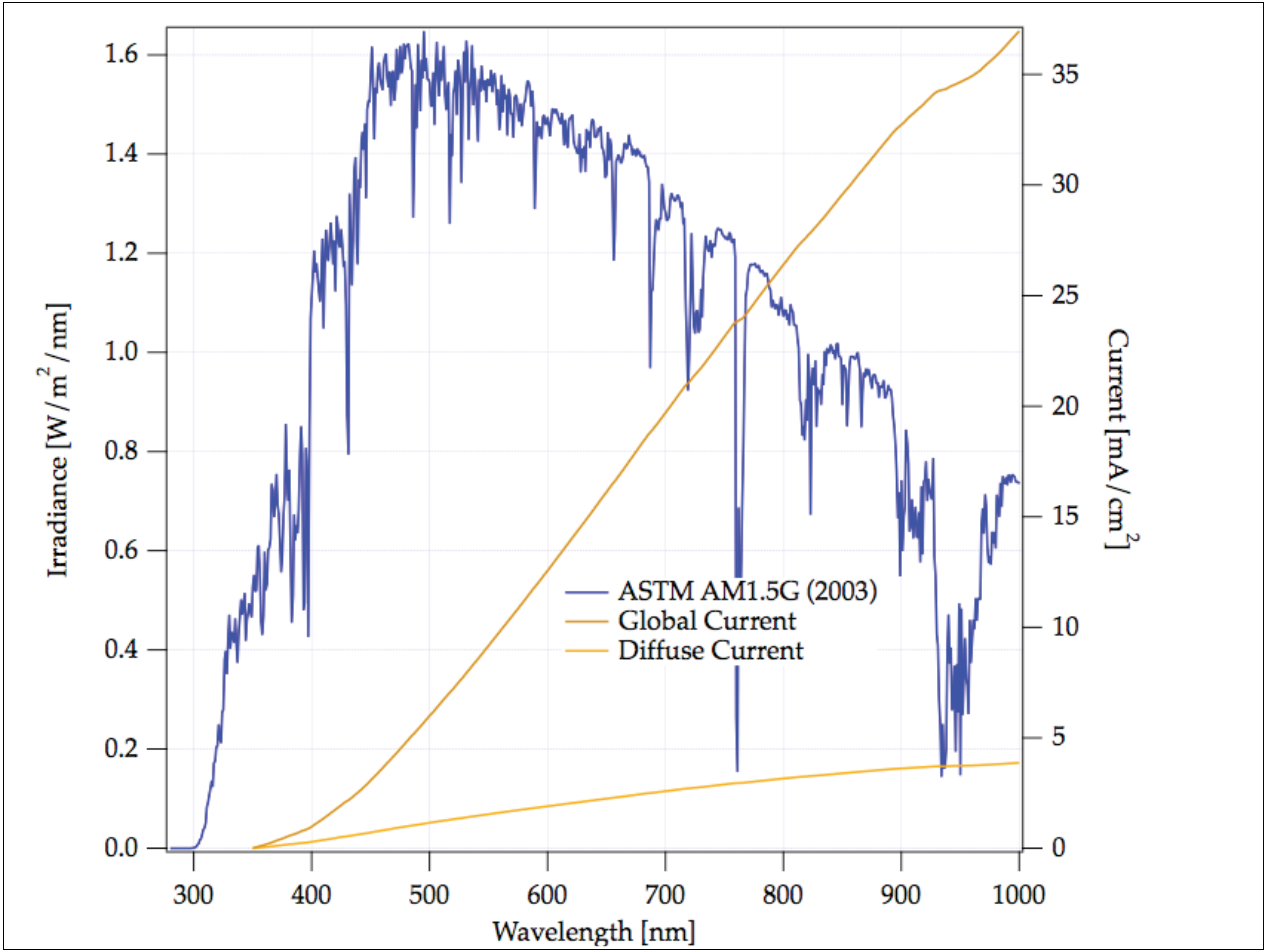






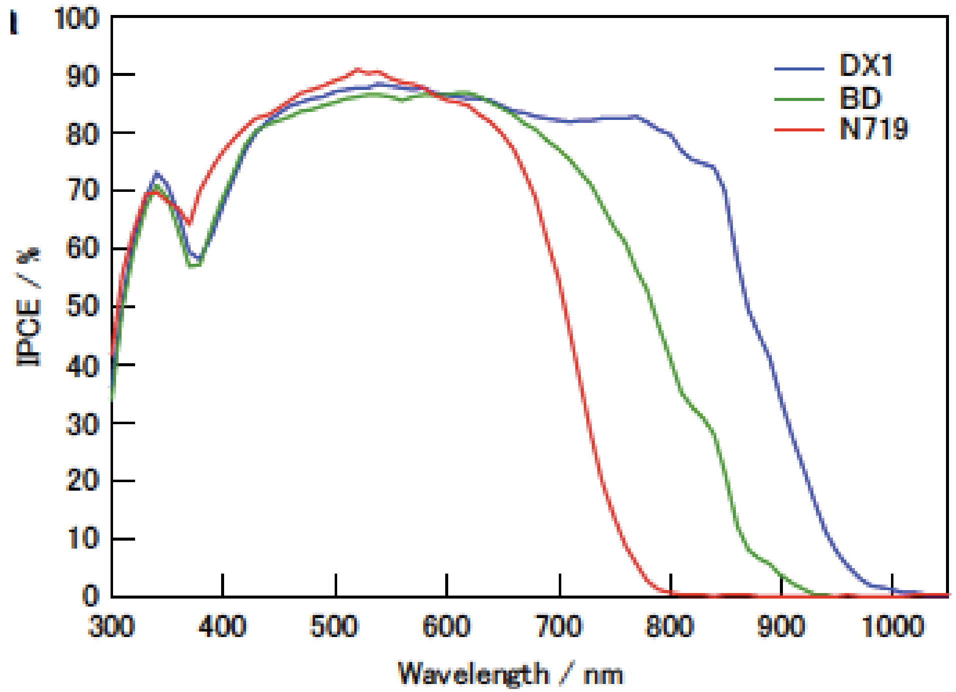
Ongoing and Future Research

- Enhanced light harvesting by advanced meso-structures
- New sensitizers
- New redox mediators
- Solid state heterojunctions
- Quantum dot injection cells
- Tandem devices
- New counter electrodes
- New solid nanocomposite electrolytes



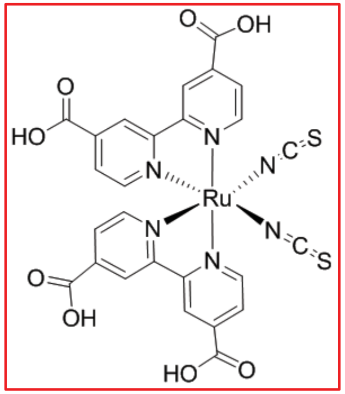
Irradiance [W/m²/nm]
Current [mA/cm²]
Wavelength [nm]
ASTM AM1.5G (2003)
Global Current
Diffuse Current
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
0
5
10
15
20
25
30
35
300
400
500
600
700
800
900
1000

Sensitizer Engineering

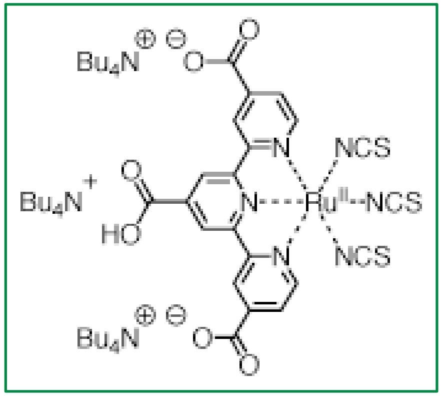


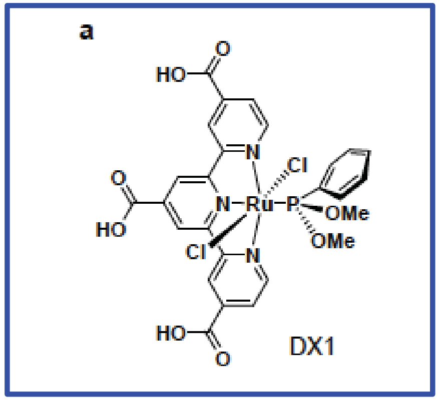
	V_{oc} (V)	J_{sc} (mA/cm^2)
a-Si:H	0.860	**12.5**
GaAs	0.994	**23.2**
nc-Si	0.539	**24.4**
CdTe	0.845	**26.1**
Dye X	0.550	**26.6**
Si module	0.492	**29.7**

