The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2269-22

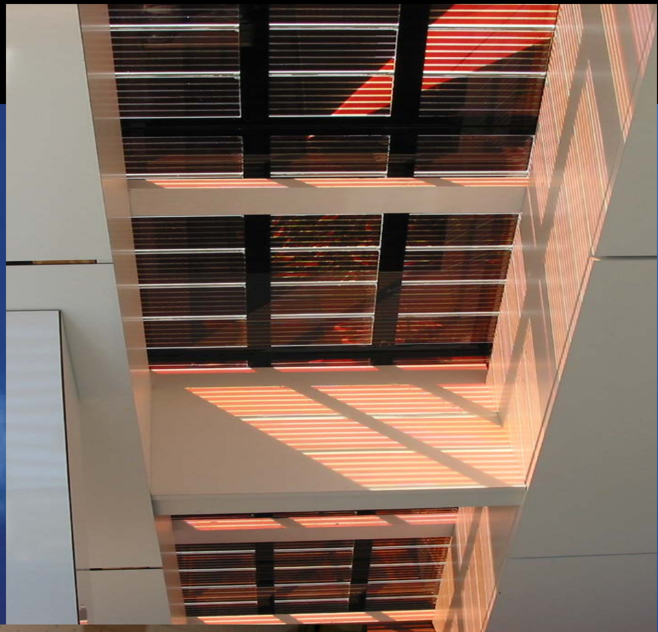
Workshop on New Materials for Renewable Energy

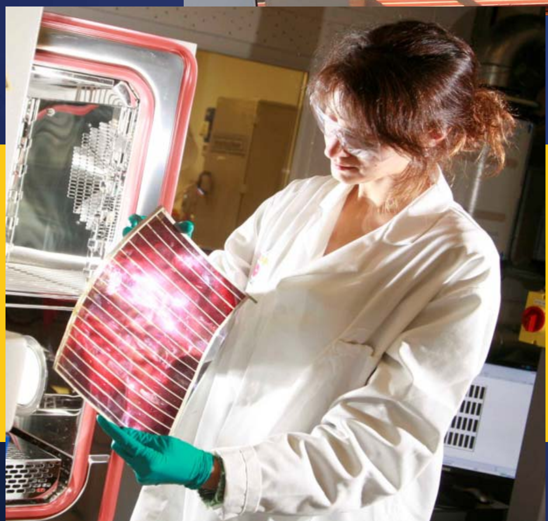
17 - 21 October 2011

3rd Generation Solar Technology. Dyesol approach to DSSC: State of the art and future developments

Luca SORBELLO

Dyesol Italia, Roma
Italy





3^{rd} Generation Solar Technology

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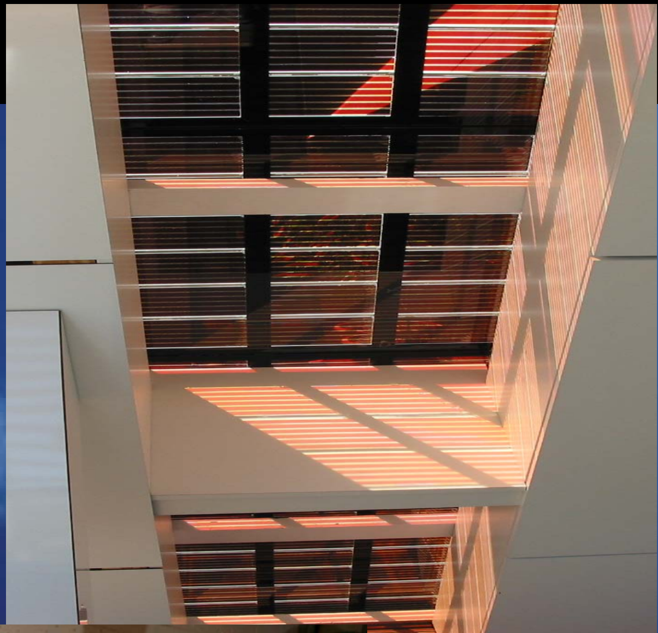
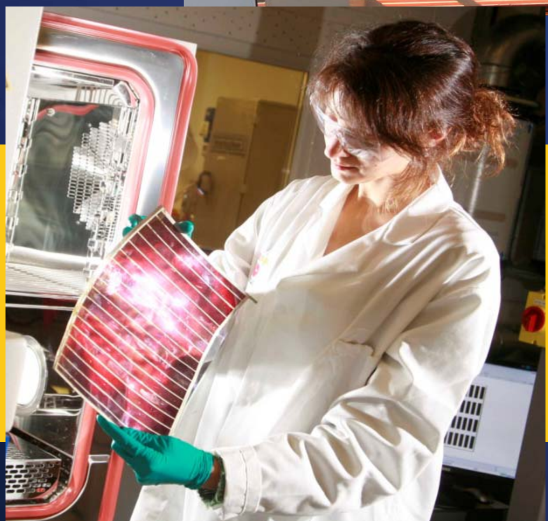
September 2011





Company Overview

Company Overview

Company Background

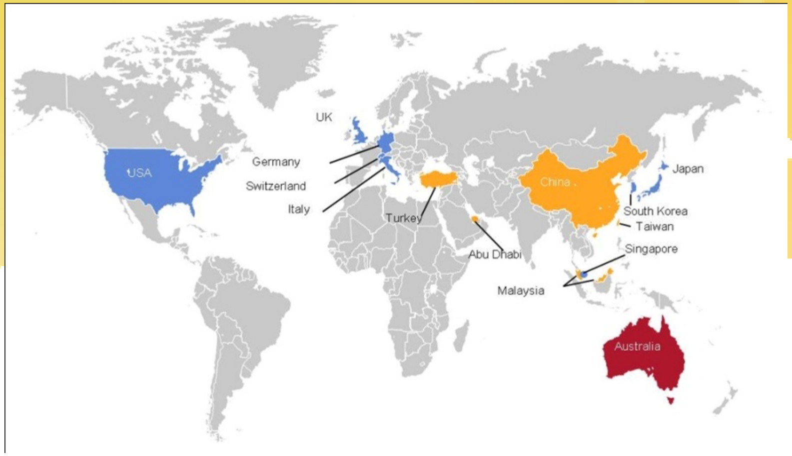
Dyesol, a solar technology company, engages in the commercialization of dye-sensitized solar cells (DSSC)

- Strong IP position with patented materials, equipment and processes for DSSC manufacturing
- One of three original DSSC technology licensors; first to focus on steel roof, glass façade and window applications
- Founded in 2004 and headquartered in New South Wales, Australia. Listed on ASX in 2005.

Ticker (ASX)	DYE
Price[1]	A$0.42
Average Volume (3m)	257,053
Market Capitalization[1]	A$66.1M
Shares Outstanding	157.48M

[1]As of September 7, 2011

Global Footprint



Global headquarters

Subsidiaries: Germany, Italy, Japan, Korea, Singapore, Switzerland, UK and USA

Representatives, agents or contracts: Abu Dhabi, China, Malaysia, Taiwan and Turkey

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Global Leaders in Dye Solar Cell Technology

Dyesol Italia

R&D	Name	Aim
Projects	DEPHOTEX	Textile PV
	MOLESOL	Transparent Conductive material based on Carbon
	MATERA	TiO_2 Laser sintering
	Hi-ZEV	DSC for electric mobility
	DyeCell	BIPV

Dyesol italia was founded in 2007

Collaboration
CNR Perugia
CNR Lecce
CNR Palermo

Commercial	Geographical areas
Materials supplier	All around Europe
Equipment supplier	
Technical support	
Consulting	

Offices	Laboratories
Rome	Near Rome

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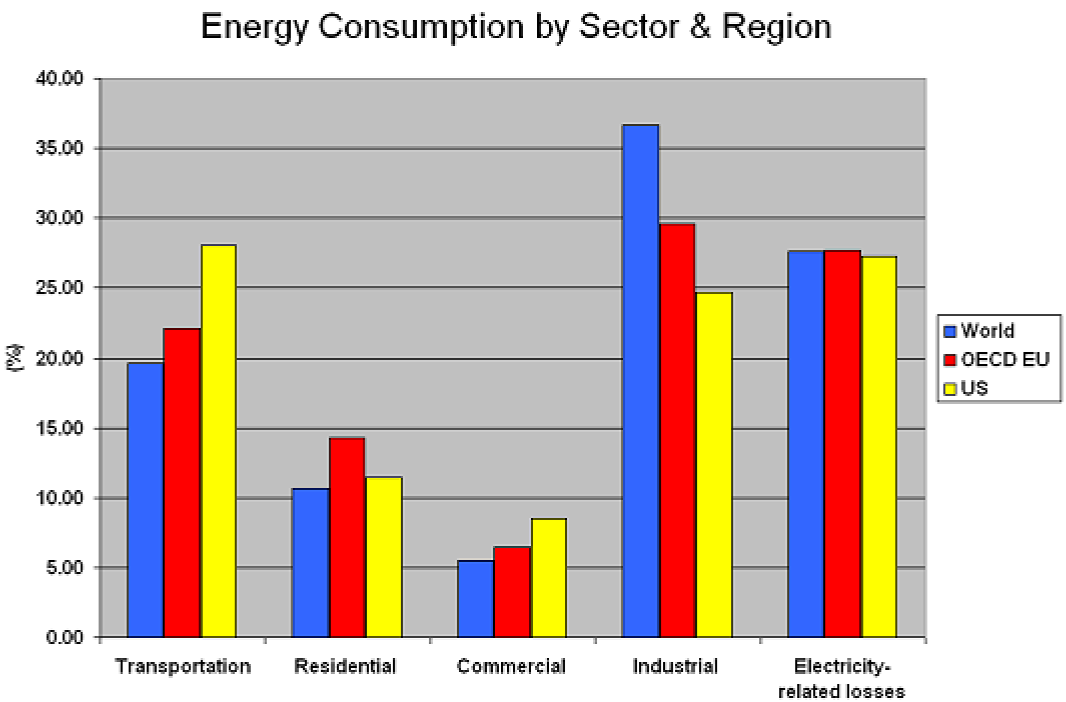
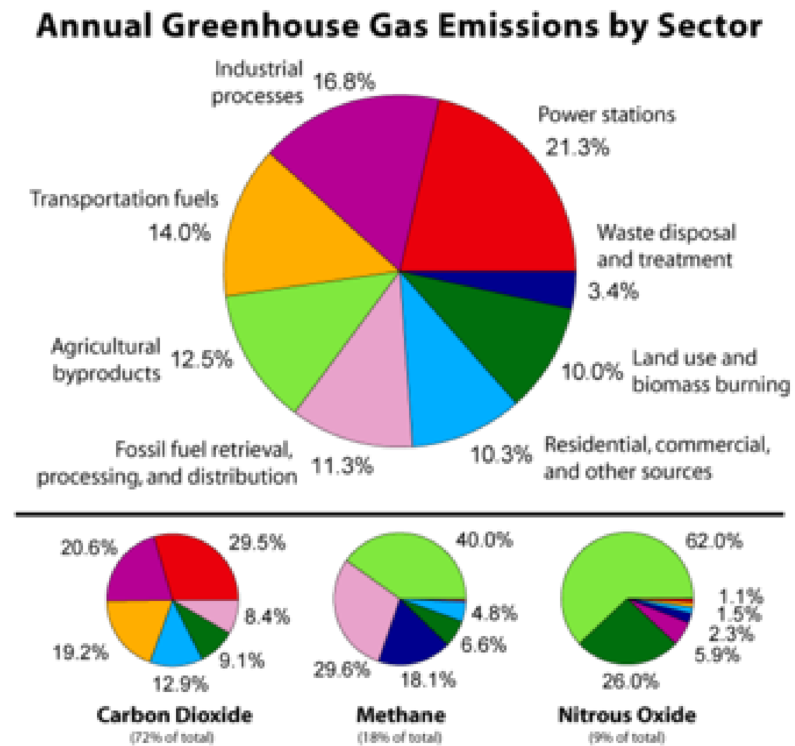
Where is Energy Used?

