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Challenges in solar energy conversion

Professor James Durrant

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& Deputy Director, Energy Futures Lab

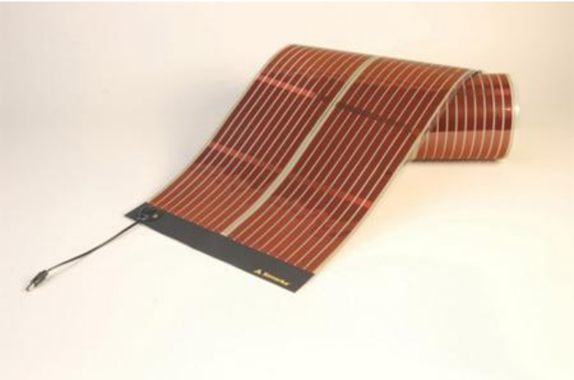
www3.imperial.ac.uk/people/j.durrant

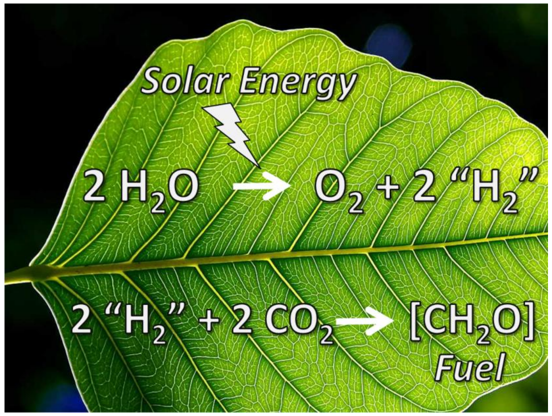
The Centre for Plastic Electronics

energy futures lab

Lecture Content

- *Solar*
- *Imperial's solar programme*
- *Molecular photovoltaics*
  - *Technology opportunity*
  - *Science challenges*
- *Solar to fuels*





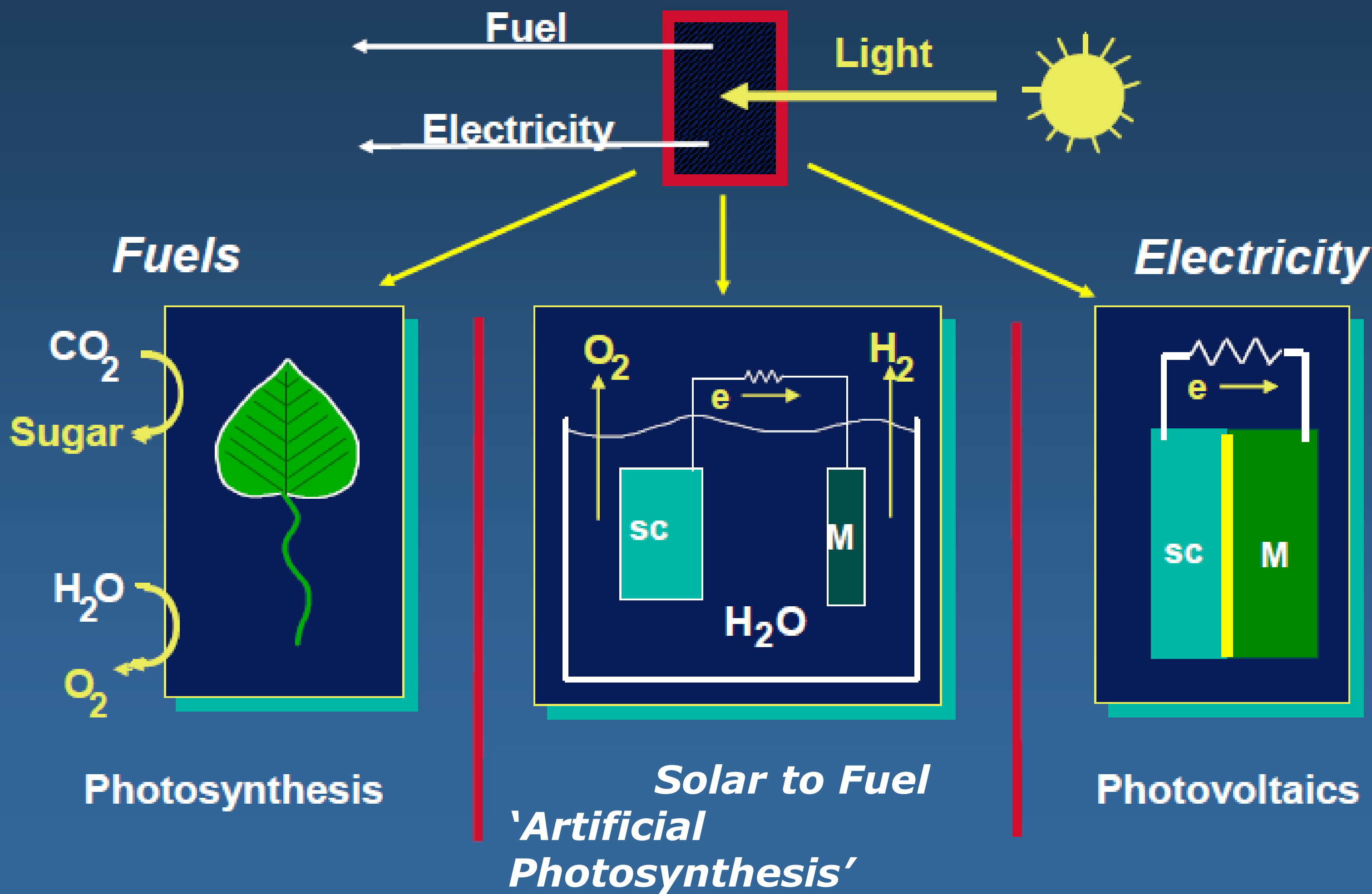
Solar Energy Potential in India

Full Sun: 1000 W / m^2

- *Average density over the year:*
  - *India: ~ 250 W / m^2*
  - *UK: ~ 100 W / m^2*
- *Typical solar cell efficiency 15%:*
- *In India need 3 m^2 per person to supply average electricity demand (compared to 40 m^2 in UK).*
- *Gives100 km^2 to supply national demand*