N719



"Black dye" BD





DX 1 data presented by Prof. S Uchida,Tokyo University; at NTU Singapore Symposium July 26 2011

Ongoing and Future Research

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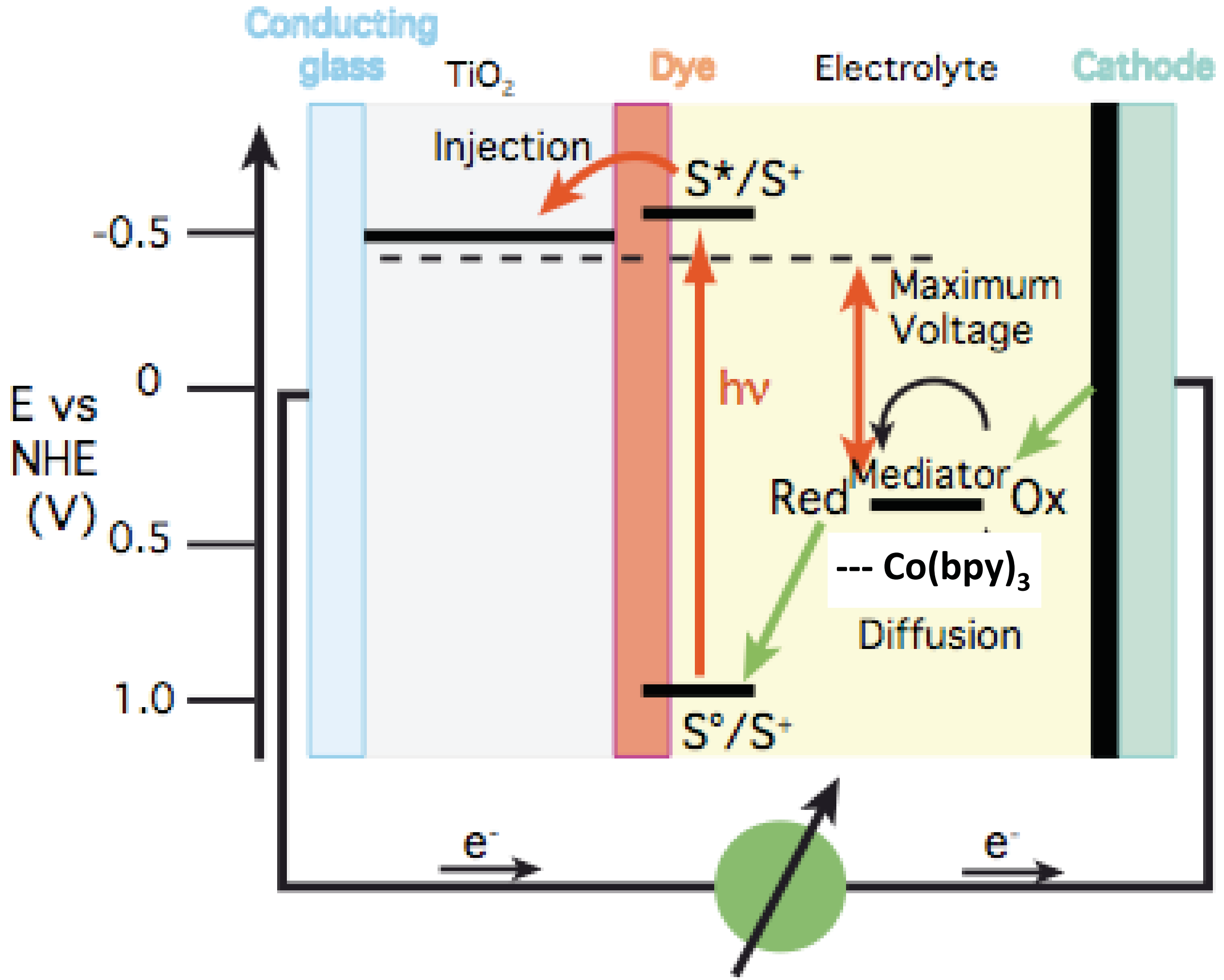
Improvement by matching of energy levels

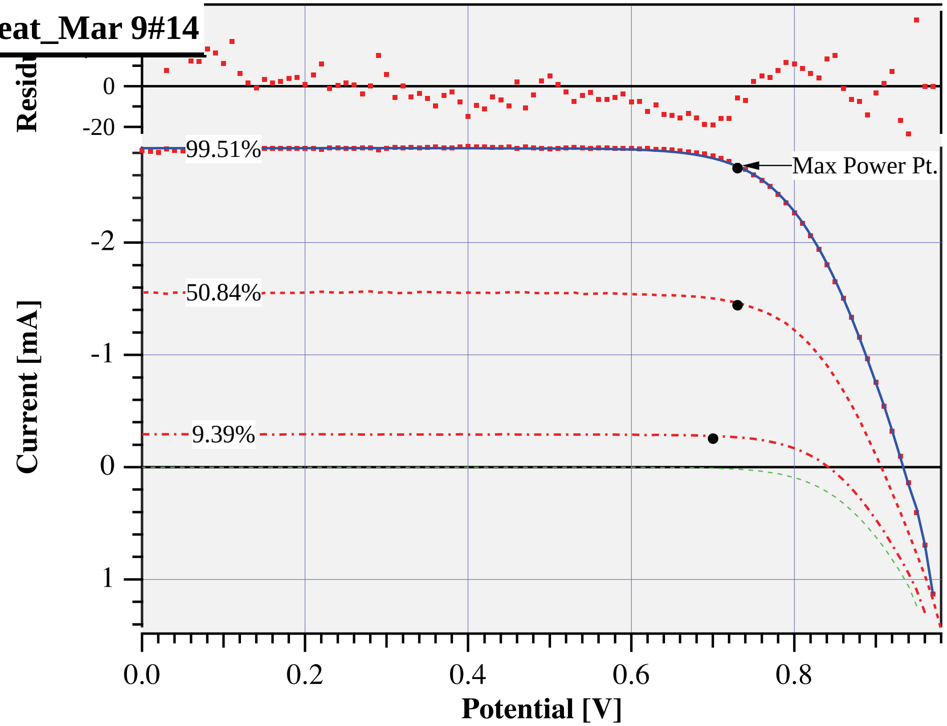


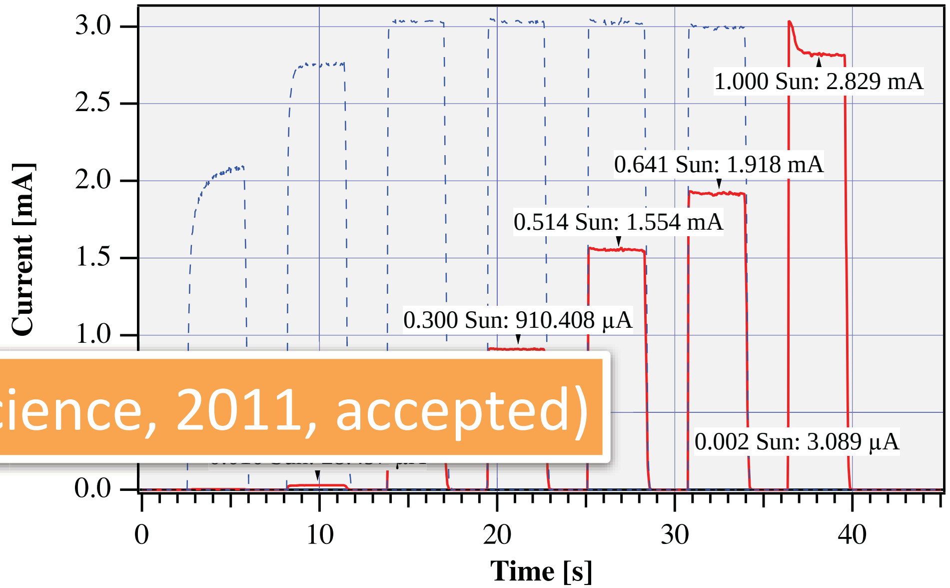
$$\eta_{global} = \frac{\left(I_{ph} \cdot V_{oc} \cdot FF\right)}{I_s}$$