Built environment > 45% WW
Mobility 17%





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BIPV Roofing & Cladding Market World Wide

Estimated Completed Roof Accessible Market (@40%), 2021 (M m2)

UK 3,534, France 3,393, Germany 4,093 Netherlands 901 Spain 2,166
Rest of EU15 35,510, EU12 22,187, Eastern EU 10,000
USA 44,296, Canada 3,964
India 182,785, S Asia 40,000
China 42,154, East Asia 40,000, SE Asia 40,000
Brazil 25,998 Rest of S America 35,000
SE Asia 47,000, Australasia 3,000
Russia 30,000, North Asia 30,000
Turkey 17,000, West Asia 20,000
North Africa 25,000, Central Africa 10,000, Southern Africa 15,000

Total 605 B m^2

At 5% access per annum, market value is $600B/annum

(Source: IEA, Apropedia, BIPVChina.com, Freedonia, Colors, Dyesol)

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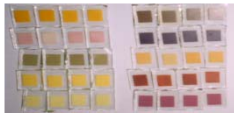
Business Model

Dyesol has a capital efficient, or "capital-light" business model: (1) own technology IP; (2) licenses to manufacturing partners and (3) typically has exclusive materials supply agreements in place:

- IP Portfolio:
  - Portfolio of over 20 interlocking patents and registered designs covering equipment, processes and key materials
  - Registered in major markets: USA, Japan, EU; selectively in Korea, India, China, Singapore, Australia and South Africa
- Global partnering with focus on 5 market sectors:
  - Steel BIPV
  - Glass / window BIPV
  - Automotive/ Flexibles
  - Electronic applications
  - Built environment – Indoors or BAIPV
- Products/Services:
  - DSSC Materials (~30%+ margin): dye, semiconductor pastes, electrolyte, conductor
  - DSSC product components
  - DSSC prototyping and testing equipment
  - Collaborative and contract R&D
  - Consulting and training services
  - Technology upgrades



Dyes

TiO_2 Paste

Building Integrated Photovoltaic (BIPV)

- BIPV is solar cells embedded into building materials used to replace conventional building materials in parts of the building envelope such as the roof, skylights, or facades
- In addition to new construction, existing buildings may be retrofitted with BIPV modules
- Provides access to multi-$100 billion target markets

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Key Strategic Partners

Partner	Market	Region	Details
TATA STEEL	Steel / wall & roof applications	UK/Global	• Fifth largest steel producer in the world • Co-develop and commercialise DSC on coil-coated steel • £10+ million joint-programme under the Welsh Assembly Government (WAG) contract • Production and distribution forecast by FY 2013
MERCK	Materials supply	Germany/ Global	• World leader in development and manufacture of ionic liquids and electrolytes • Co-develop electrolytes for use in DSC
PILKINGTON Smart Glass Solutions	View and non-view glass applications	US/Global	• Part of NSG Group, world's 2nd largest manufacturers of glass and glazing products for building, automotive and specialty glass markets • Commercialise DSC on view and non-view glass, utilising Pilkington's TEC series of transparent conductive oxide (TCO) coated float glass and Dyesol's DSC materials • Ohio State Third Frontier Fund – US$ 1 million Development grant confirmed
SAM Singapore Aerospace Manufacturing	Engineering and process solutions	Singapore/ Global	• Co-develop proto-type manufacturing facilities for use by Dyesol applications partners • Owned by Singapore Government • Instrumental in controlling DSC "know-how"
Timo Technology		Korea/ Global	• Dyesol-Timo is 50/50 JV for development and commercialisation of DSC in Korea • Timo Technologies is a listed electronics supplier to large MNCs such as LG

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R&D Around the World

Module designs: Dyesol Australia

Dyes: Dyesol Australia, CSIRO Australia, NIMS Japan, CNR Perugia (FP7)

Optimised TiO_2 paste and layers: Dyesol UK, Dyesol Australia, CNR Palermo

Modified TiO_2 – bulk and surface: Dyesol UK + FP7 program

Electrolytes: Dyesol Australia + Merck (Germany + Japan)

Improved counter electrodes: Dyesol UK, Dyesol Australia + QUT (Australia), ARC Linkage

Conductors: Dyesol UK, Sefar, FP7

Sealants and barriers: Dyesol UK, Dyesol Australia, Dyesol Italia

- **Manufacturing: Dyesol Italia**

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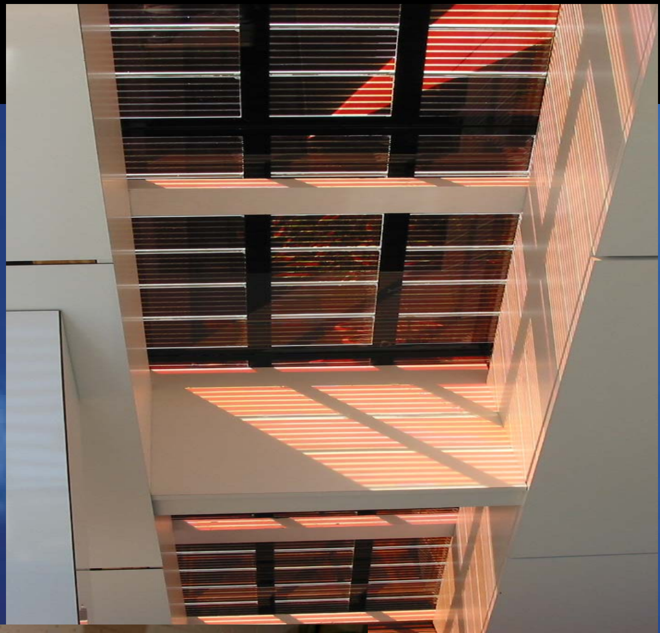
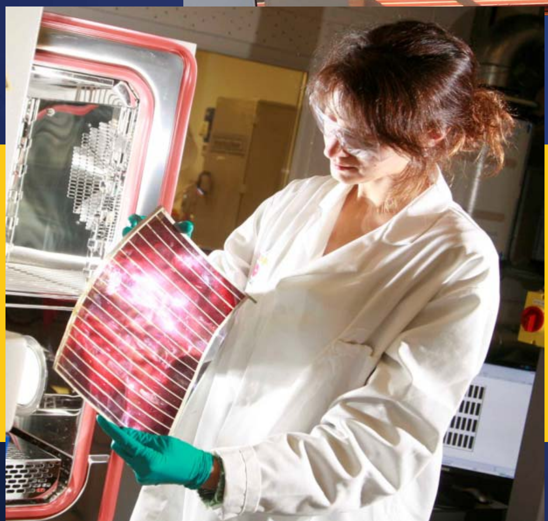




Technology Overview

PV Technology Background

First Generation - Crystalline Silicon

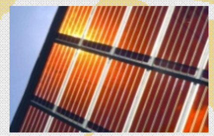
By far the most prevalent bulk material in solar cells. It is separated into multiple categories: monocrystalline, polycrystalline and ribbon silicon. Crystalline silicon cells account for around 90% of the market. The annual growth rate is expected to be 30%.

Second Generation - Thin Film Semiconductor

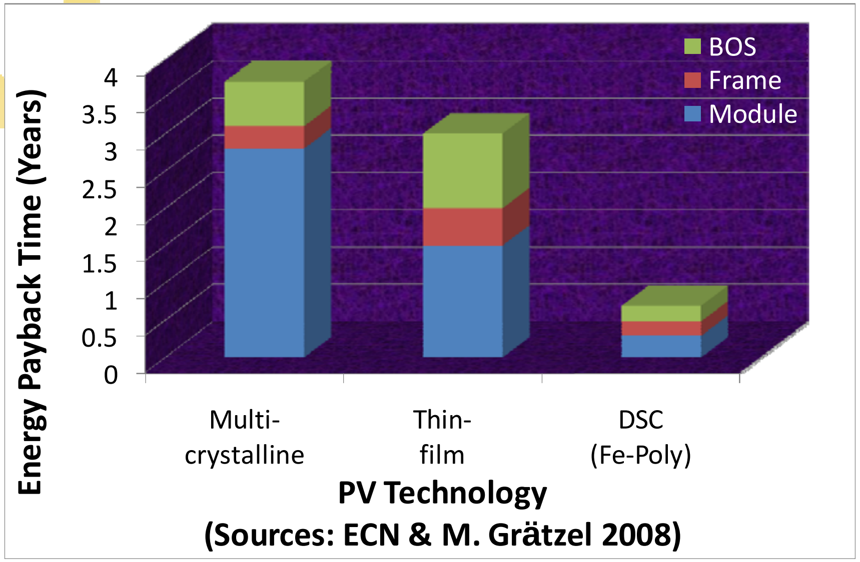
Categorized by the cell materials: amorphous or nano-crystalline e.g. CdTe. The thin film share, in terms of actual production, was 13.5% in 2010. The expected CAGR is around 25%

Third Generation – Artificial Photosynthesis, Nanotechnology

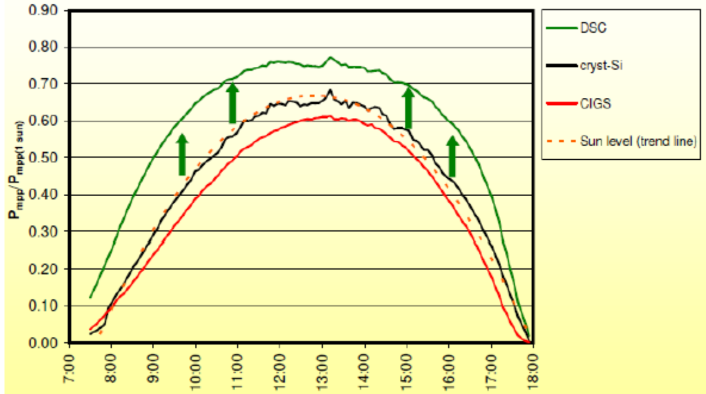
Third generation PV includes multiple technologies that seek to improve upon first two generations through a combination of cost reduction and increased energy efficiency.