100 km^2

Energy Conversion Strategies



Adapted from Lewis: "Powering the Pla

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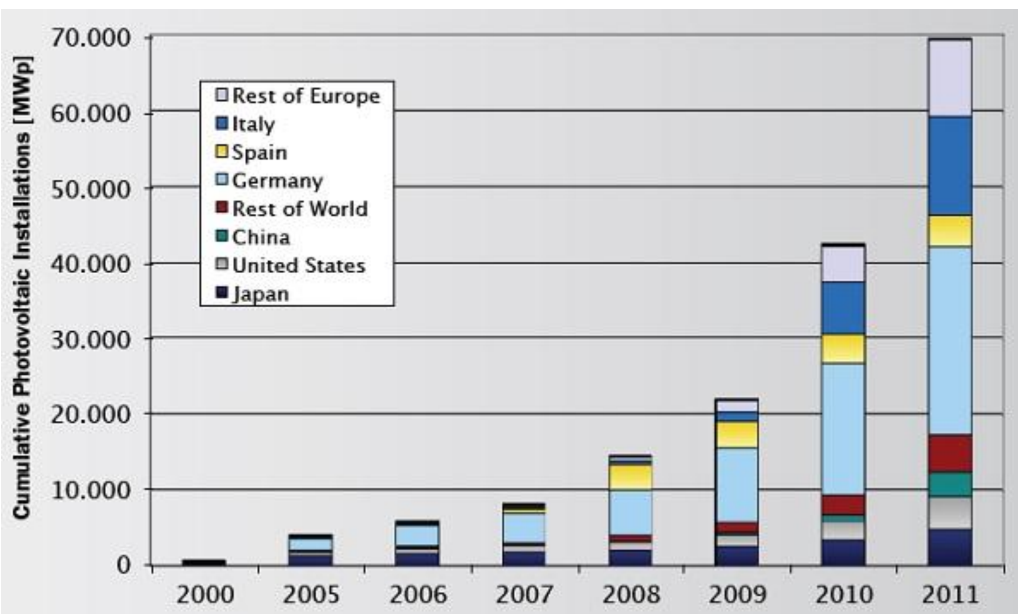
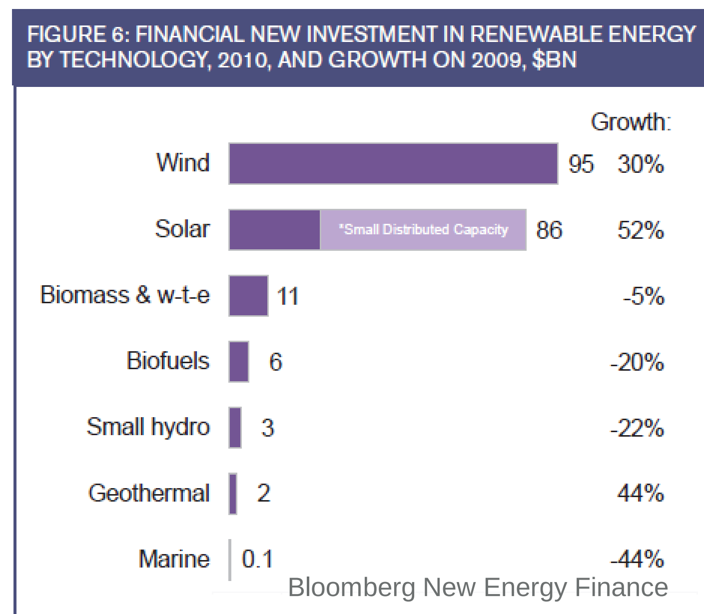
Photovoltaics





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Photovoltaic Technologies

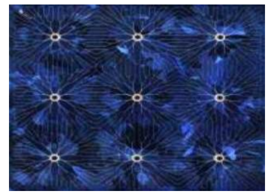
Courtesy : bp solar

crystalline silicon (mono & multi)

This will be the PV-backbone technology and leader of the BIPV sector.

module efficiency:

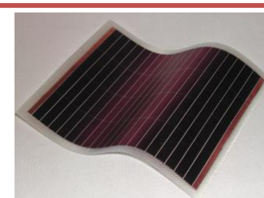
13% ········→ **20%**



thin film: a-Si, CdTe, CIGS

Viable competitor in BIPV and roll-to-roll process for flexible substrates.
module efficiency:

9% ········→ **15%**

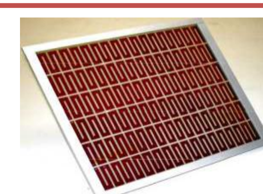


Dye cell and organic

Initially niche market oriented, but breakthroughs could push field towards mass power generation.

module efficiency:

4% ········→ **10+%**



new concepts

2000 **2010** **2020** **2030**

$0.30/kWh

$0.05/kWh

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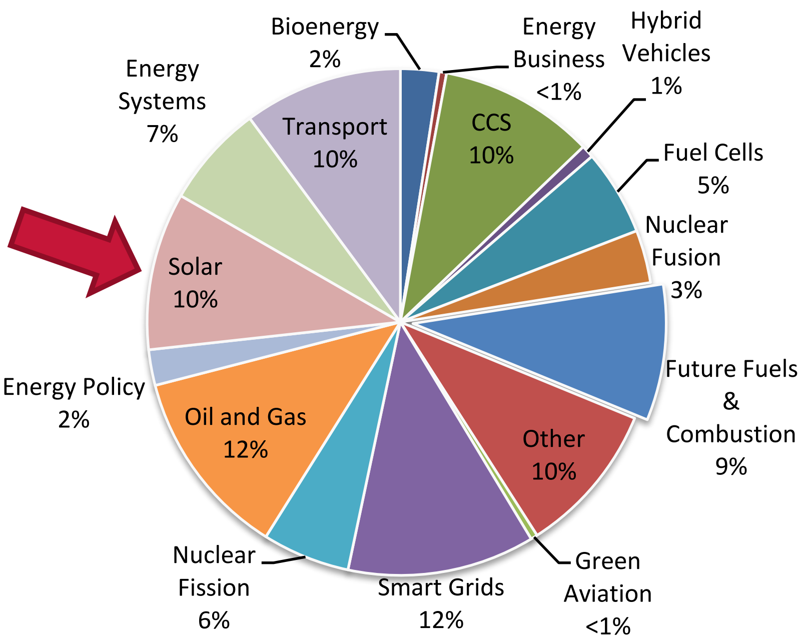
Imperial's Energy Programme: The Energy Futures Lab

energy futures lab

-Achieved Institute Status in 2009

-Integrates research, training and outreach across Science, Engineering, Policy and Business in the energy sector



Imperial's Energy research income

-Imperial College has a research budget of £30M pa for energy research

-Around 370 energy projects, and 600 research staff and students undertake energy research.

- Largest university energy portfolio in the UK

-One third of funding from industry.

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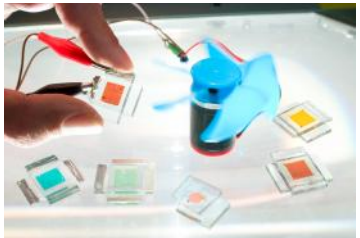
The Imperial Solar Network

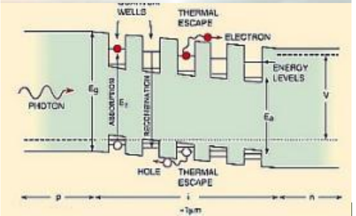
- Largest solar energy research program in UK
- Over 120 research staff and students in 8 departments supported by ~ £6m funding p.a.
- Partnerships through EPSRC, TSB & EU funded projects, including 10 projects > £1m each.
- Strong industrial partners engagement including two startups:

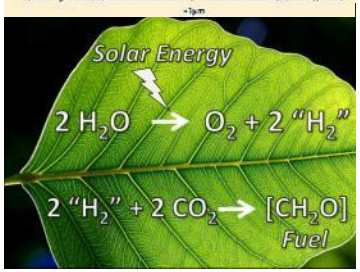
SolarPress Solar Power For Everyone

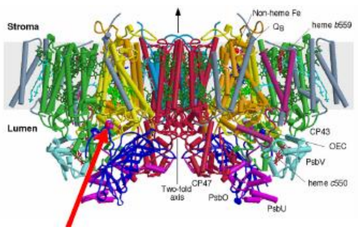
QuantaSol®

Network Leaders: Prof. James Durrant & Dr Ned Ekins-Daukes
Website: www.imperial.ac.uk/solar









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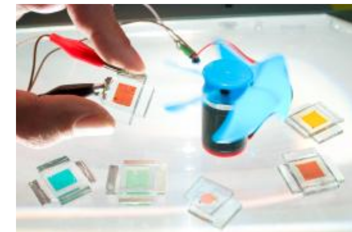
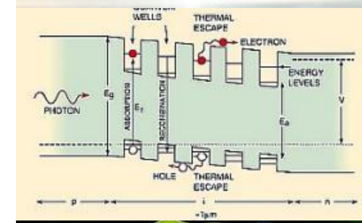
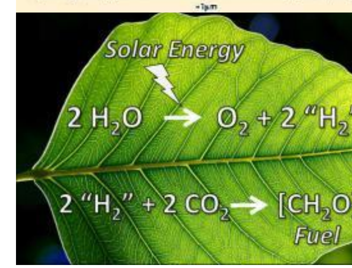
Solar Network: Research Strengths

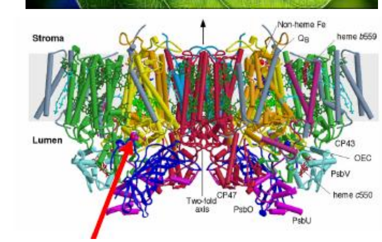
- Photovoltaic Technologies
  - **Organic & dye sensitised photovoltaic cells ('Molecular Solar Cells')**
  - New concepts for high efficiency photovoltaic devices
  - PV systems and environmental analysis
- **Solar Fuels: The Imperial Artificial Leaf initiative**
  - **Solar hydrogen generation**
  - CO_2 reduction
- Molecular Processes of Photosynthesis

The Centre for Plastic Electronics









Imperial collaborations with India in Solar

- Analysis of atmospheric aerosols on Concentrator PV in Rajastan

  Ned Ekins-Dawkes (Imperial) + IIS Bangalore + Daido Steel Japan
- Impact of PV installation on indian grid.

  Bikash Pal (Imperial) + IIT Kharagpur
- Low-carbon development pathways in India to 2050

  Simon Buckle & Ajay Gambhir (Imperial) and IISc Bangalore
- Assessment of potential of PV for rural electrification and carbon emissions mitigation in India

  Jenny Nelson, Rob Gross (Imperial) + IISc Bangalore
- Advancing the Efficiency and Production Potential of Excitonic Solar Cells

  James Durrant, Brian O'Regan, Saif Haque (Imperial) plus 6 Indian insitiutes plus 4 UK universities plus 6 companies (£5m)

Imperial's Quantum of Sol at Techfest IIT Bombay 2010.