Cell Name: 08032011_YA1074_repeat_Mar 9#14

Measurement Date	: Wed, Mar 9, 2011 / 12:57:13 AM
Type of cell	: AY_Al Back
Cell Active Area	: 0.16 cm^2
Light Source	: Xe 450W @ AM1.5G
Dye Sensitiser	: B11, 0.3mM, tBu/Ac, Dinhop4:1
Additional Remarks	: MG8 + Y123
Electrolyte h+ Conductor	: 3/4 co2 & 1.5 Co3 + 0.8 M TBP
Working Temperature	: 298 K
SemiConductor Layer	: Nok 5/4 + 2.5mL TiCl4
Layer Thickness, Porosity	: 5 µm, 68 %
Working Electrode Glass	: NSG 10/cm
Counter Electrode Type	: LOF 7/Pt
Data File Name	: 08032011_YA1074_repeat_Mar 9#14
Current Compliance	: 2 mA
Settling Time, ΔU, Meas. Delay	: 0.04 s, 10 mV, 0s

	9.4% Sun	**50.8% Sun**	**99.5% Sun**
$Thermopile_{ref}$	-296.576 µSun	-1.597 mSun	-10.273 µSun
$Current_{ref}$	-355.163 µA	-1.923 mA	-3.764 mA
$Power_{in}$	9.391 mW/cm^2	50.841 mW/cm^2	99.515 mW/cm^2
Norm. Std. Dev.	0.25	0.32	0.37
Module U_{oc}	841.56 mV	906.35 mV	933.87 mV
Cell U_{oc}	841.56 mV	906.35 mV	933.87 mV
I_{sc}	-293.243 µA	-1.555 mA	-2.825 mA
J_{sc}	-1.833 mA/cm^2	-9.722 mA/cm^2	-17.659 mA/cm^2
U_{pmax}	702.33 mV	727.91 mV	727.18 mV
I_{pmax}	-1.7 mA/cm^2	-9.2 mA/cm^2	-16.9 mA/cm^2
$Power_{out}$	1.22 mW/cm^2	6.69 mW/cm^2	12.27 mW/cm^2
Total $Power_{out}$	195.59 µW	1.07 mW	1.96 mW
Fill Factor	0.793	0.759	0.744
Efficiency η	13.02%	13.15%	12.33%





A recent new efficiency record ! (Science, 2011, accepted)

Series Resistance @ 1 Sun: 25.73 ± 1.3 %, (160.83 /cm ^{2})

Calibration File: KIDAC: Ref Cell#9, Mon, Jan 14, 2008

© RAHB: KIDAQX *Measured by Takeru* *Date: Wed, Mar 9, 201*

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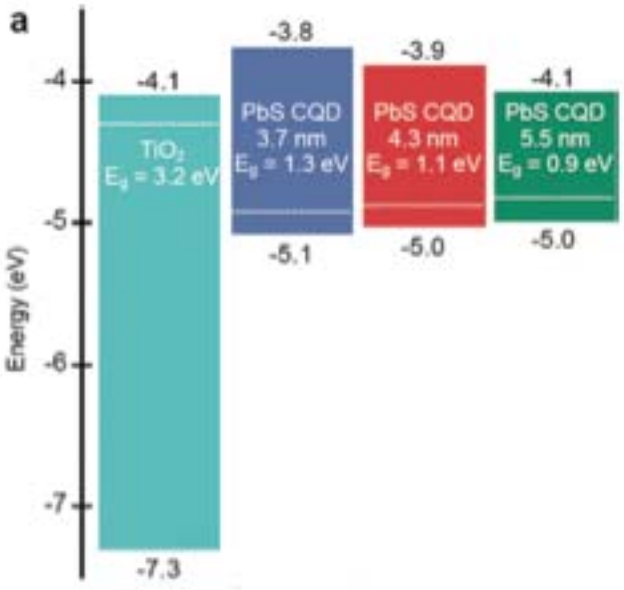
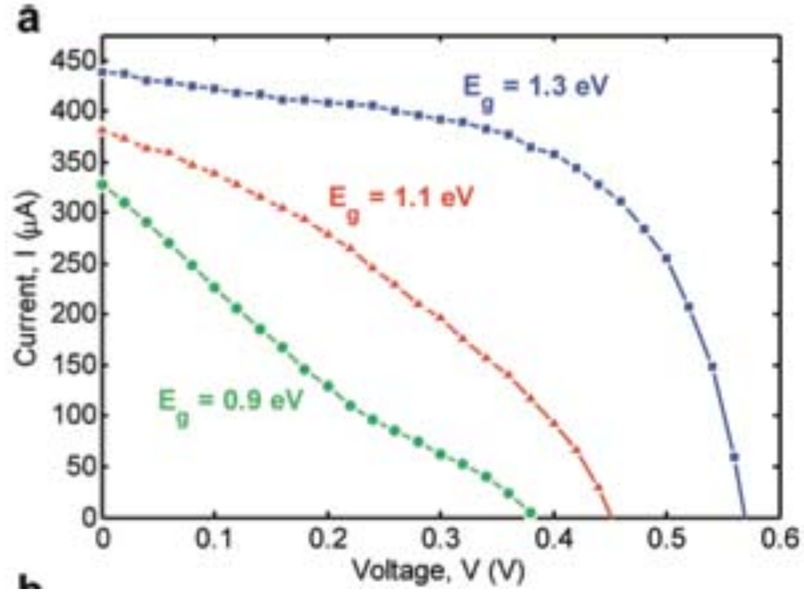
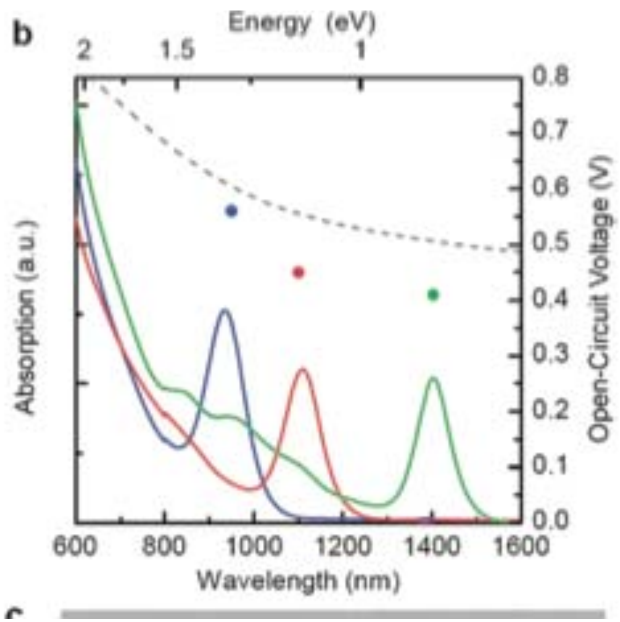
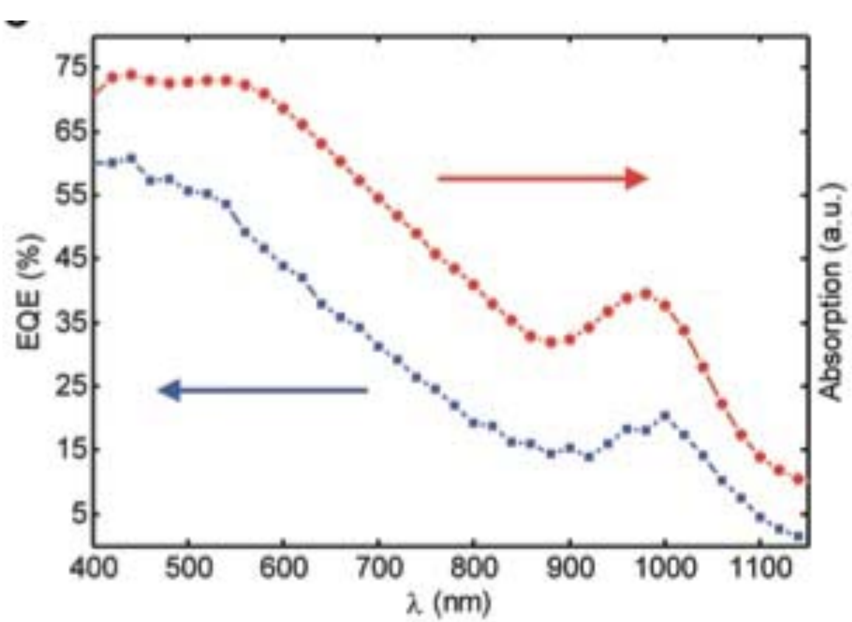
Q.D size effect