Payback Time



Solar Efficiency



Source: Dyesol

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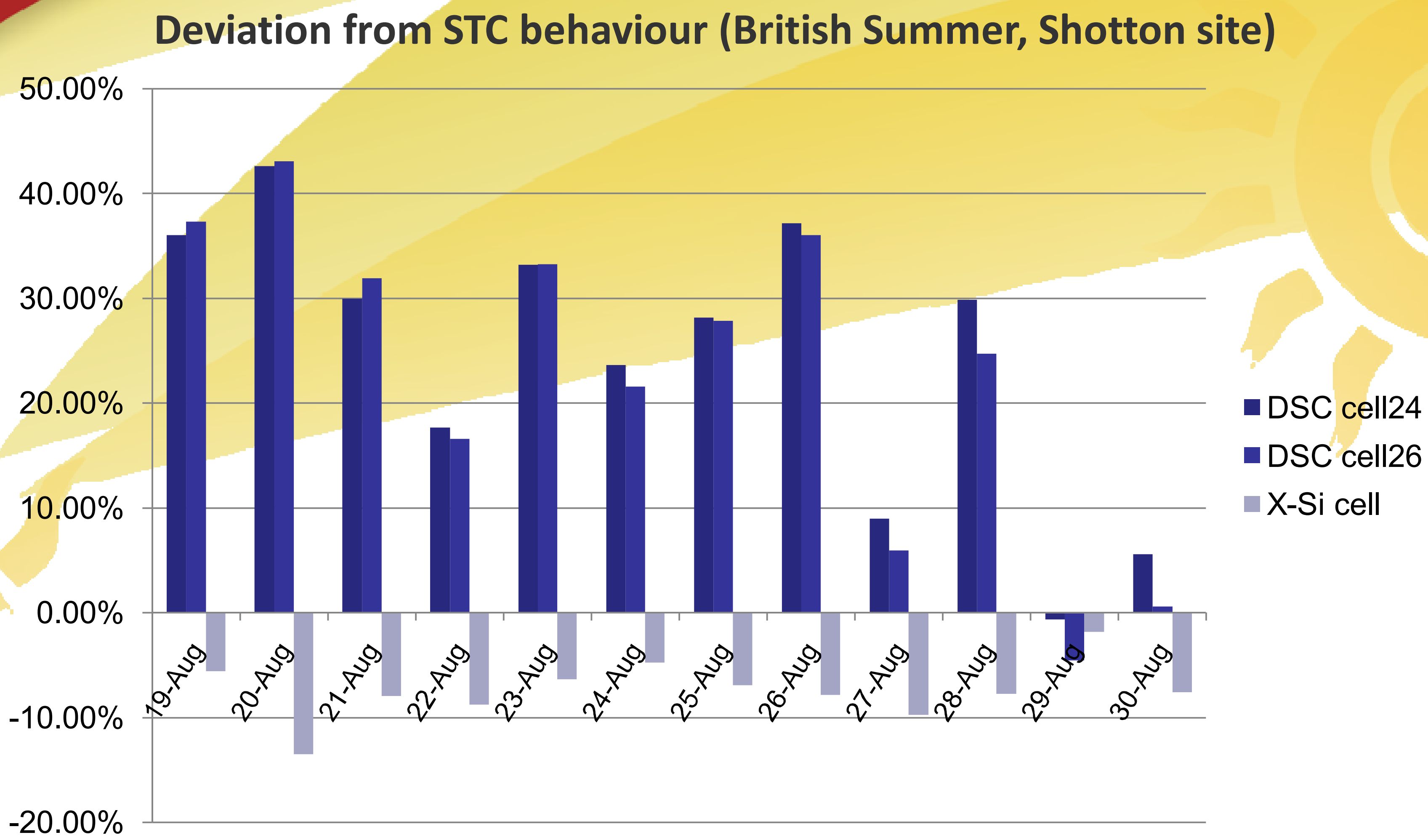
Comparison between DSC and Silicon Panels Outdoor



DSSC Advantages

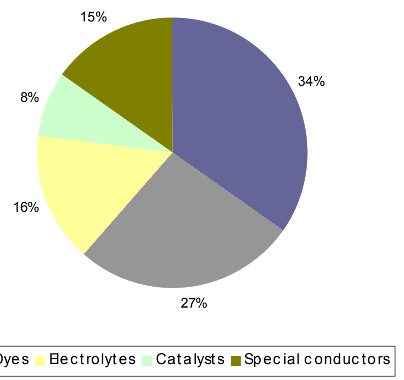
Technology	Efficiency	Cents/kwh	Sunlight	Stability (yrs)	World solar enery consumption	Payback period (yrs) Current	Payback period (yrs) Anticipated
DSSC	10~13%	10.6	ambient light conditions	25		0.75	0.5
Thin Film	5~13%	13~18	direct	25	20%	3	1
Crystalline	15~20%	16~19.6	direct	25	80%	3.5	2

DSSC Material Cost Competitiveness

DSSC materials

The US Spot price in March 2011 for titanium dioxide (TiO_2)/dye is $1.30-1.44/lb, which represents a **7%** increase from 2010

DSC Material Cost Breakdowns



1ST (Crystalline) and 2nd (TFT) Generation Materials

- Spot silicon has risen to between $1.65 and $1.72/lb throughout the first quarter of 2011 from $1.25 to $1.30/lb this time last year, an increase of **30%**
- Cadmium telluride (CdTe) is the basis of the largest sector of thin film solar cells. However, with the growing demand for CdTe in producing 2nd generation solar cells, the availability of the rare element tellurium could be a serious problem in a medium term

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DSSC Market Dynamics

Several global companies are participating in developing and commercializing DSSCs in the near future, many of which are Dyesol's existing customers

Company	Region	Product focus
	Producing	
Dyesol Limited	Australia	R&D, supplier
G24 Innovations	UK	R&D, nanotechnology
	Upcoming	
3GSolar	Israel	R&D
Acrosol	Korea	R&D
Aisin Seiki	Japan	Auto & built environment
Dyetec Solar(Dyesol-Pilkington JV)	USA/global	Glass for Buildings and auto
Fujikura	Japan	Devices
Nissha Printing	Japan	Industrial components, printing solutions
NLAB Solar	Sweden	Nanotechnology R&D
Oxford Photovotaics Ltd	UK	Solid state manufacturing
PECCELL	Japan	University JV R&D
Solar Print	England	Printable DSSC devices
Solaronix SA (JV with 3GSolar)	Switzerland	Laboratories and companies
Sony Corp	Japan/global	Devices
Tata	UK/India/global	Steel roofing

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Indicative material cost

For a 100.000 m^2 production (7MW$_p$)

2010 cost status

Component	Quantity for 100,000 m^2	Present price		Target price
Dye (N719)	100 - 140 kg	20 US$/g	20 - 28 US$/m^2	< 10 US$/g
Ru (N719)	8.0 - 11.2 kg	6,000 - 28,000 US$/kg	0.5 - 3.1 US$/m^2	Met
TiO_2	2,000 - 2,500 kg	> 1,000 US$/kg	20 - 25 US$/m^2	< 250 US$/kg
Electrolyte (solvent based)	~ 5,000 kg	< 140 US$/kg	< 7 US$/m^2	Met *
Glass/TCO	100,000 m^2	> 10 US$/m^2	> 10 US$/m^2 **	< 10 US$/m^2
Pt	~ 2 kg	> 48,000 US$/kg	~ 1 US$/m^2	Met

* Cost reduction required for pure ionic liquid-based electrolytes

** >20 US$/m^2 if two glass/TCO substrates are required

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A few words on costs

- **Estimated materials costs for relatively small-scale DSC module production (7MW$_p$ p.a.): 70US$/m^2, corresponds to 1$/W$_p$ @ 7% module efficiency**
- **$/W$_p$ is inadequate metric for DSC, particularly if mounted on façades**
- **In contrast to Si, DSC efficiencies highest around average sun levels (0.2-0.4 sun) and around 40ºC**
  ↳ LCOE (levelised cost of energy) based on
  - Practical performance, f(sun level, temperature)
  - Solar radiation data, e.g. Meteonorm
  - Comparison with multicrystalline Si practical perfomance based on NREL's SAM (Solar Advisor Model)

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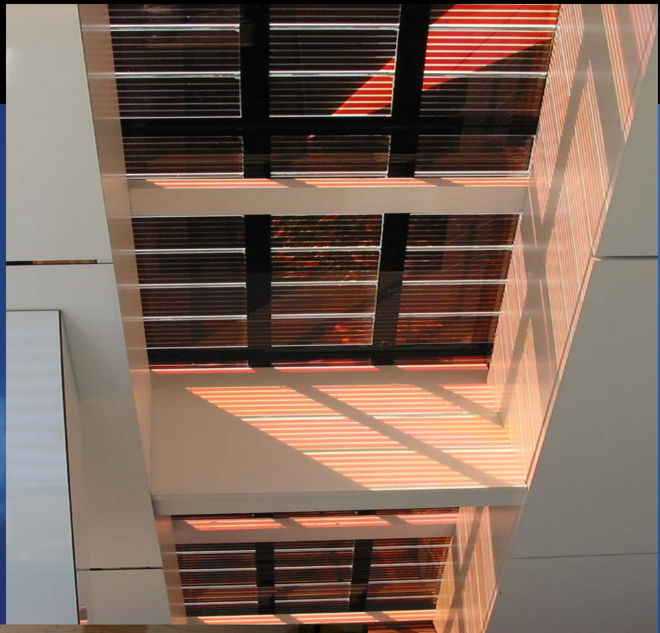
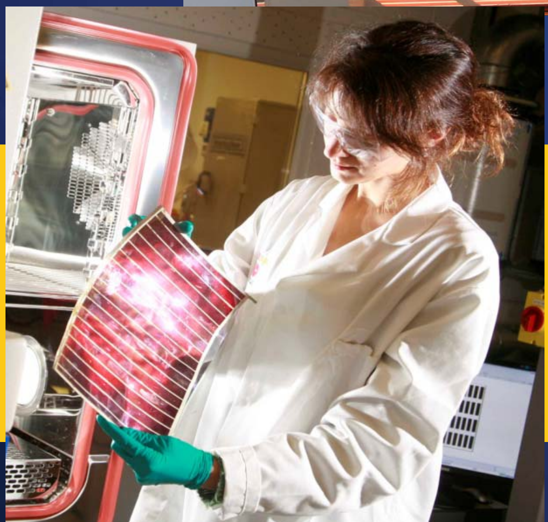