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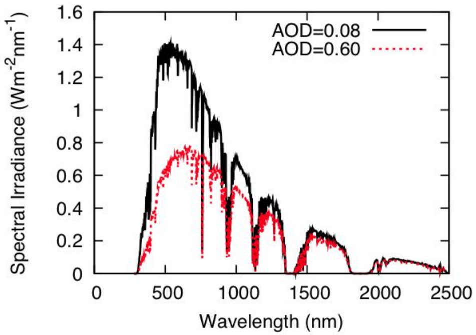
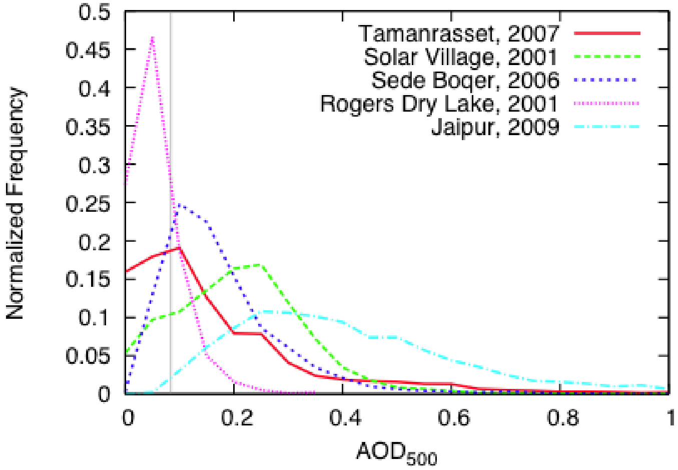
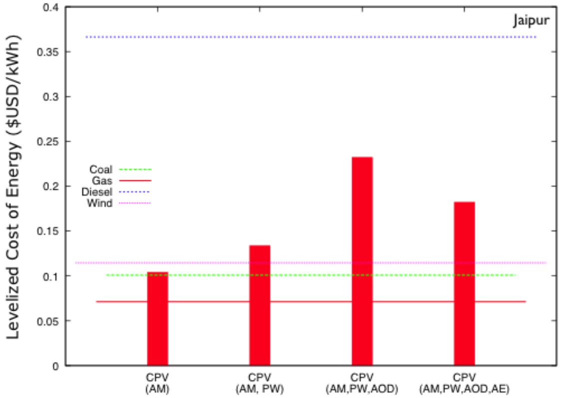
Concentrator PV in India: Impact of aersols





Sheela K. Ramasesha, Divecha Centre, IIS Bangalore.
N.J.Ekins-Daukes, Imperial College London,
Kenji Araki, Daido Steel, Japan.



Project : Stability and Performance of Photovoltaics

- **Sponsors :**

EPSRC Engineering and Physical Sciences Research Council

ESPRC, UK

Department of Science & Technology Ministry of Science & Technology

DST, India

- **Partners :**

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IIT-Kharagpur

  – Principle Investigators : Dr.Bikash C Pal (ICL), Dr. Chandan Chakraborty (IIT)

- **Research Objectives :**
  – Modelling and Control of Utility Scale Solar Plants in Grid Integrated Operation (ICL).
  – Impacts of large integration of Solar on Power Systems stability and voltage control (ICL).
  – Solar inverter topology design and PV module laboratory test set up (IIT).

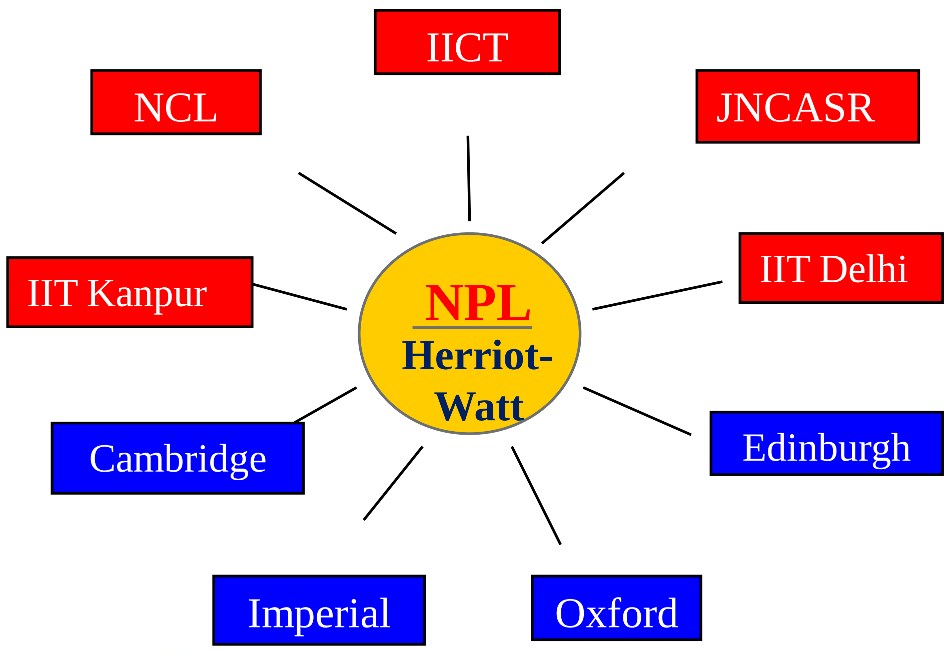
- **Collaborative activities :**
  – Asansol (West Bengal) Solar Power Plant Visit.
  – Practical data collection & study of operational issues.
  – Joint research dissemination.