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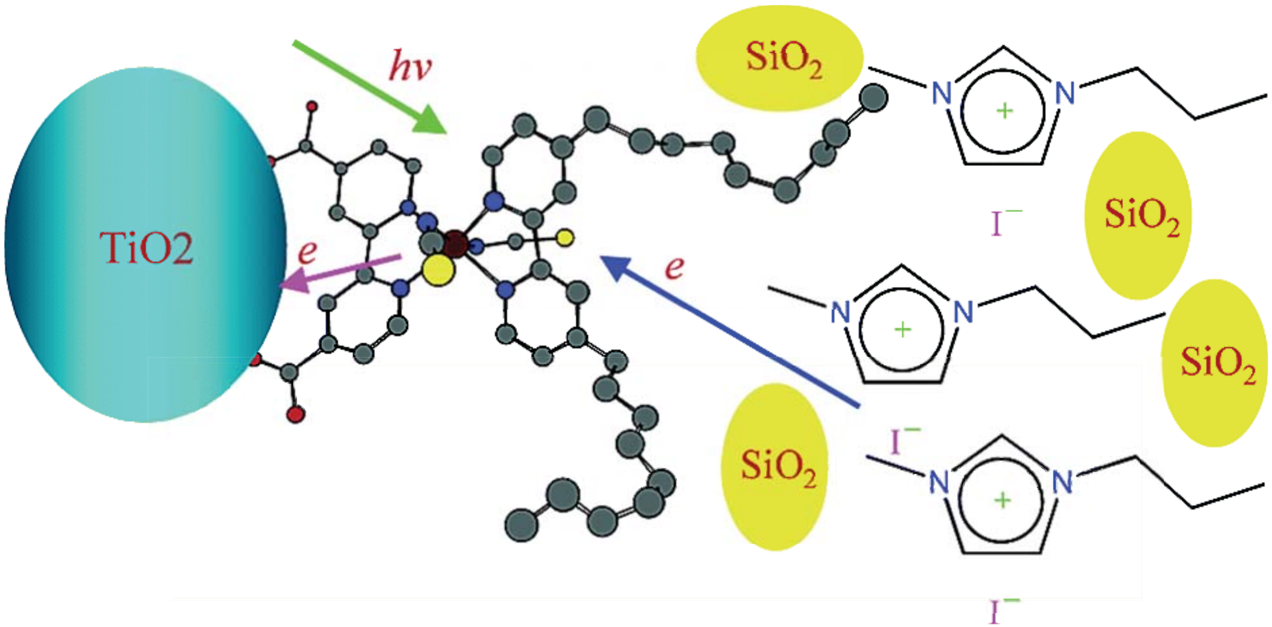
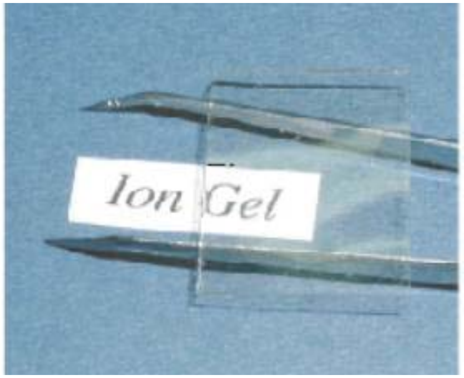
Ionic Liquids

The Attractive Features of Ionic Liquids

- Non volatile, consist of ions only
- Liquid under wide temp. Range, e.g. -50°C to 400°C
- Easy to solidify, e.g. by addition of SiO_2 nanoparticles
- Chemically stable and non combustible
- High ionic conductivity





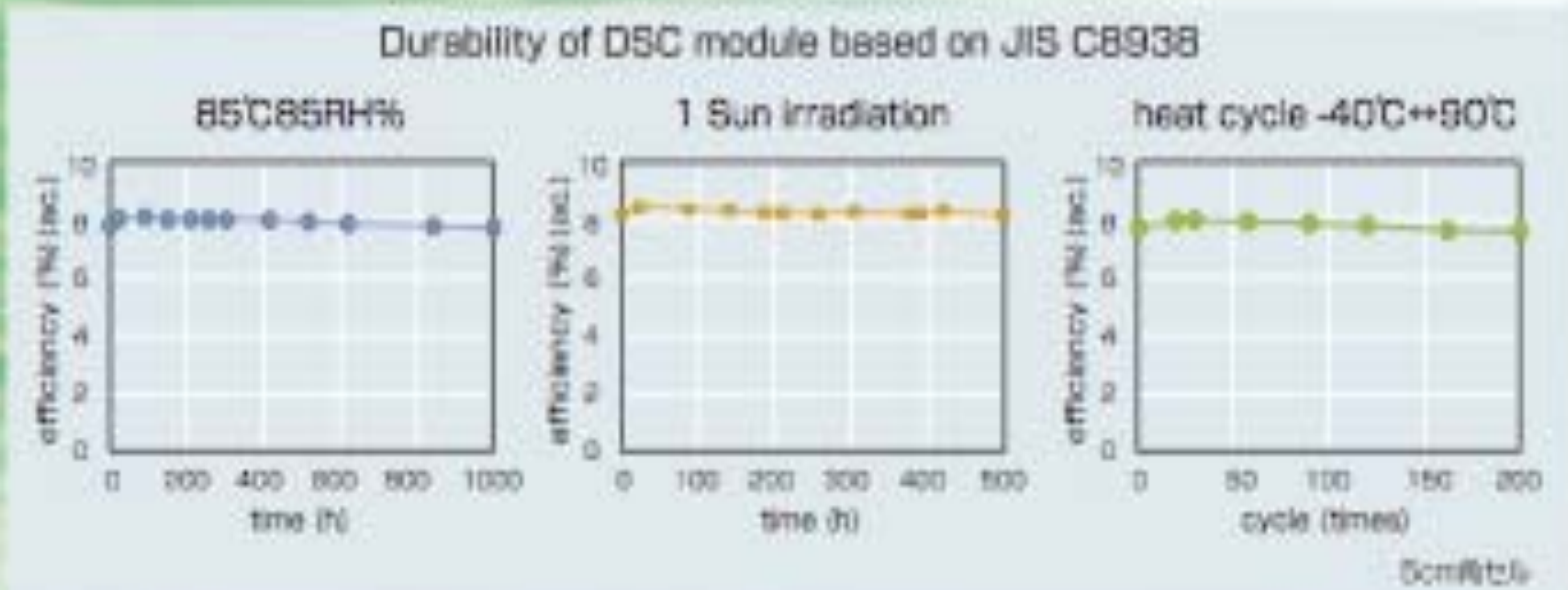
Green Power from Fujikura
色素増感太陽電池の発電原理
DSCの発電には、写真フィルムにも使われている色素増感という現象を利用します。
酸化チタン粒子で作ったナノレベルの多孔質膜の上に色素を吸着させ、その色素が光を
受けて電子を放出する作用を利用して電力を得ます。
Operating mechanism of DSC
Fujikura
株式会社フジクラ
透明導電ガラス
Transparent conductive glass
入射光
ヨウ素電解液
Iodine electrolyte
白金付対極
Platinum coated counter electrode
N719 Dye
TiO2 多孔質膜
TiO2 mesoporous film
増感色素
Sensitizing dye (ex.N719 dye)
耐久性20cm角サブモジュール
Durable 20x20cm square submodule
耐久性20cm角サブモジュールで
変換効率7.6%達成
Current (A)
Voltage (V)
0
0.2
0.4
0.6
0.8
Jsc : 16.5 mA/cm2
Voc : 0.68 V
FF : 0.65
η : 7.6 % (ac.)