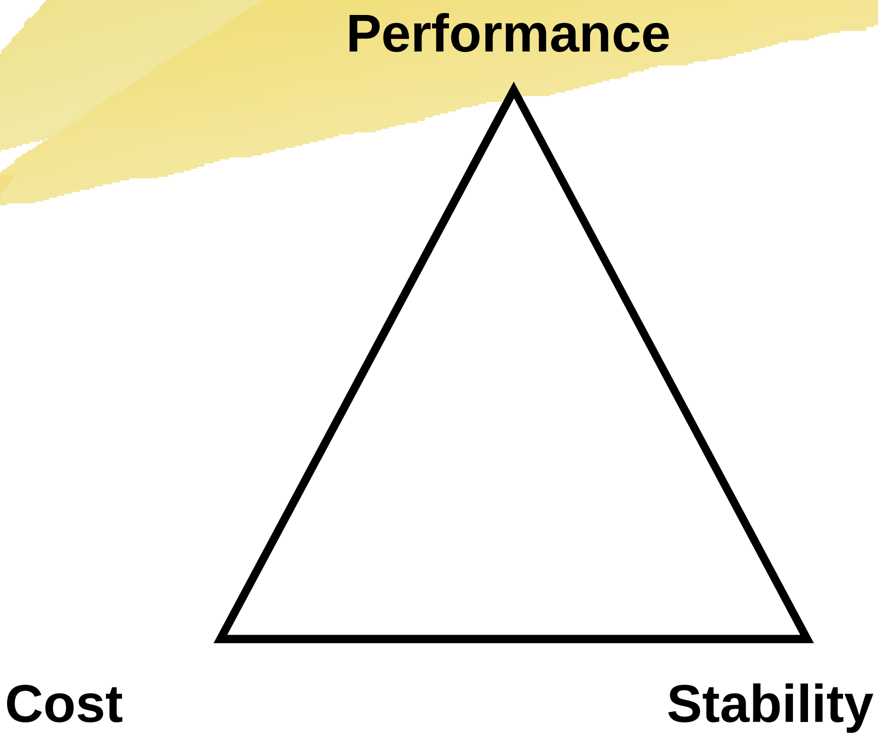


Dyesol state of the art

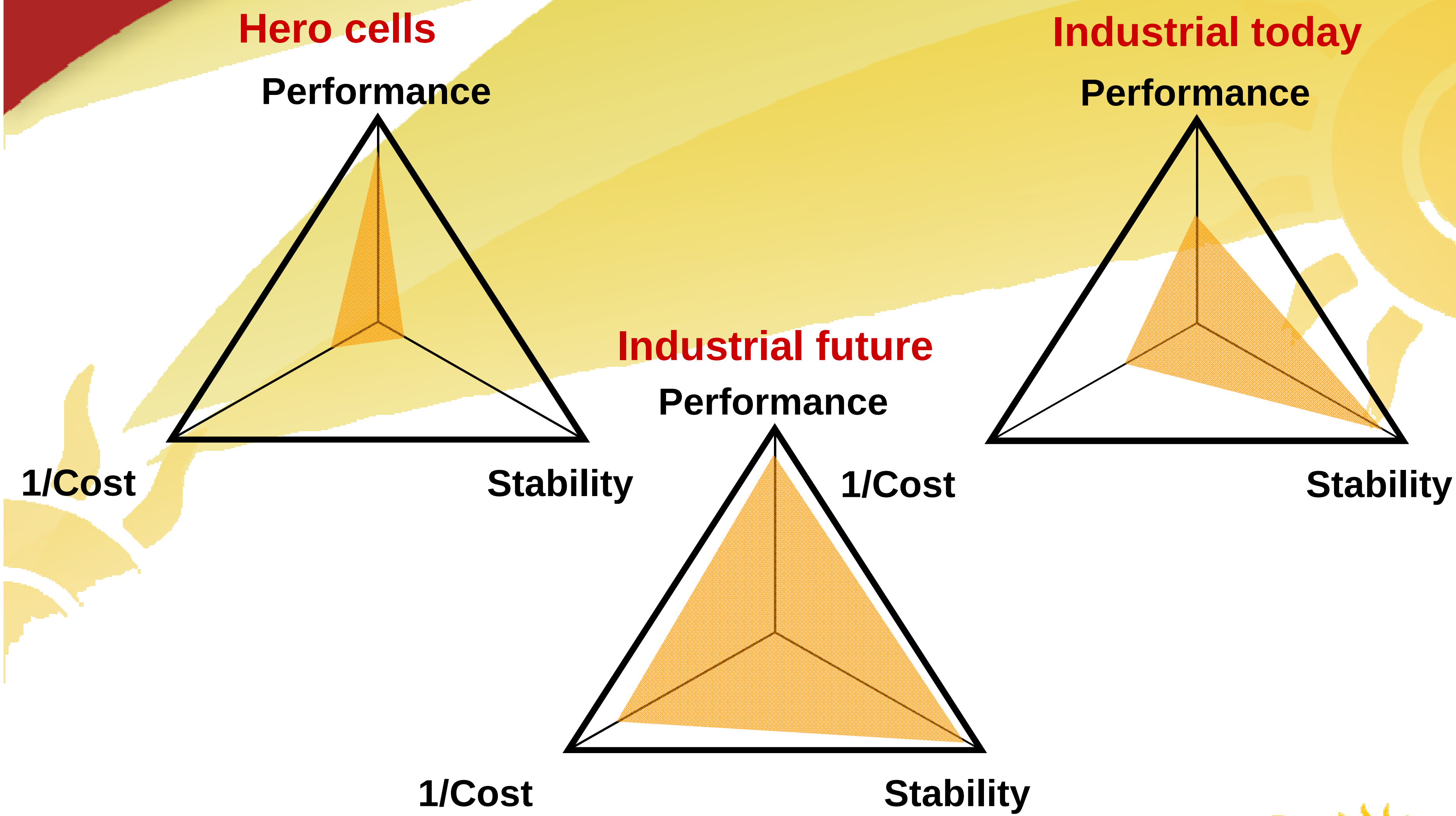
September 2011

The challenge for industrially viable DSC

Meet at the same time stringent criteria of Performance, Stability, Cost



A few cases


Hero cells
Performance
1/Cost
Stability
Industrial future
Performance
1/Cost
Stability
Industrial today
Performance
1/Cost
Stability

Components vs Impacts

Dyesol investigated all materials and design aspects of DSC

Component	Impact
Module design	I_{sc}, cost, processability
Dyes and Dye cocktails	I_{sc}
TiO_2 – pastes and layers	I_{sc}, cost, processability
Modified TiO_2	I_{sc}, V_{oc}
Electrolytes	Lifetime, FF, I_{sc}
Sealants and barriers	Lifetime
Counter electrode	FF, I_{sc}
Conductors	I_{sc}, lifetime, active area

⇨ **Dyesol continues to provide its leadership role in DSC development towards industrialisation**

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Front-lit cell design

Design and concept work

WO/2009/105807 “SUB-ASSEMBLY FOR USE IN FABRICATING PHOTO-ELECTROCHEMICAL DEVICES AND A METHOD OF PRODUCING A SUB-ASSEMBLY”

Sourcing of substrates

First successful coating trials and reduction to practice

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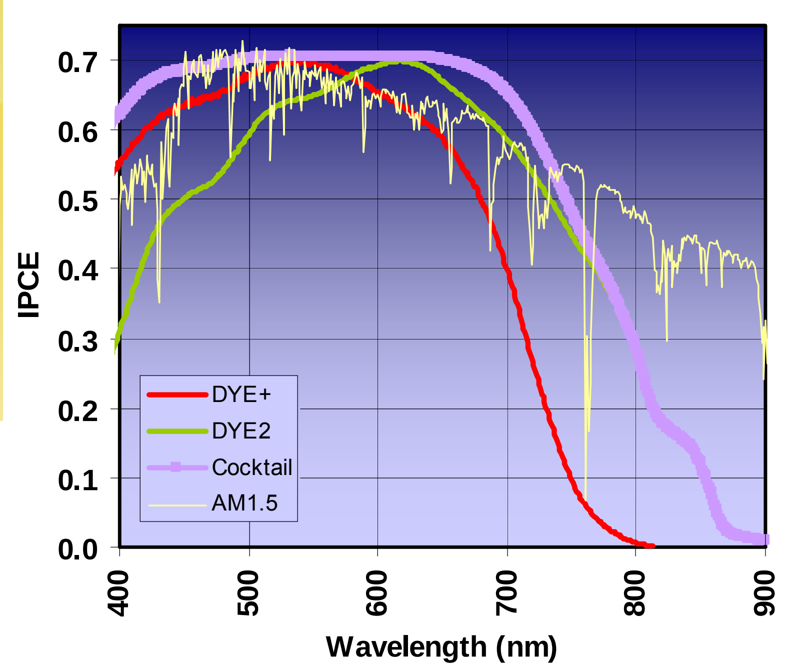
Dyes and dye cocktails

Dye combination selected for initial evaluation program

> 34% current increase expected from benchmark dye

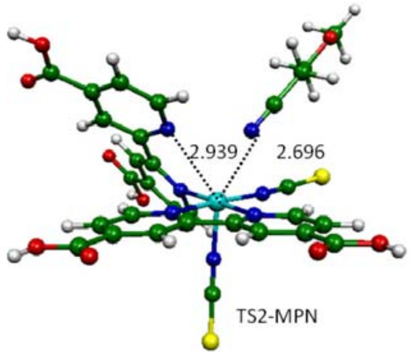


CSIRO: stability of broad band absorbers, linker chemistry

CNR Perugia (world leaders in Ru dye modeling)

- Performance modeling
- Modeling of stability of dye-TiO_2

NIMS: Synthesis of high-extinction broad band absorbers



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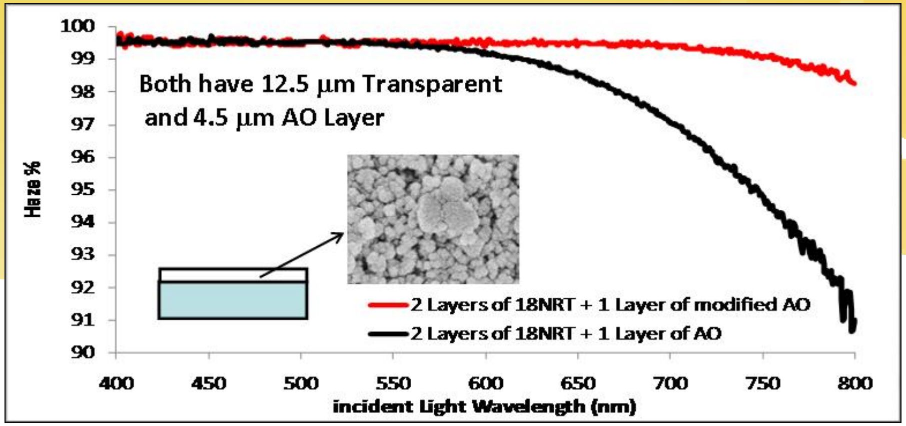
Optimized TiO_2 paste and layers

Thorough understanding of paste rheology ⇨ tailored formulation programs

- Commercially available TiO_2 powders
- Proprietary additives
- Process simplifications, thus lower costs
- Better understanding paste shelf life