Imperial and IIT researchers at Asansol Power Plant

Control & Power Research Group

UK / India Programme on Molecular Solar Cells

Advancing the Efficiency and Production Potential of Excitonic Solar Cells (APEX)



£5m over 3 years

Industrial partners

SOLAR ENERGY CENTRE

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Solar Network: Research Strengths

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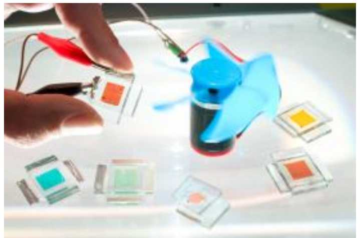
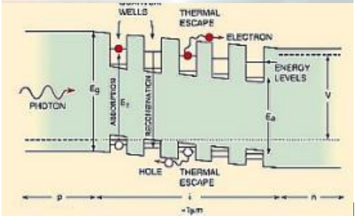
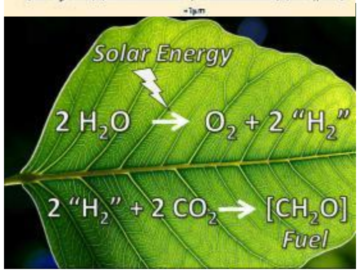
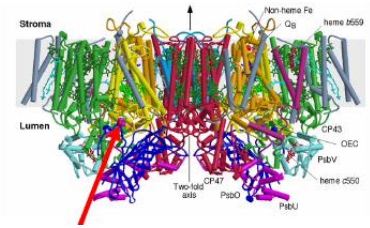
  - CO_2 reduction
- Molecular Processes of Photosynthesis









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Molecular photovoltaic technologies at Imperial

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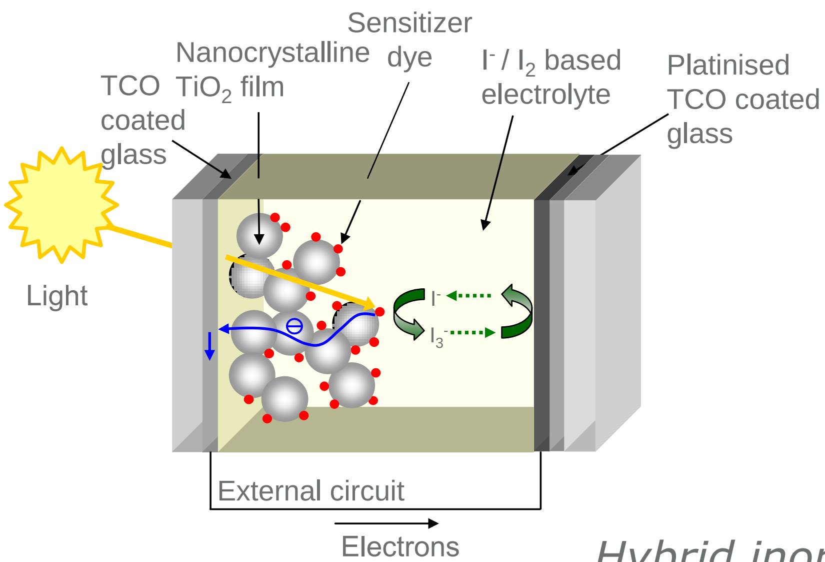
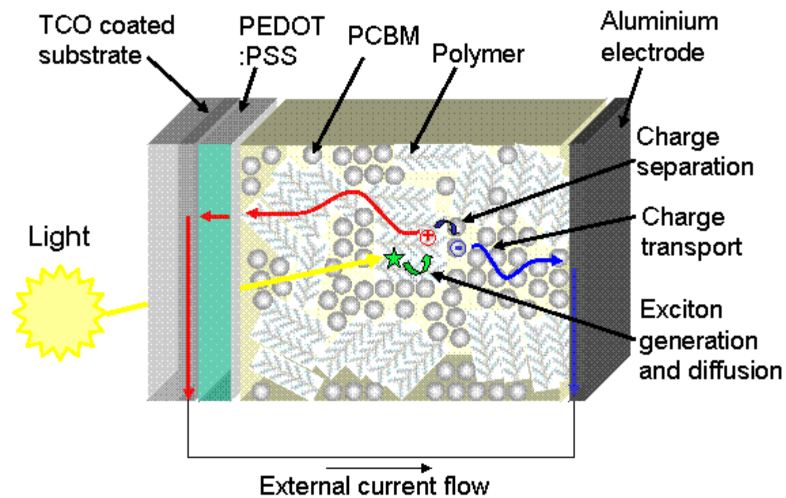
Dye sensitized solar cells

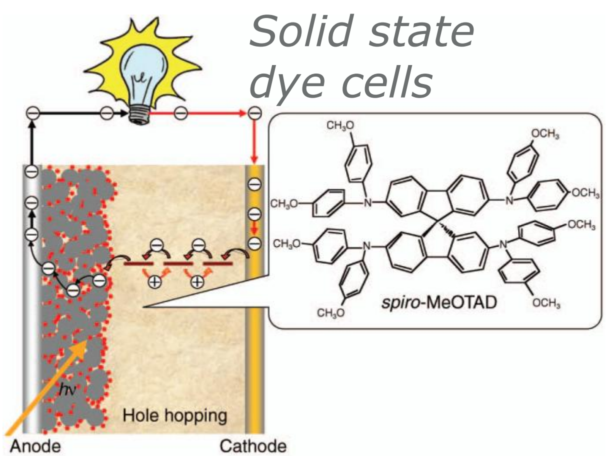


Polymer/Fullerene solar cells

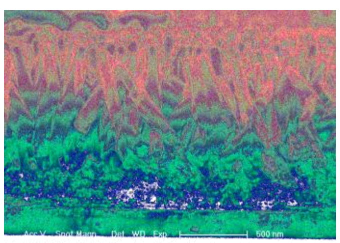


Hybrid inorganic / organic solar cells

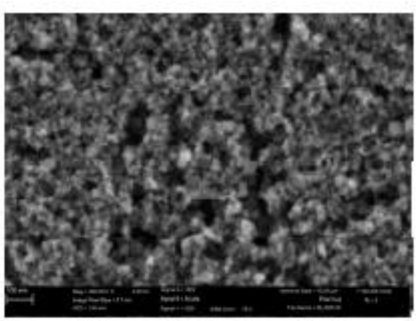
Solid state dye cells



ZnO Nanorods



CdS mesoporous Networks



Nelson, Haque, Riley, Ryan, McComb, McLachlan

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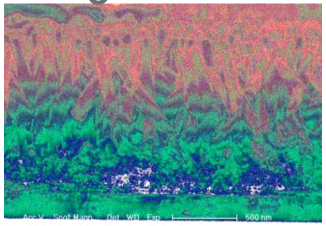
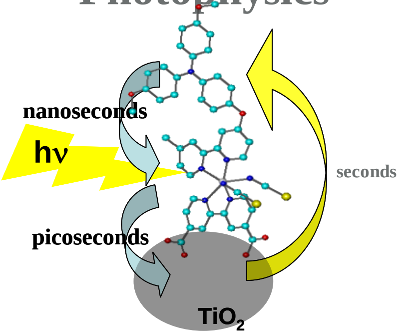
Imperial Molecular PV Research