JIS耐久性試験をクリア

ガスバリア性に優れた独自の封止構造を開発し、さらに、不揮発性のイオン液体を電解質に適用することで、耐久性を大幅に向上させました。試作した素子は、DSCとしては世界で初めて、グラフのような過酷な環境下での耐久性試験をクリアしました。

We have improved (are improving) durability of DSC by applying our specific (unique) gas tight sealing structure and nonvolatile ionic liquid electrolytes. Our DSC successfully bears the severe endurance tests as shown in the graphs.

Highly durable DSC cell and module



Fujikuras DSC modules pass all stability tests for outdoor applications

The DSC can meet future customer demands and needs

Emerging and new applications call for:

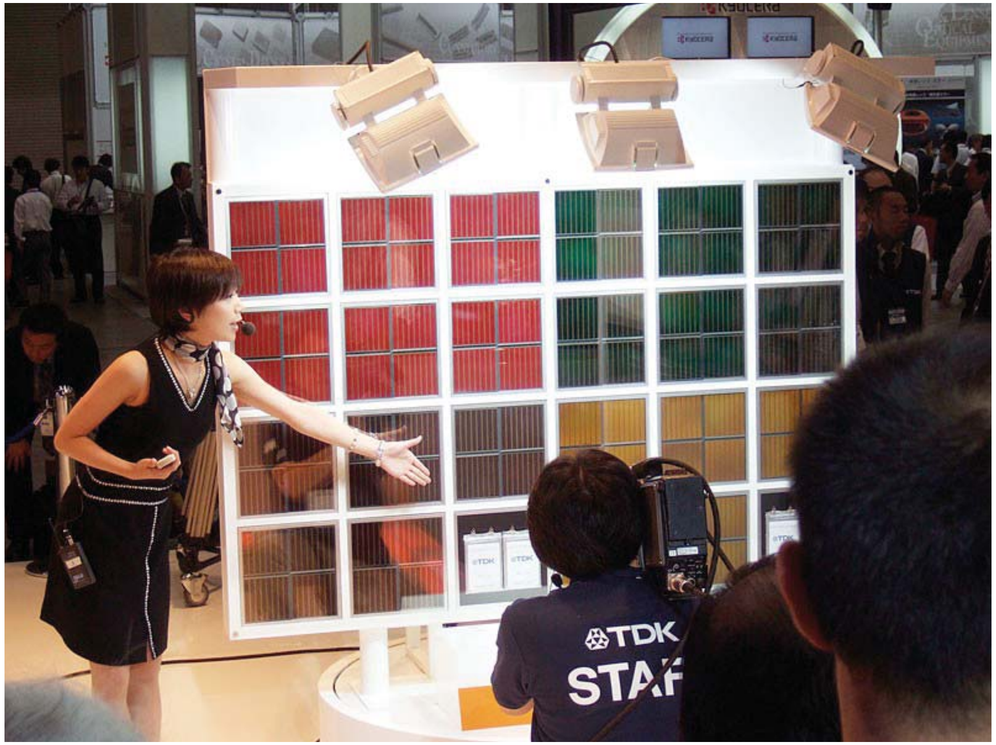
Low production cost

Short Energy payback time

Transparency and multicolor

Flexibility and light weight

Light angle Independence



Outperforms competitors for indoor applications and real outdoor condition

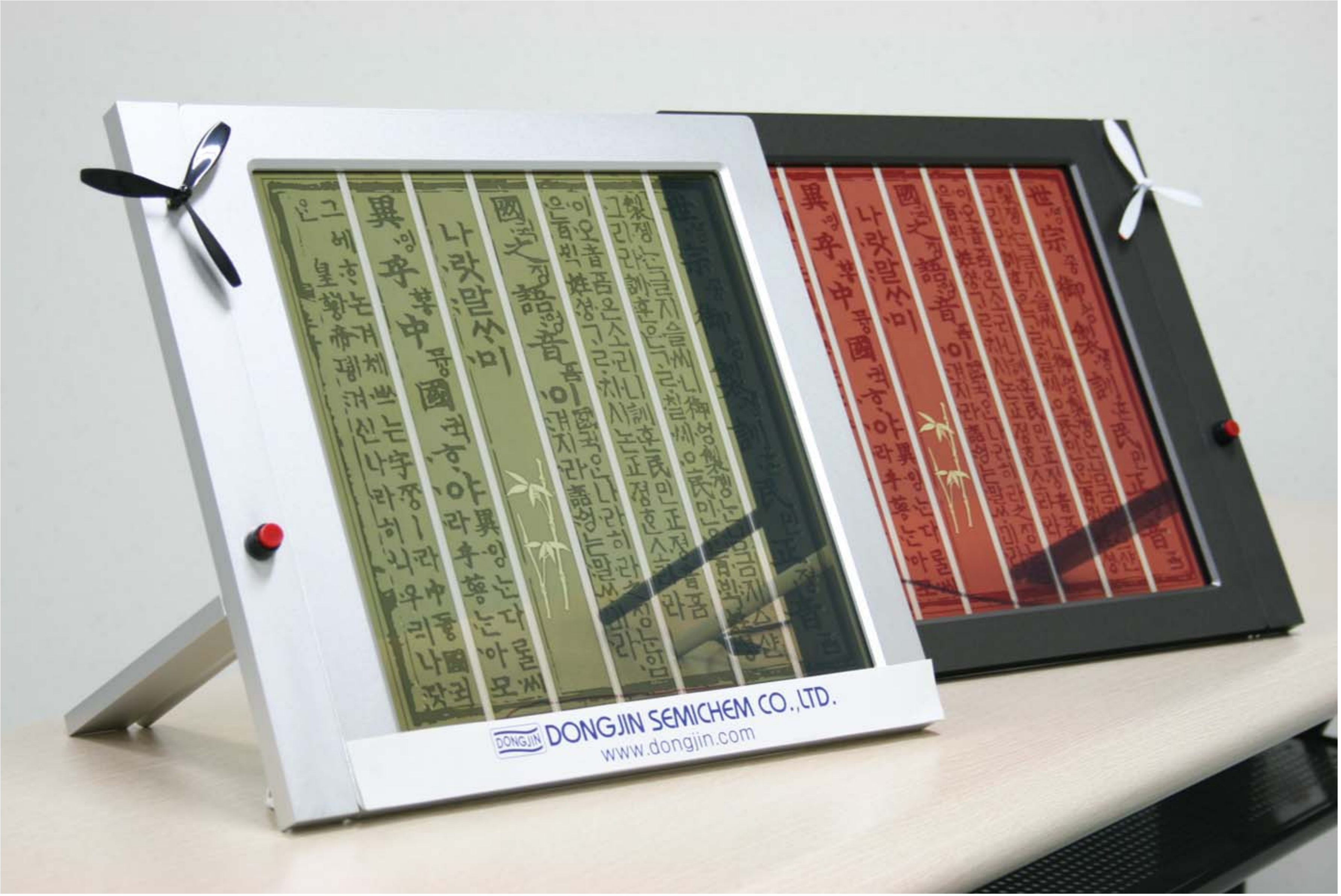
Large dye sensized solar cell module produced by the Fraunhofer Institute for Solar Energy in Freiburg Germany, Courtesy Dr, Andreas Hinsch

http://www.ise.fraunhofer.de/presse-und-medien/presseinformationen/presseinformationen-2011/auf-dem-weg-in-die-fassade-fraunhofer-ise-praesentiert-weltweit-groesstes-farbstoffsolarmodul-in-siebdruck

Tata Steel and Dyesol produce world's largest dye sensitised photovoltaic module

DONGJIN SEMICHEM
www.dongjin.com

Energy, Wears Color !