Optimised light harvesting, haze

- Important for light absorption in the red and IR part of spectrum

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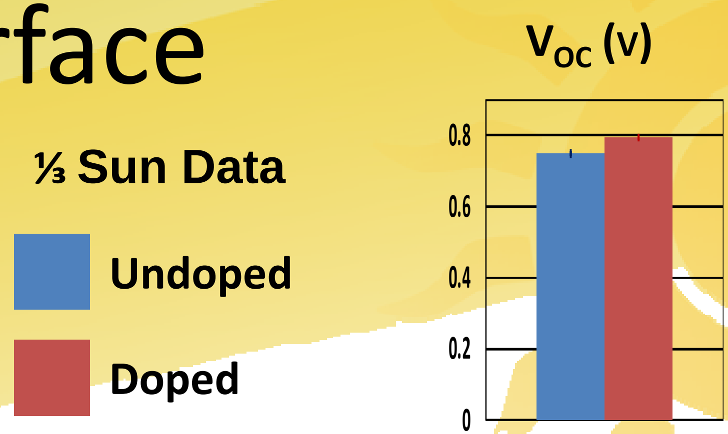
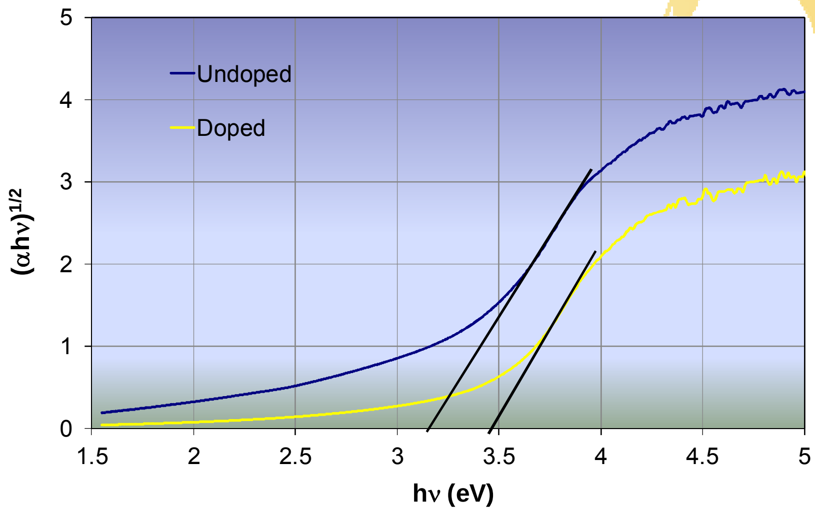
Modified TiO_2 – bulk and surface

Bulk doping of titania to increase conduction band

- Higher cell voltage
- Due to higher band gap (CB)

Surface doping of titania to increase device performance

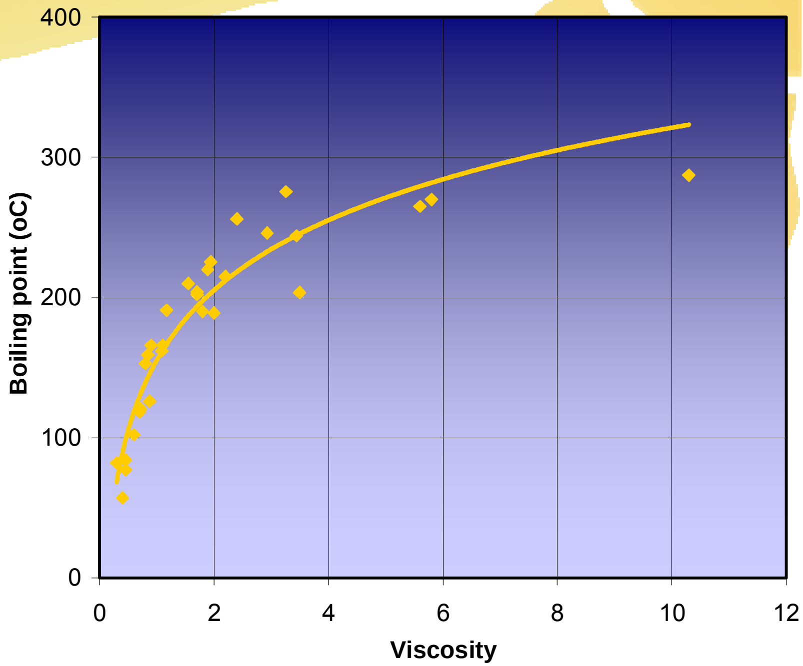


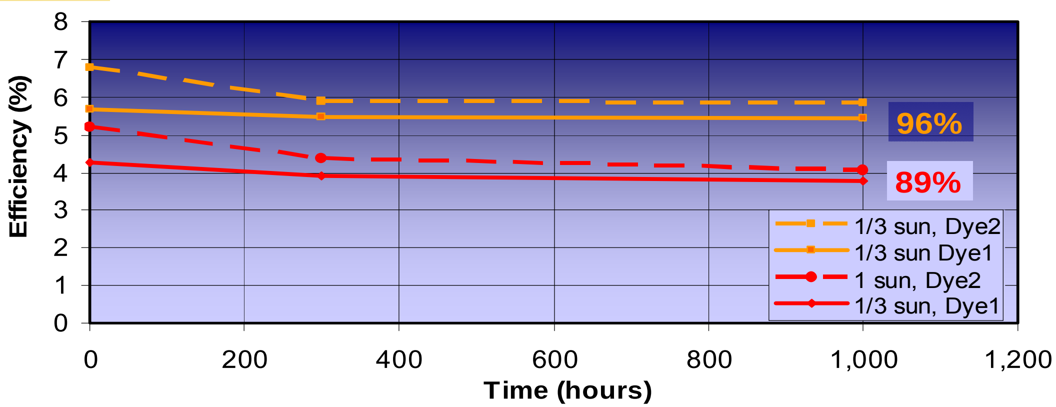


Electrolytes

In house and Merck

– 1'000h, 85°C stability (IEC 61646)
– Optimised stability/performance
– More than 70 solvents reviewed and >20 tested
– Establishment of thorough understanding of all electrolyte components on performance and cost
– Understanding the importance of impurities on stability and performance
– Redox mobility enhancement
– Electrolyte immobilisation





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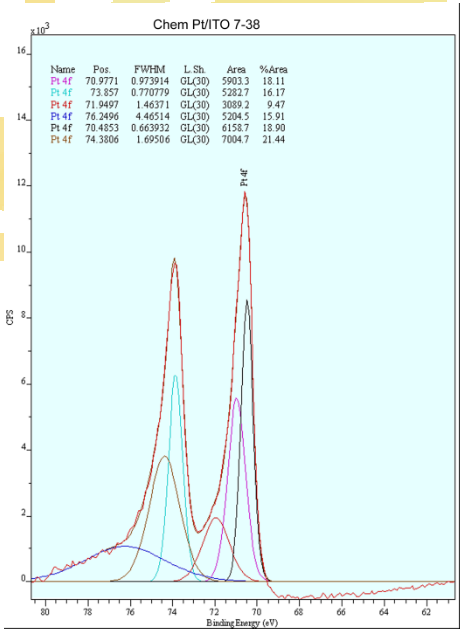
Improved counter electrodes

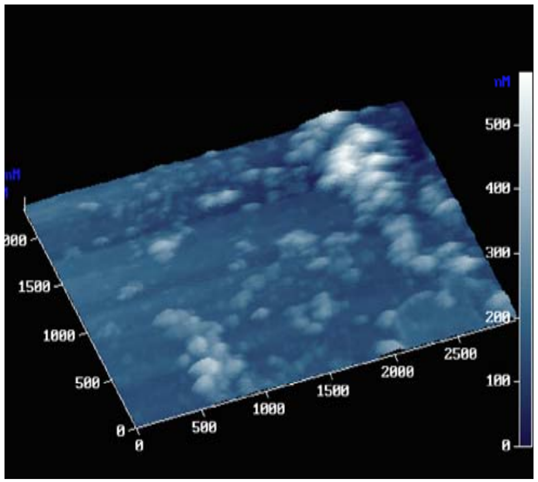
- **Pt vs C-based**

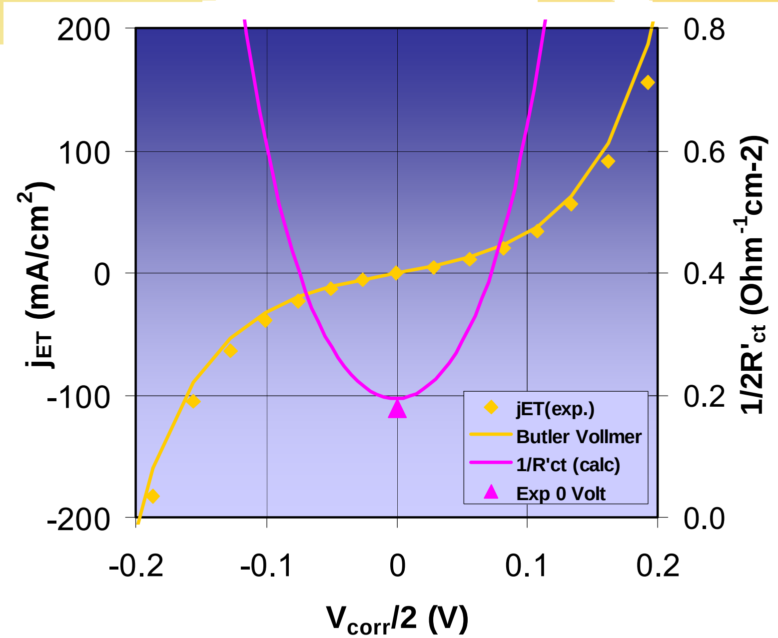
  Deposition methods and annealing conditions

  Influence of various substrates

  Analytical characterisation
  - SEM, XPS, AFM
  - EIS/electrochemistry







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Conductors

In house developed new formulations for high bulk conductivity screen printable Ag pastes: 70-80 nOhm m (benchmark)
⇨ 50-60 nOhm m

Mesh development with partner

- **Lower cost alternatives to silver bus bars and current collectors**
- **Transparent conductors: TCO and carbon based**

  MOLESOL project (All carbon platforms for highly efficient molecular wire-coupled dye-sensitized solar cells)

- **Z-interconnects: polymers filled with arious conductors**

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Sealants

Investigation of various classes of sealants

- Epoxies
- Thermoplastic
- ORMOCERs

- **Verification**
  - Thermal cycling tests -40/+85ºC (IEC 61646)
  - 1,000h+ at 85ºC (IEC 61646)
  - Developed highly sensitive, electrochemical seal quality test

	WVTR	mol/(m^2 day)
MOCON	5×10^{-4} g/(m^2 day)	**3×10^{-5} mol/(m^2 day)**
OLED requirement	1×10^{-6} g/(m^2 day)	**6×10^{-8} mol/(m^2 day)**
Electrochemical testing	-	**< 1×10^{-8} mol/(m^2 day)**

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Excellent stability over >20'000h

- 20,600 hours = 28.4 months of continuous illumination
- Corresponding to 16,600 kWh/m^2
  - Middle Europe: ~1,000 kWh/m^2 p.a. solar irradiation (London: 970 kWh/m^2 p.a.)
  - Southern Europe or Sydney: ~1,700 kWh/m^2 p.a.
- Annual average device temperature during solar irradiation: ~45^{o}C, in Canberra
- Acceleration factor of 2-3 per 10^{o}C temperature increase
- Assuming a (conservative) factor of 2:
  - Middle Europe: 33 years
  - Southern Europe or Sydney 20 years