Hybrid organic/ Inorganic devices



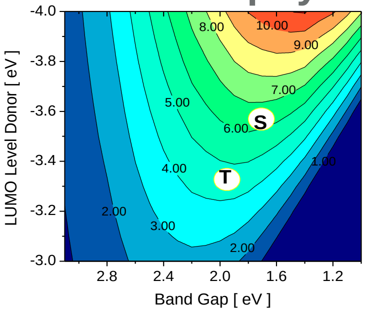
ZnO nanorods

Photophysics



Interfacial electron transfer dynamics

Device physics



Device efficiency modelling

Processing

- 7 new academic appointments in last 4 years – 4 with industrial experience
- >80 researchers in 12 research groups ranging from materials synthesis to module processing .
- Leading expertise in materials and device characterisation and modelling
- Key element of EPSRC funded Doctoral Training Centre in Plastic Electronics
- Broad range of commercial partnersincluding lead partner in Carbon Trust funded OPV start up Solar Press Ltd.

SUMITOMO CHEMICAL · PLEXTRONICS · MERCK · PILKINGTON First in Glass · G24 INNOVATIONS · TATA STEEL · SOLVAY · SolarPress Making solar power affordable

Technology Development for Molecular PV

Efficiency

Cost

Stability

Increasing Market Potential

Light weight
Flexible
Semi-transparent

Demonstrator Applications

'Niche' Markets
Consumer Products
Off-grid in Developing World

Mainstream Grid connected generation
BIPV

2010

2012

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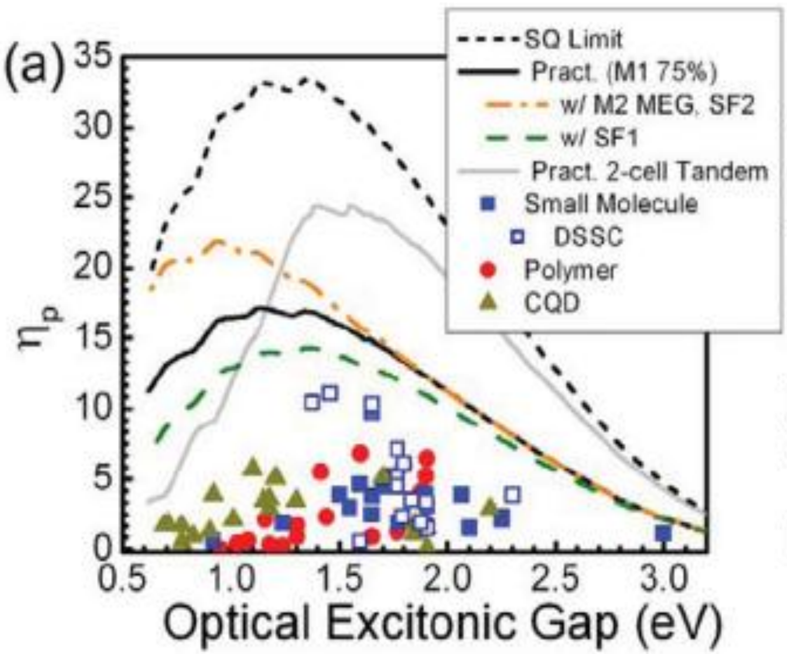
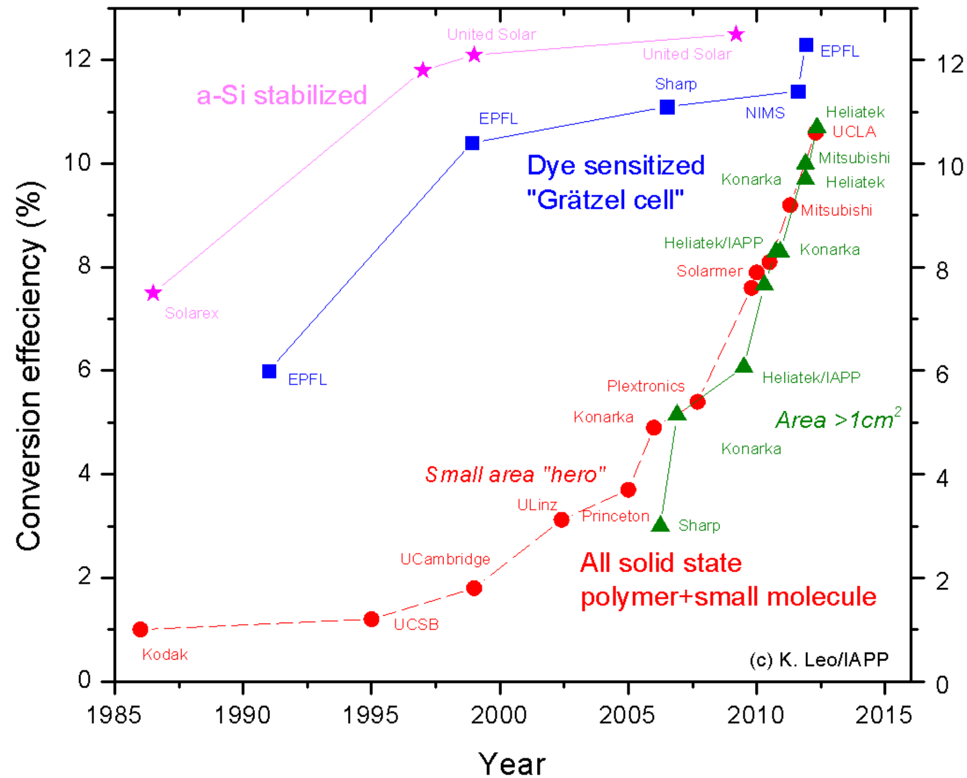
Efficiency