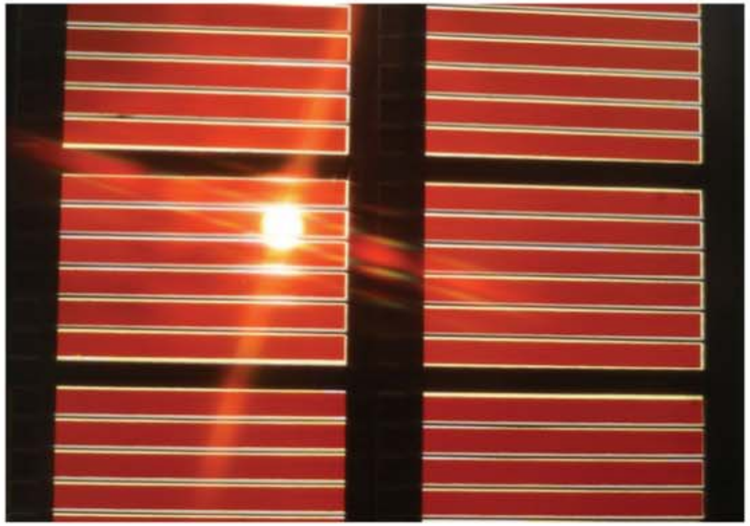


DYESOL TIMO

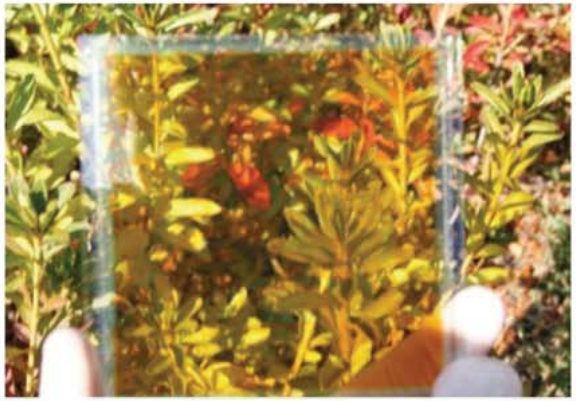
Energy, Wears Color !

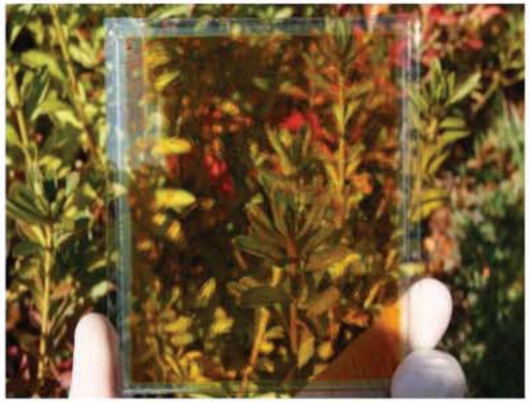
Dyesol -Timo develops and Manufactures . . .

[Module designed by Dyesol-Timo]



[Panel manufactured by Dyesol-timo]





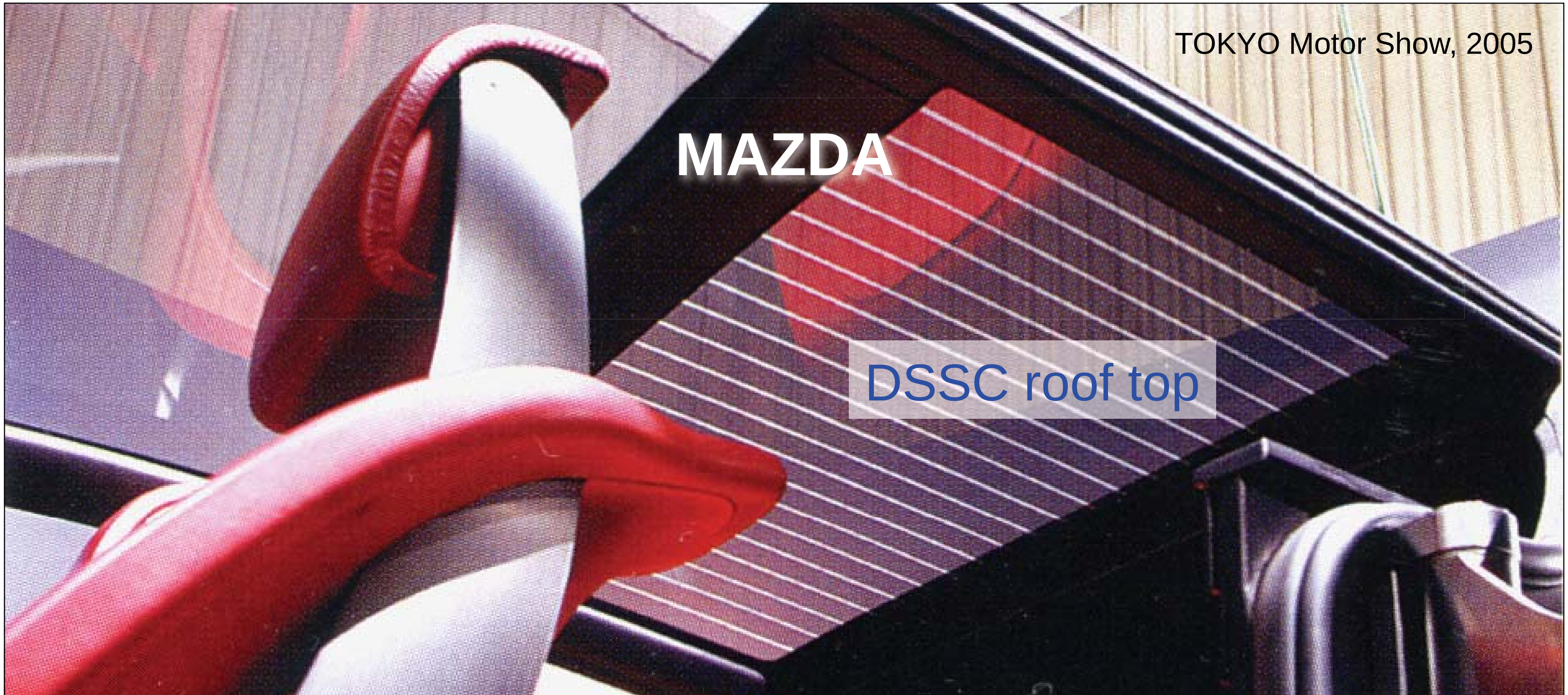
Sony lamps powered by ambient light

The DSC powered car finished within the first ten of 35 contenders in the race

Courtesy Professor Satoshi Uchida: http://kuroppe.tagen.tohoku.ac.jp/~dsc

TOKYO Motor Show, 2005

MAZDA



DSSC roof top

Concept Car
先駆 (Senku)

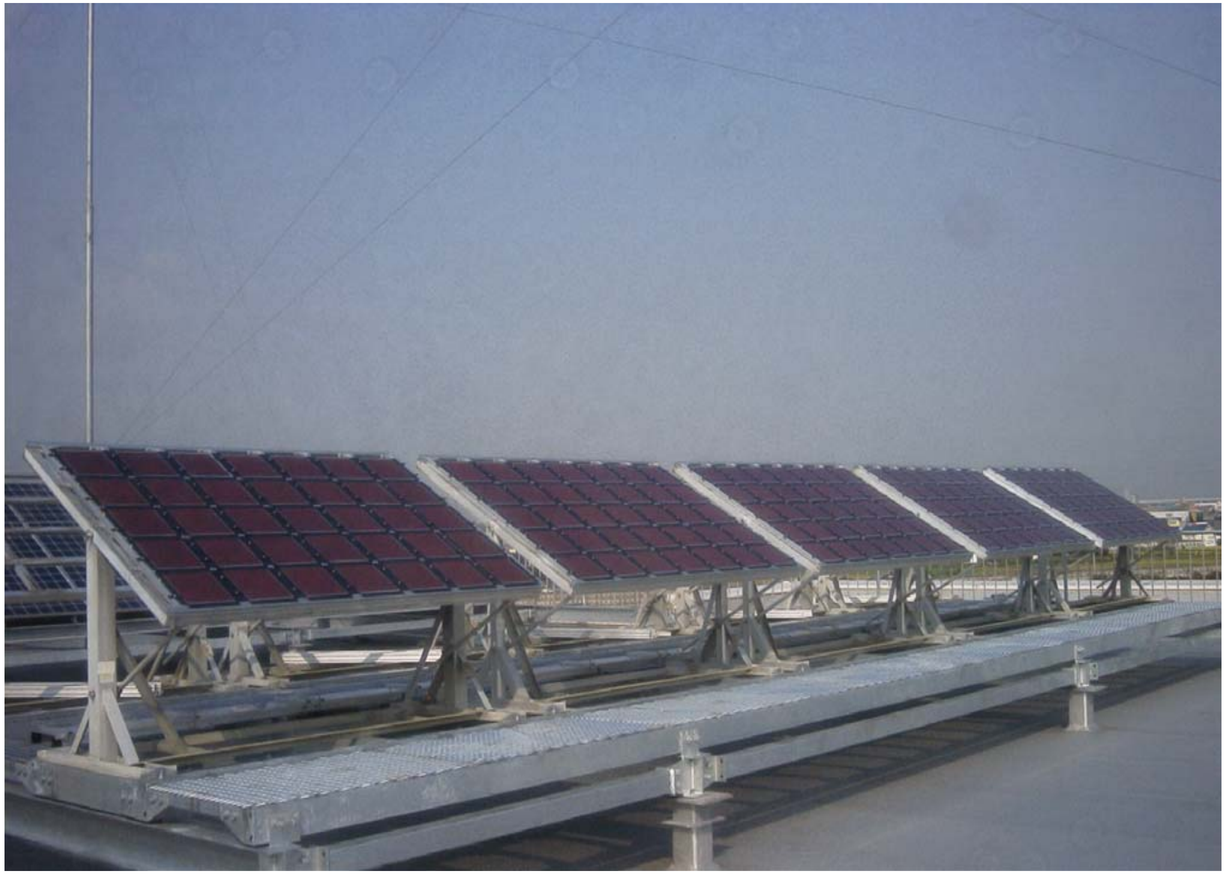
http://www.benzinsider.com/2011/09/the-future-of-vehicles-smart-forvision/