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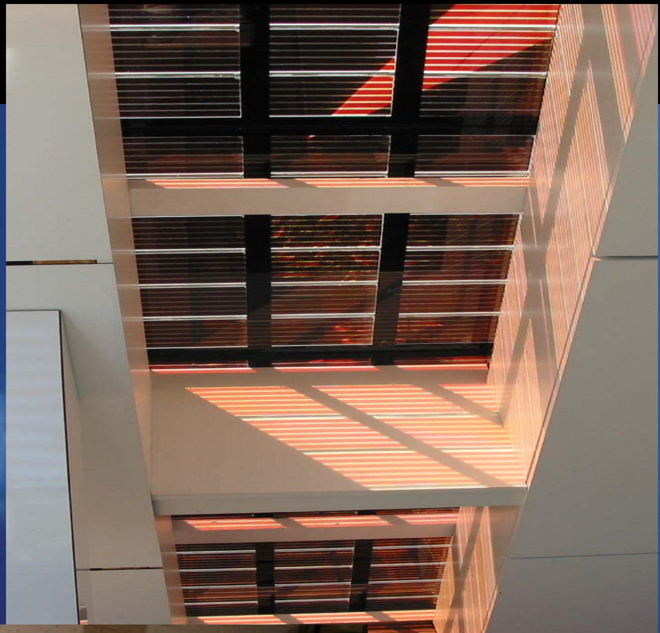
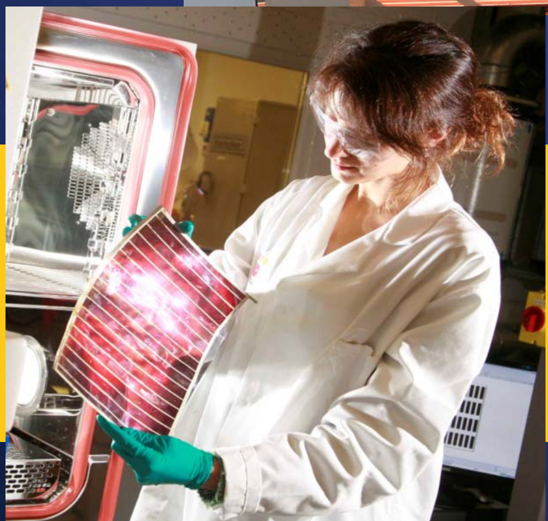




Future developments

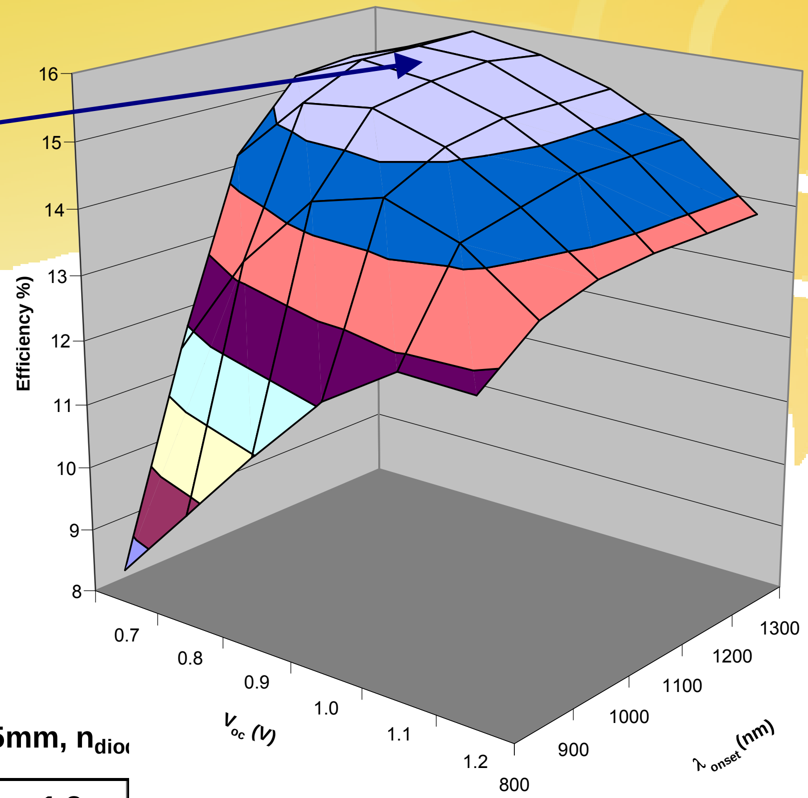
Evolution vs revolution

September 2011

Realistically achievable efficiencies
3 cases

Total driving force =0.6 eV (I_3^-/I^-), w_{TiO2}=3mm, w_s=0.5mm, n_{diode}=1.3

λ_{onset} \ V_{oc}	0.7	0.8	0.9	1.0	1.1	1.2
800 nm	8.5	9.7	11.0	12.1	12.8	12.8
900 nm	11.7	13.3	14.4	14.7	14.3	13.4
1000 nm	14.4	15.4	15.5	15.1	14.5	13.7
1100 nm	15.4	15.8	**15.7**	15.3	14.7	13.8
1200 nm	15.5	15.8	15.7	15.3	14.7	13.8
1300 nm	15.4	15.8	15.6	**15.3**	14.7	13.8



Total driving force=0.6eV (I_3^-/I^-), w_{TiO2}=8mm, w_s=0.5mm, n_{diode}=1.3

λ_{onset} \ V_{oc}	0.7	0.8	0.9	1.0	1.1	1.2
800 nm	7.8	8.9	10.0	11.1	12.1	12.4
900 nm	10.3	11.8	13.1	13.7	13.7	13.2
1000 nm	12.4	13.8	14.3	14.2	13.9	13.4
1100 nm	13.3	14.3	**14.5**	14.3	13.9	13.4
1200 nm	13.4	14.3	**14.6**	14.3	13.9	13.4
1300 nm	13.3	14.3	14.4	14.3	13.9	13.4

Total driving force=0.3eV (optimised hole transport), w_{TiO2}=8mm, w_s=0.5mm, n_{dio}

λ_{onset} \ V_{oc}	0.7	0.8	0.9	1.0	1.1	1.2	1.3
800 nm	7.8	8.9	10.0	11.1	12.2	13.3	14.4
900 nm	10.3	11.8	13.2	14.7	16.2	17.4	17.1
1000 nm	12.4	14.2	16.0	17.7	19.0	19.1	17.6
1100 nm	13.9	15.9	17.8	19.0	19.6	19.3	17.7
1200 nm	15.3	18.1	18.7	19.2	19.7	19.4	17.7
1300 nm	16.1	17.9	18.7	19.1	**20.0**	19.2	17.7

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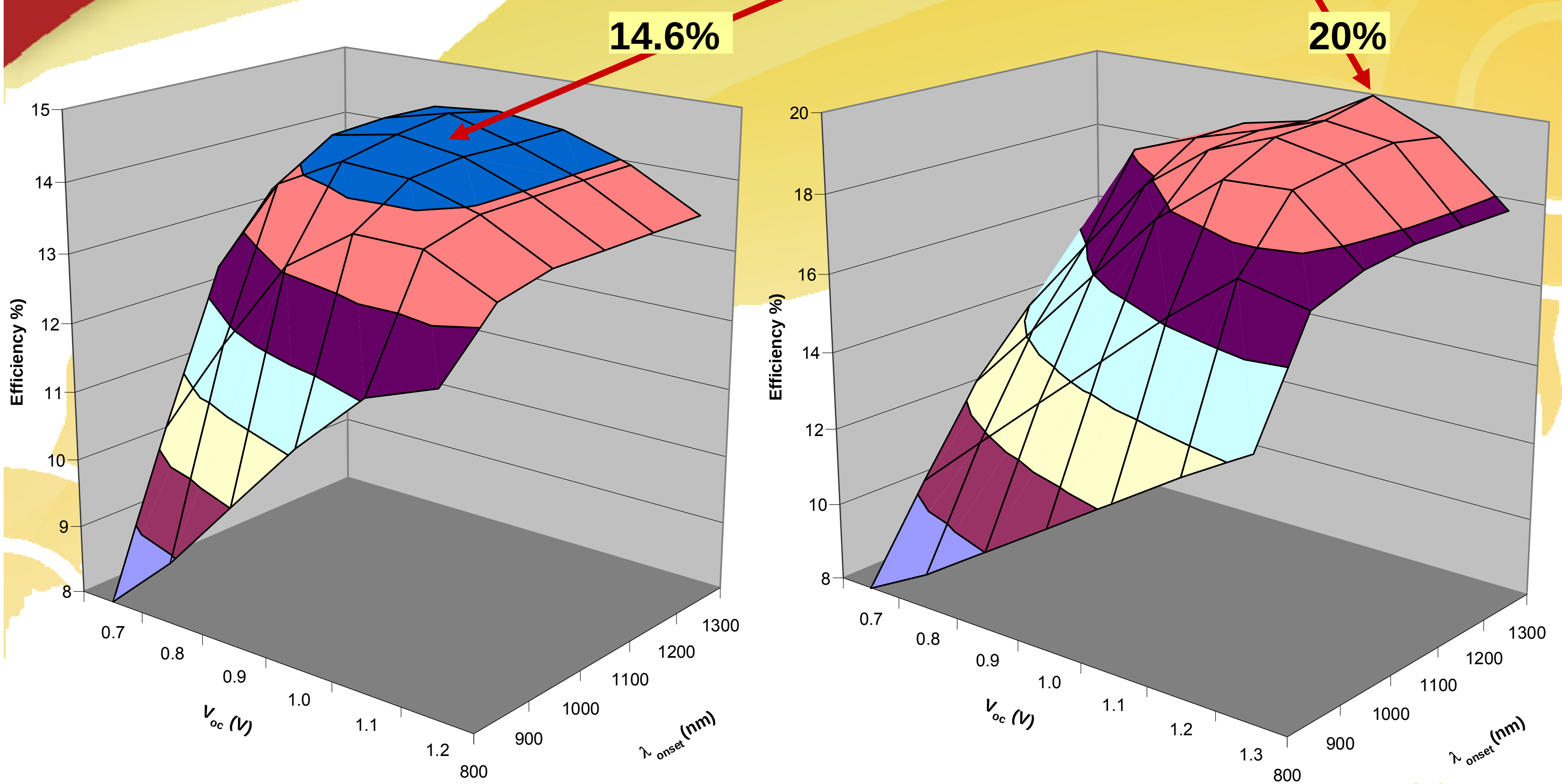
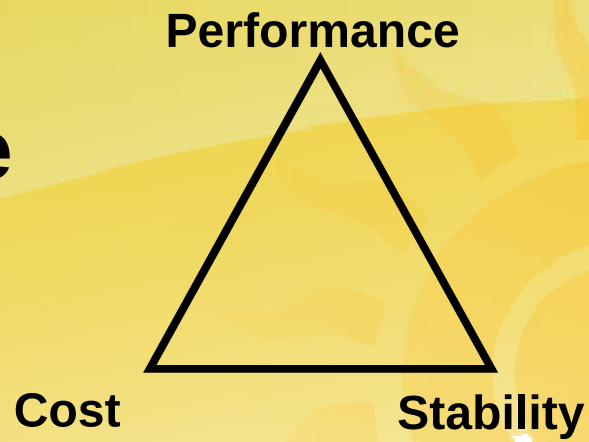
Realistically achievable efficiencies

Industrial design, I_3^-/I^- vs optimised hole transport



How to further improve DSC performance?