Lunt et al. Adv. Mat 2011



Current Achieved Efficiencies:

- *~ 10 % for solid state devices under AM1.5*
- *~ 12% for DSSC with liquid electrolytes under AM1.5*
- *Modules: 3 – 8% depending upon compromise with stability and cost*
- *All work better at low light levels / higher temperatures – so produce significantly more power than Si cell with same efficiency rating.*

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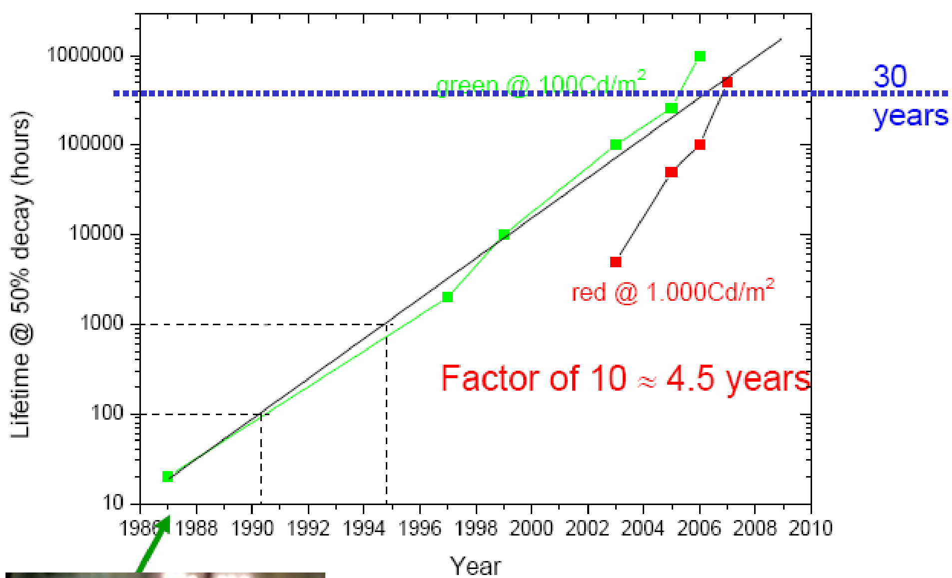
Stability Potential