Photographer - Thomas Bloch

Courtesy of

Conference Center at EPFL

Real Outdoor Test of DSC Modules



Series connected
64 DSC cells

Kariya City at lat. 35°10’N,
Asimuthal angle: 0°
Facing due south, Tilted at 30°

Real Outdoor Test of DSC Modules

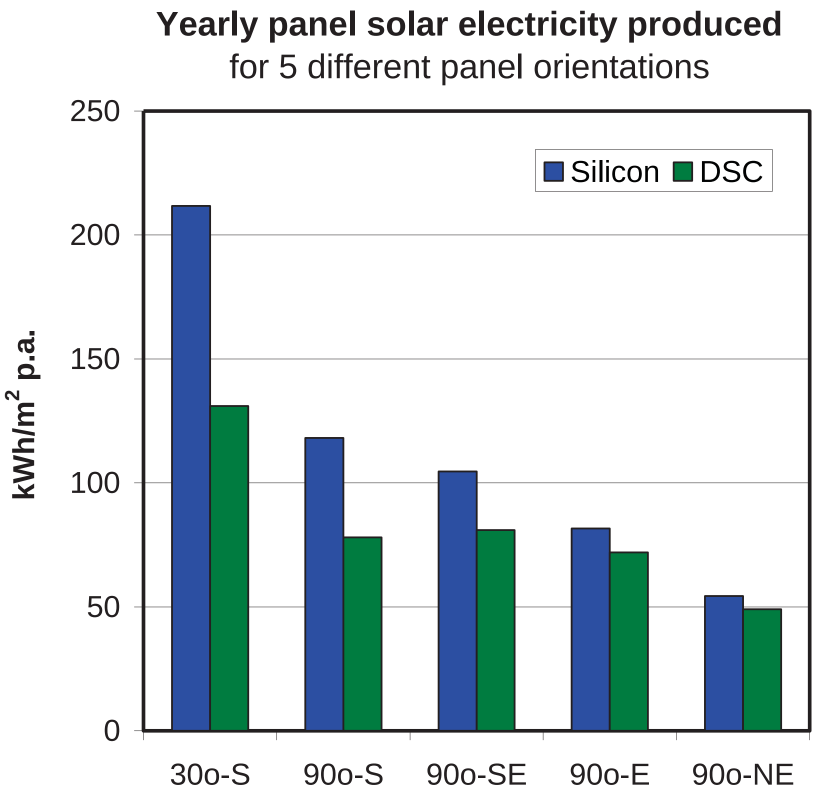
3G Solar twin module DSC prototype - each module 32 series-connected cells of size 225 sq cm

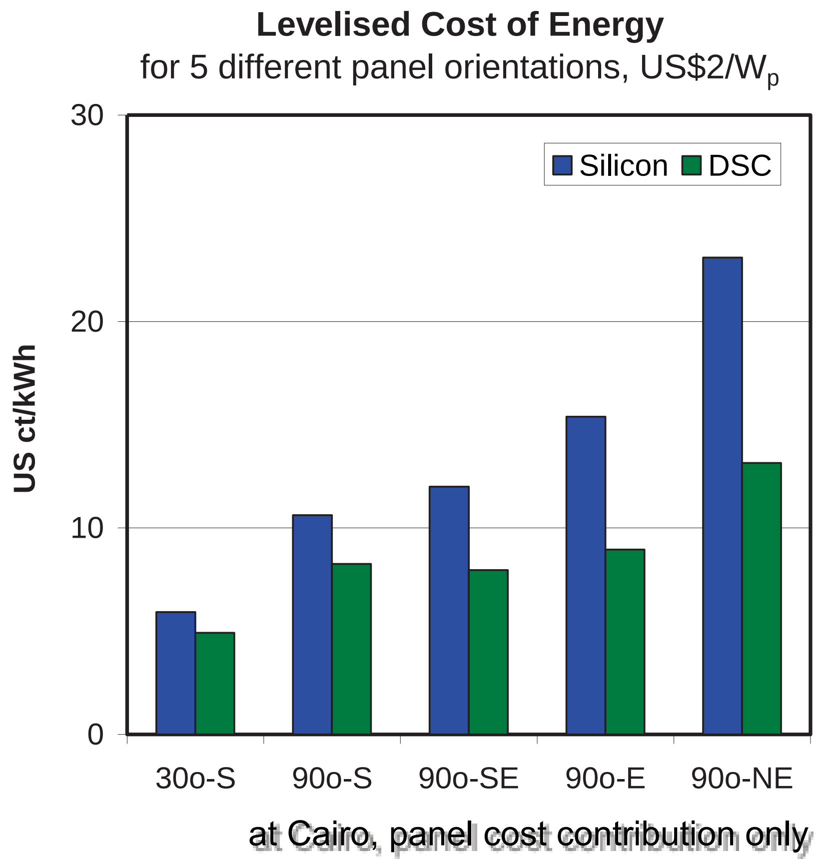
8）バイオトイレ正面

www.G24i.com

Flexible dye-sensitized solar panels attached to bags for
recharging electronic equipment, courtesy: Mascotte Industrial Associates