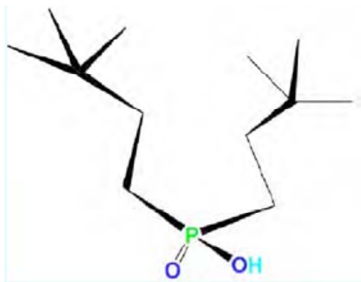


Step 1 (2010-11): Dye, TiO_2, Electrolyte **EVOLUTIONARY**

- Dye with better absorption of red and IR light, high ε
  Experimental and modelling work
  Optimised scattering layers for better IR response
  ⇨ j_{sc} ~22 mA/cm^2
- TiO_2/electrolyte combination, coadsorbents *) ⇨ V_{oc} 0.8-0.85V

⇨ η to **~11% for industrial DSC (from 8-9% base)**

*) e.g. DINHOP



available from Dyesol

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Industrially viable DSCs
Why is their performance lower?

- **Only use standard materials industrially available in kg quantities at realistic costs**
- **Low volatility and low toxicity solvents**
- **Optimization for 20+ years product life, not just peak performance, UV filter!**
- **Cell Width of ~10 mm**
- **Length: at least 10 mm**
- **Scalability to larger modules**

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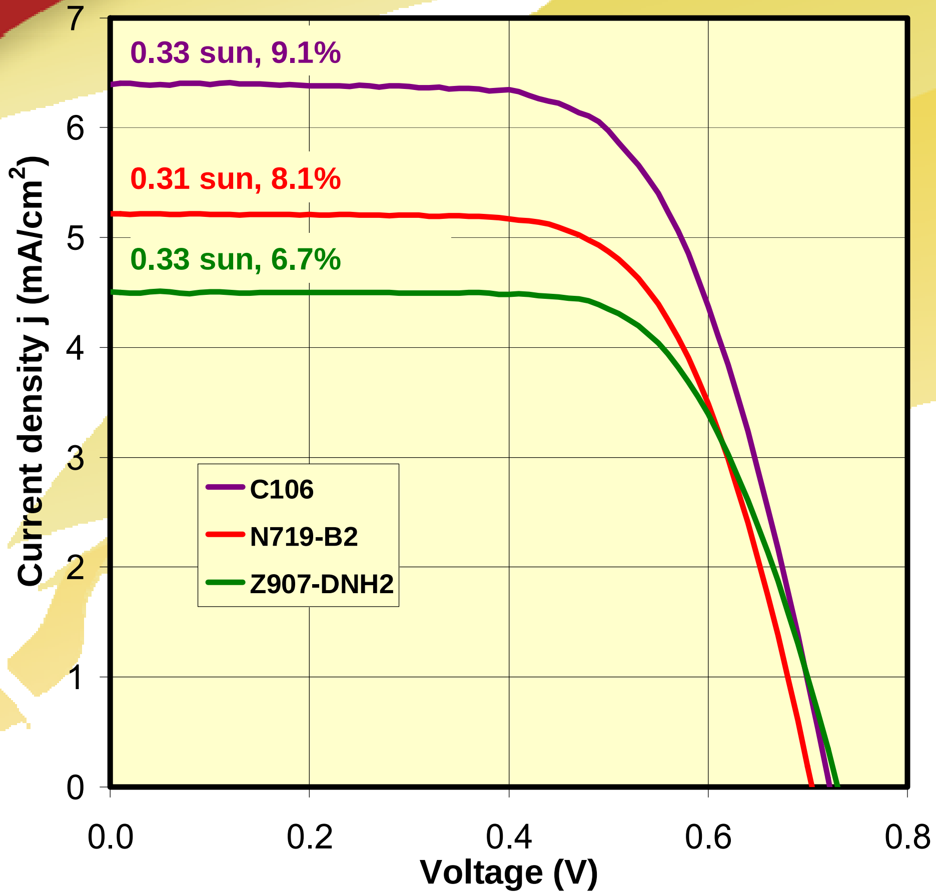
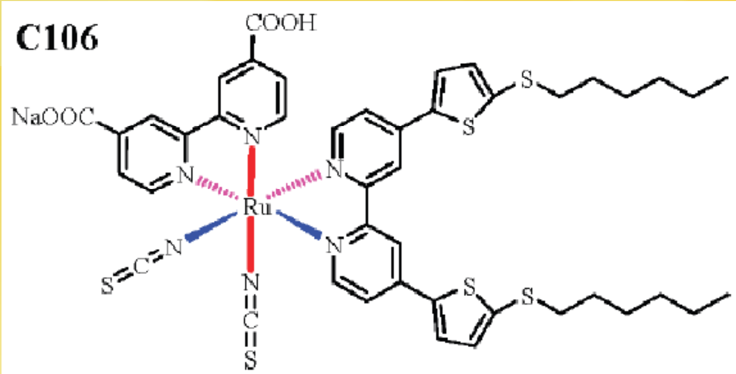
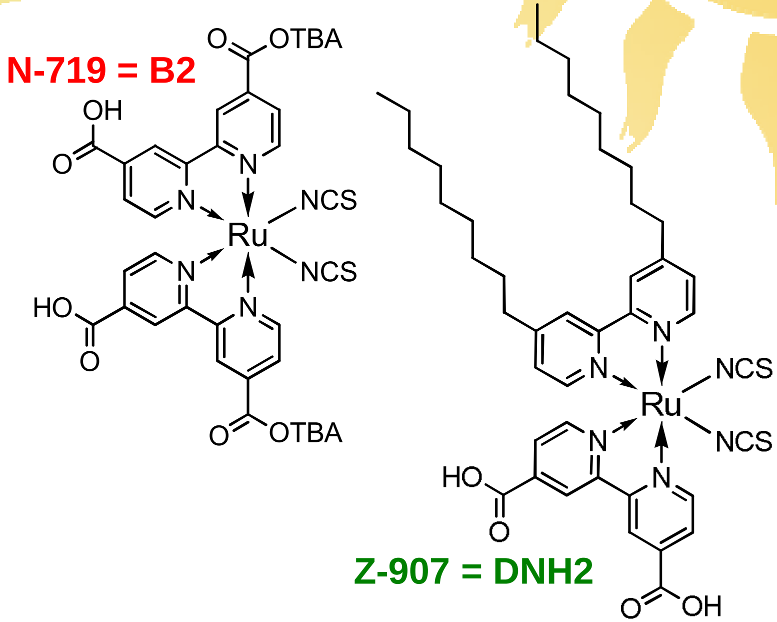
Performance improvement







Highest purity Dyesol dyes

- 10 kg lots for N719 (N3) and Z907
- C106 for in-house use only so far

Performance improvement

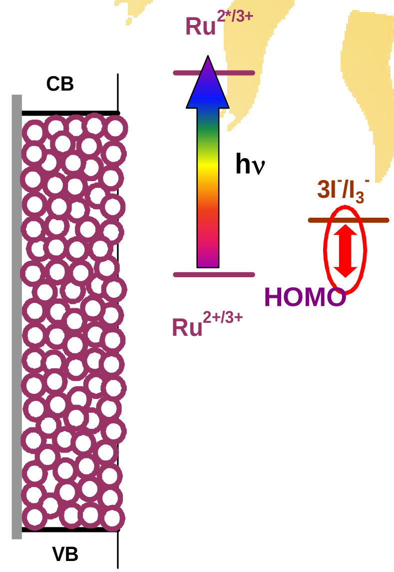
Step 2: (2012-16) **REVOLUTIONARY**

- Better match between dye HOMO and redox system ⇨ V_{oc} 0.9V; and
- Increase of j_{sc} to 24 mA/cm^2: further optimised dyes, conductive transparent substrates, AR layers, optical engineering

  ⇨ **14% for industrial DSC**

  16% for hero cells!
- Faster, better matched redox couple or effective hole transport system (beyond 2016?)

  ⇨ **18% for industrial DSC**



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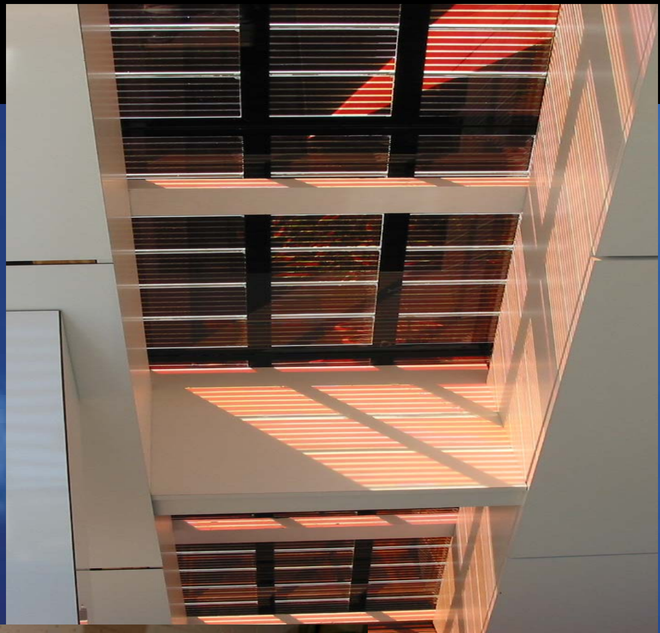
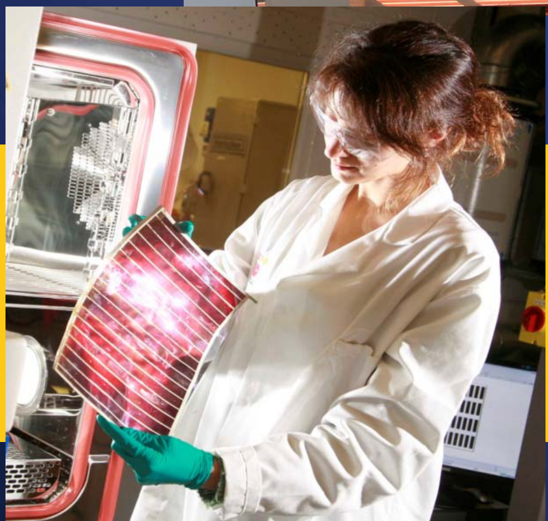
Performance improvement (cont.)

- Optical up-conversion and/or down-conversion
- Alternatively better use of UV through higher bandgap semiconductor





BIPV Market Opportunity

Steel Roofing

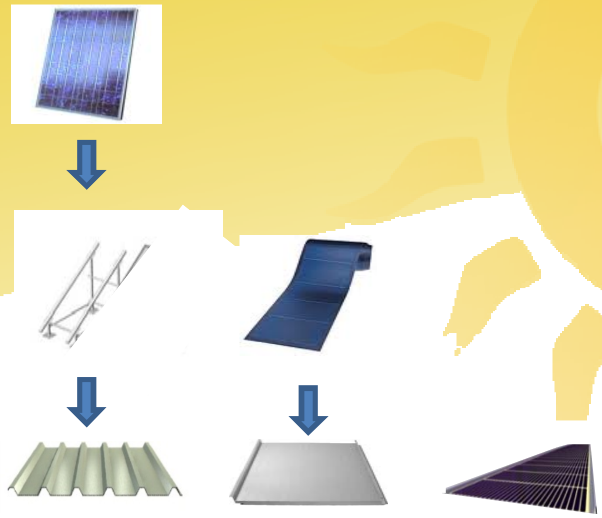
World Coated Steel Market:

- Over 1 Billion square meters per annum, growing at 7-8% p.a.
- Represents market of ~$150 Billion per annum
- Potential for DSC coated steel cladding is 20%, which represents an addressable market of:
  - ~200 million square metres p.a.
  - ~$30 Billion p.a.
- Equivalent to over 10 GW installed per annum, compared to 2007 installations of 2.8 GW

Coil Coating Line

Steel Roof

Benefits of Rooftop Building Integrated PV



Installation	PV		
	Frame	PV	
	Roof	Roof	PV Roof

Materials	Glass/Glass PV	Metal Carrier PV	PV Metal Roof
	Support Frame	Metal Roof	
	Metal Roof		

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Tata-Dyesol JV

Dyesol-Tata Steel ~ BIPV commercialization

TATA STEEL

Objective: establish product, process and supply chain that can be commercialized

Phases:

•**Alpha Phase** (Complete) – Processibility trial at pilot plant ~ 2010 & 2011

–Welsh Government provided £5 million grant towards North Wales pilot-project (total cost $11M split between Dyesol and Tata)

–Produced world's largest dye-sensitized solar cell module:

✓ 6 metres long and 1.8 square meters
✓ Single length rather than cells connected together

–Can produce 300mm x 6000mm panels

•**Beta Phase** – Performance enhancement and cost reduction phase at NW plant ~ 2011 & 2012

–Increased investment to ramp up rate of achieving grid parity

–Expand pilot plant to cater for new processes

•**Gamma Phase** – 25-year life solar roofing product ~ 2013 & 2014

–Install another roof manufacturing line for 25 year life solar panels, thus enabling ~20% of Tata' roofing steel (20 million m^2 p.a.) to be solar.

Buildings as Power Stations

- Tata supplies > 100 million m^2 of roof and wall cladding
- Large buildings approach 100,000 m^2 in area
- Most of the roof area is under-utilised
- Vision is to **Functionalise** the whole roof surface

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Glass Façade & Dyesol-Pilkington JV

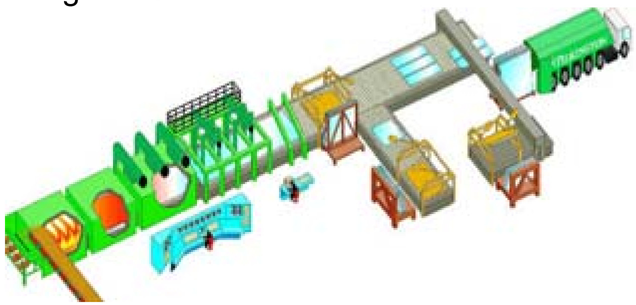
World Flat Glass Market:

- Over 6 Billion square metres per annum, growing at 5% p.a.
- Building applications are roughly 70% of market, or 4.2 billion square metres per annum
- Breakdown of 60%/40% for view and non-view; DSSC addressing non-view market at this stage
- Represents an addressable market of:
  - 1.7 Billion square metres p.a.
  - $25 Billion per annum

Dyesol-Pilkington Joint Venture:

PILKINGTON

- Formed *Dyetec Solar*®, 50/50 JV with Pilkington, a leading multinational glass company.
- Objective is to industrialise technology for mass manufacture of glass-based BIPV, building-applied photovoltaic (BAPV) and automotive-integrated photovoltaic (AIPV) products.
- Received US$1 million grant from Ohio Third Frontier Fund to commence first phase of Toledo based large panel glass project and possibilities for ongoing funding
- Completed equipment installation at Toledo project in August 2011



DSSC Glass Manufacturing Line

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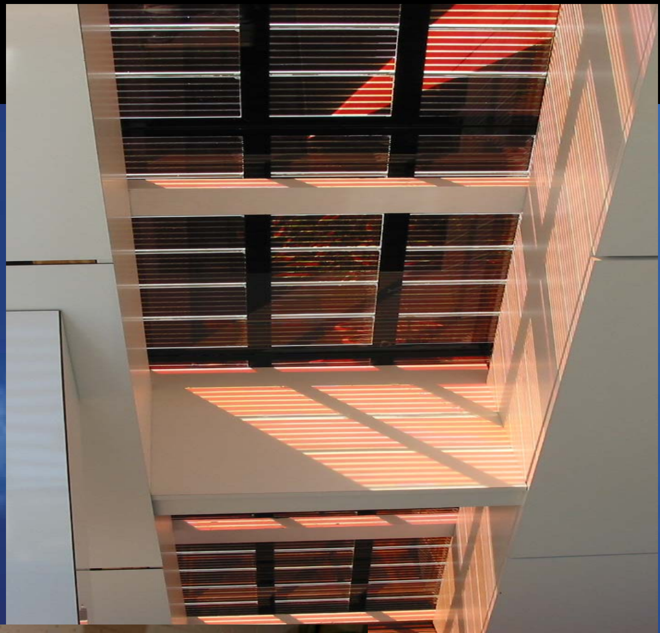
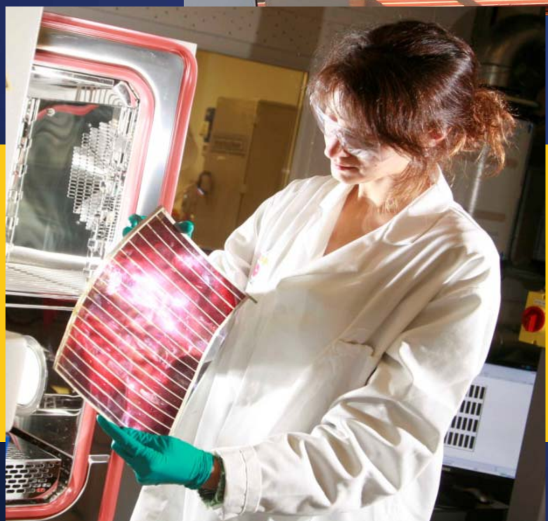
DYESOL™

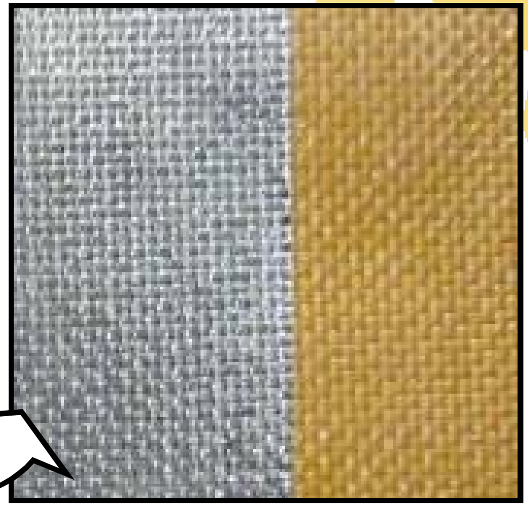




Clothing, automotive & accessorises

Texstile substrates as WE

Realization of a DSC device using at least a Textile fabric



- good flexibility
- Sheet resistance ≤ 2 Ω /sq
- Electrolyte Impermeable

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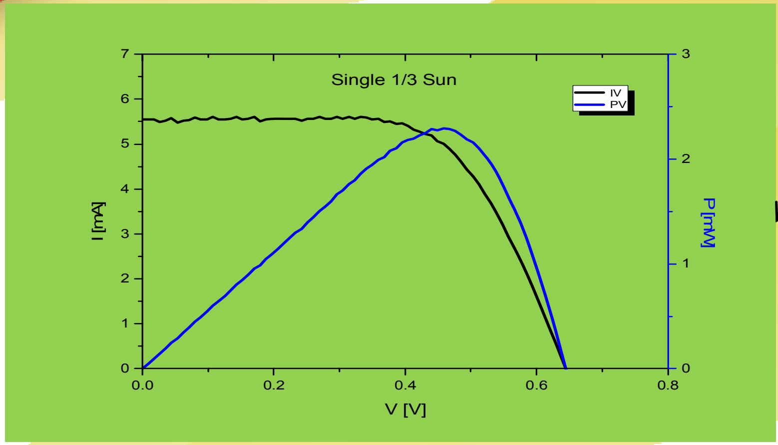
Textile PV, Dyesol Italia within Dephotex



"Fresh" cell efficiency 1,15% at 1/3 SUN

Large Area about 6 cm^2 !!!

After 2 weeks stabilization period

Irradiance (W/m^2)	Voc (V)	Isc (mA)	P. max (mW)	Vmax (V)	Imax (mA)	FF (%)	Area (cm^2)	Ef (%)
1000	0.79	30.6	6.59	0.37	17.6	27.4	5.72	1.15
500	0.75	15.3	4.53	0.42	10.7	39.3	5.72	1.59
200	0.71	5.7	2.19	0.46	4.8	54.1	5.72	1.92

Measurements performed by CENER under STC

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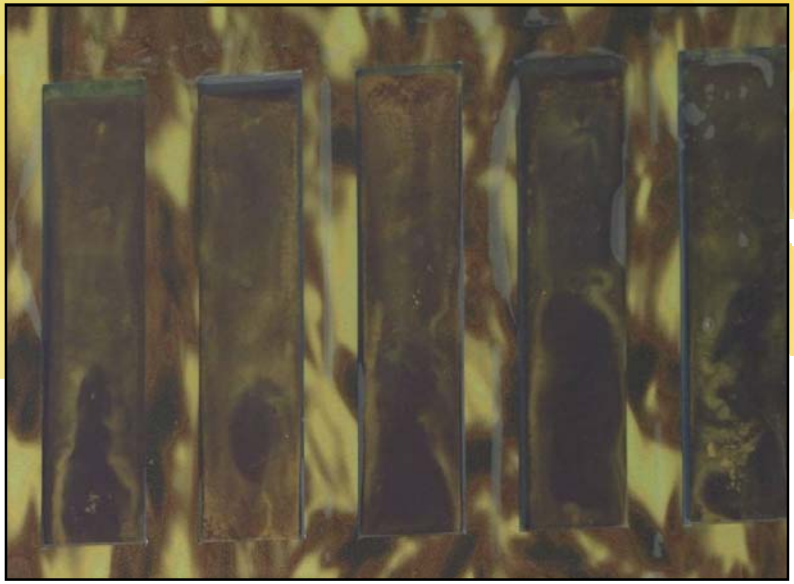
Textile integration



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Thank You!

Photographer - Thomas Bloch