Advantage under real outdoor conditions

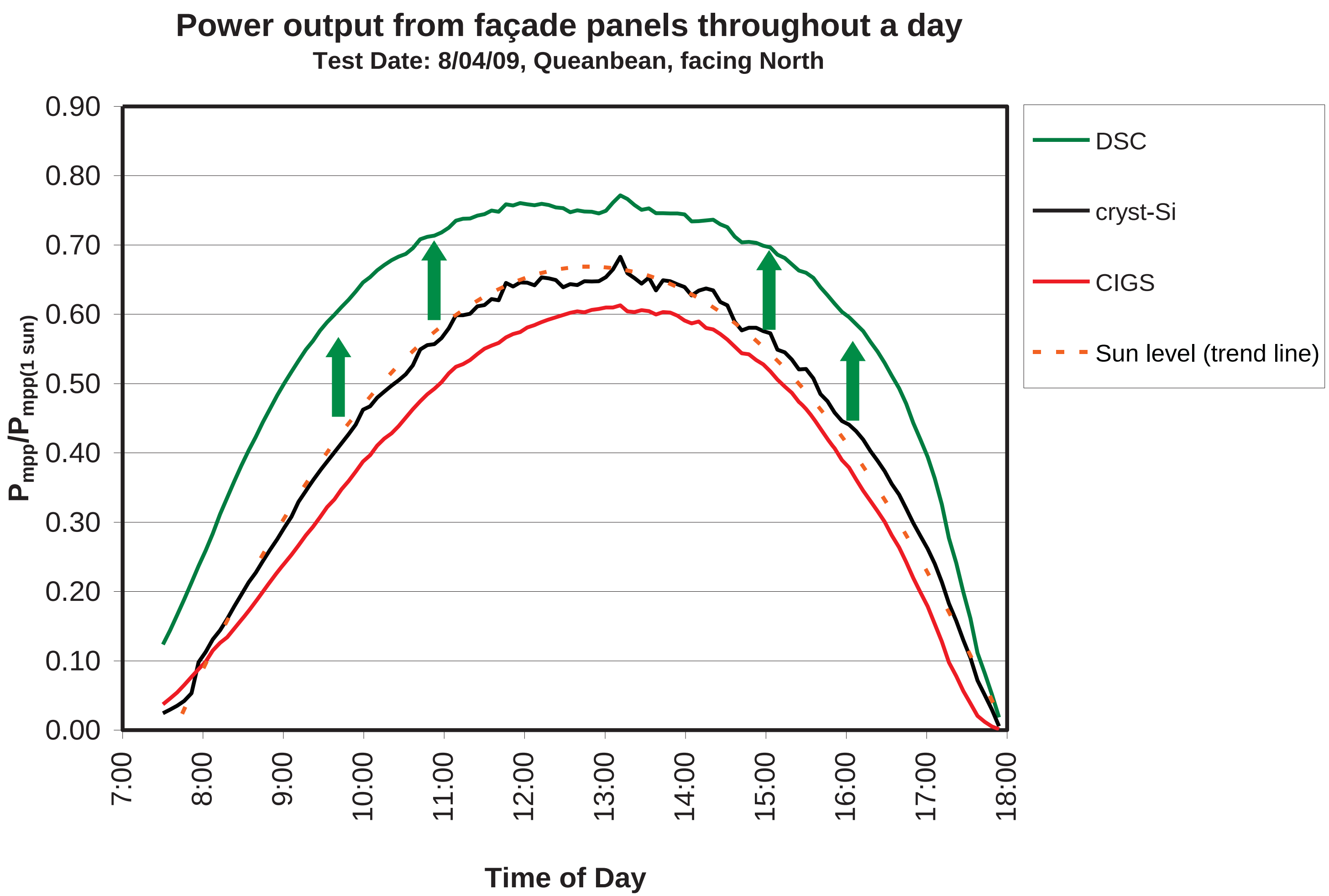




- DSC LCOE is almost independent of façade exposure

Courtesy of DYESOL

Advantage under real outdoor conditions



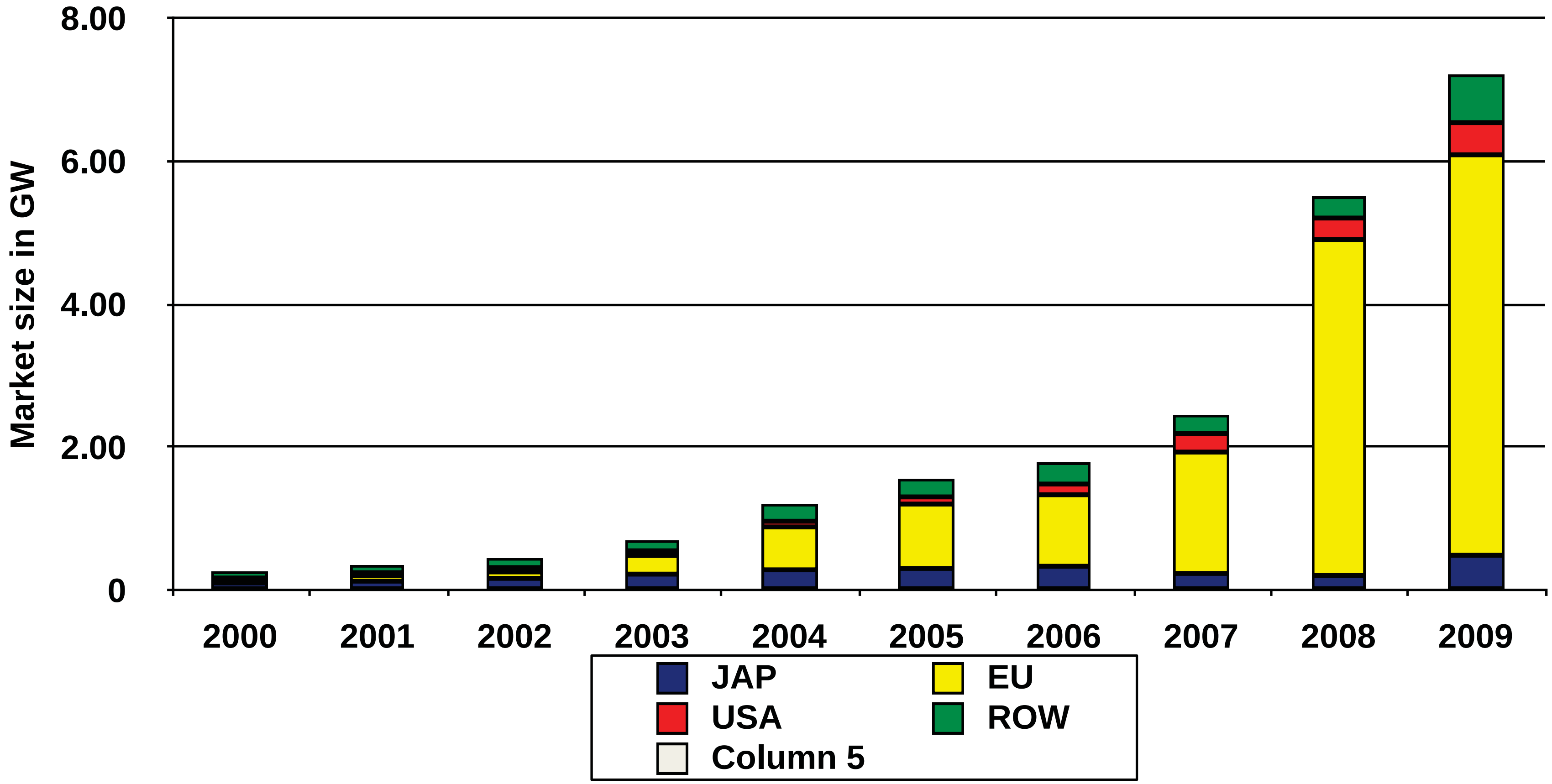
- Significantly higher output in the morning and evening hours
- In façade orientation: **+75%** (or higher) relative energy ouput every day

Courtesy of
DYESOL

The (subsidized) PV market has been growing exponentially

Average growth
45%/yr

2010 ca 12 GW



ref: European Photovoltaic Industry Association (EPIA), Navigant Consulting and Commerzbank

The commercialization of dye sensitized solar cells progresses rapidly
Dye sensitized solar cell production capacity forecast

Ongoing and Future Research

- Advanced meso-structures
- New sensitizers
- New redox mediators
- New counter electrodes

The members of LPI

- **Michael Grätzel**
- **PhD Students** : Hauke Harms, Philippe Labouchère Adriana Paracchino, Magdalena Marszalek, Jérémie Brillet, Florian Le Formal, Pootrakulchote Nuttapol, Maurin Cornuz, Julian Burschka, Amalie Dualeh, Aravind Kumar Chandiran, Leo Phillip Heininger
- **Postdocs:** Yella Aswani, Celine Leroy, Etienne Baranoff, Takeru Bessho, Takashi Hisatomi, Kevin Sivula, Jun-Ho Yum, Nok Tsao, Chenyi Yi, Peng Gao, Jared Heath Delcamp, Etienne Baranoff, Lioz Etgar, Julien Edouard Frey, Florian Kessler, Il Jung Thomas Moehl, Soo-Jin Moon
- **Staff Scientists**: Robin Humphrey Baker, François Rotzinger. Guido Rothenberger, Jaques Moser (titled professor), Peter Pechy, Carole Grätzel, Kuppuswamy Kalyanasundaram, Shaik M. Zakeeruddin, Md. Khaja Nazeeruddin, Paul Liska, Ngoc-Le Cevey, Anne Sophie Chauvin.
- **Technical and administrative staff**: Pascal Comte, Francine Duriaux Arendse, Jean David Décoppet, Manuel Tschumi, Ursula Gonthier, Nelly Gourdou.

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European Research Council, Adv. Res. Grant

GRL Korea (with KRICT)

Stanford University, KAUST Center for Advanced Molecular Photovoltaics (CAMP),

Industrial Partners,

MILLENNIUM TECHNOLOGY PRIZE

Technology for humanity


Thank you for attention!!!