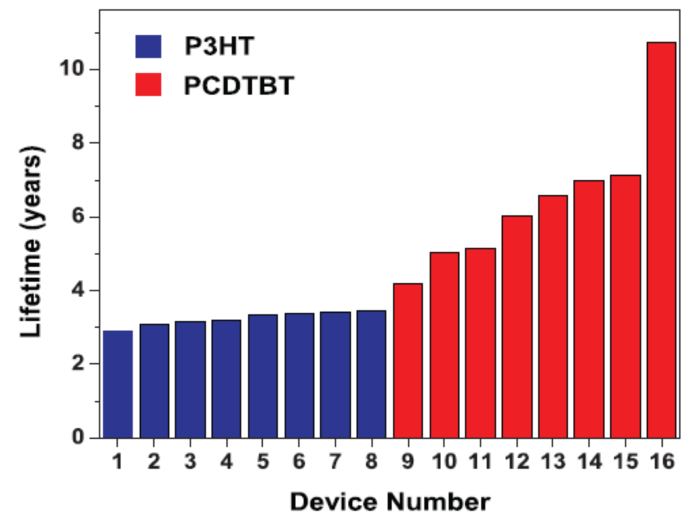
Potential



OLED stability

Current Reality

OPV stability

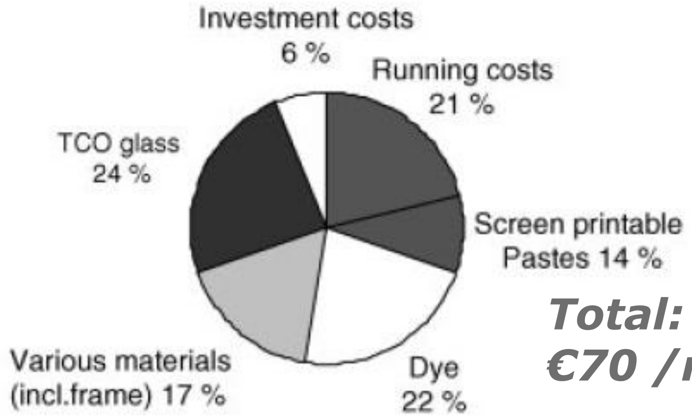


Peters et al. Adv. En. Mat. 2011

Potential: > 20 years
Current reality: 1-5 years depending upon encapsulation

Cost

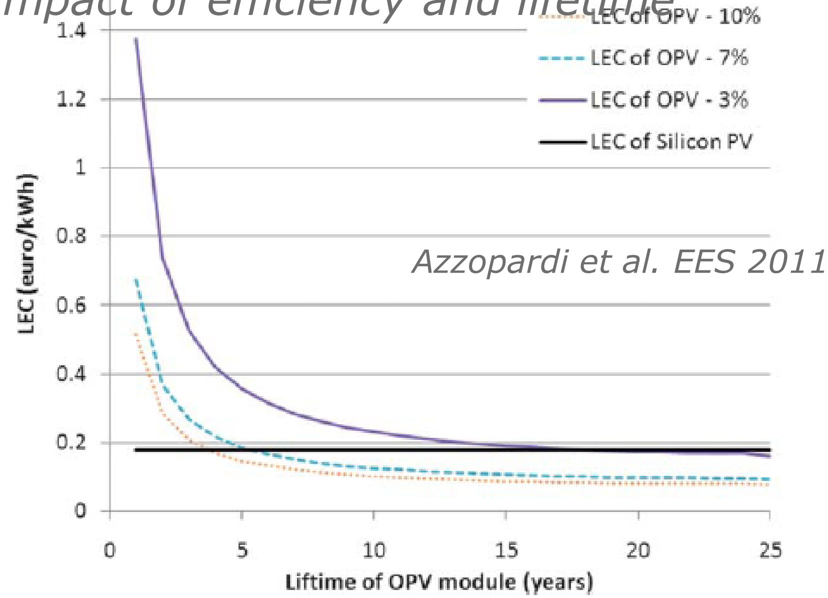
Typical analysis of DSSC manufacturing cost:



Total: €70 /m²

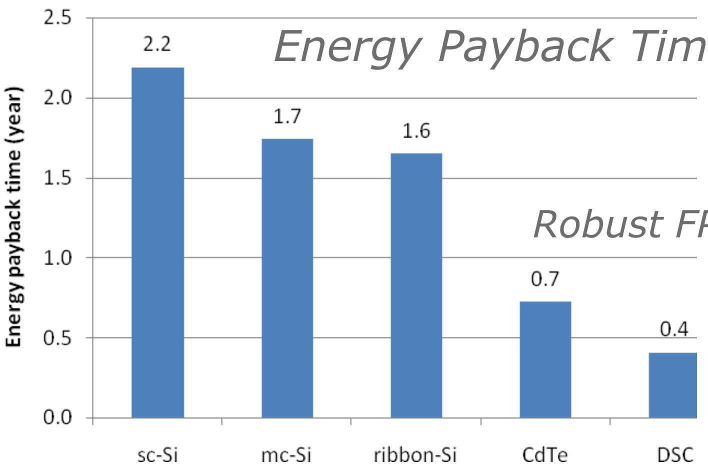
Kroon et al. Prog.Photovolt. 2007

Electricity cost:
The impact of efficiency and lifetime



Azzopardi et al. EES 2011

Energy Payback Time



Robust FP7 report

Potential:
< €0.5 W-p for both DSSC and OPV
Current reality: *Cost effective for limited applications*

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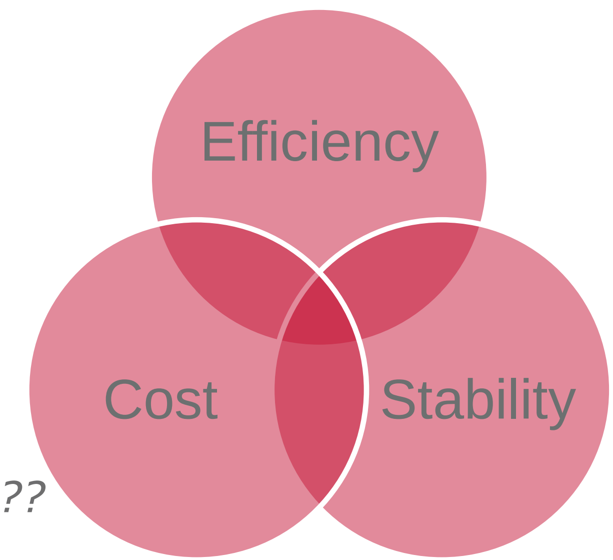
Opportunity Summary for Molecular PV

>15% champion cells
>10% modules

Higher at < 1 sun

Reasonable to expect over next 3 years



< €0.2 Per kWhr ???

Lifetimes > 10 years

Plus specific market attributes:
Solution processible, low temperature processing
Flexible, light, semi-transparent, coloured, low capital-expenditure.

Molecular solar cell commercialisation in the UK

Dye sensitized solar cells

Organic Solar Cells

G24i 's dye sensitized solar cells: more efficient than a-Si for indoor applications

G24 INNOVATIONS

TATA STEEL

SolarPress
Making solar power affordable

molecular solar

Eight19

Ossila
enabling organic electronics

PILKINGTON

MERCK

Imperial College London

TATA Steel's UK PV programme

TATA PV accelerator production line, North Wales

Partnership with SPECIFIC IKC, Swansea Uni, Imperial etc.

CIGS integrated roofing sheets

Opportunity:

- TATA UK produces 200 km^2 a year of painted steel building cladding.
- If 10% of this was 10% efficient solar cells – equivalent to building one nuclear power plant every year.
- Molecular (and other) PV technologies offer potential to integrate PV fabrication with existing TATA roll to roll fabrication under ambient conditions

TATA Sustainable Building Envelope Shotton, North Wales

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Polymer / Fullerene Solar Cell Research at Imperial

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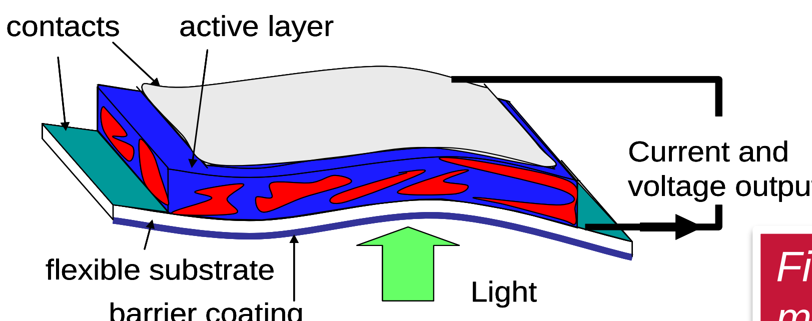

Film formation a
materials charac

Fabrication
Characterisation

sics

Nanomorphology

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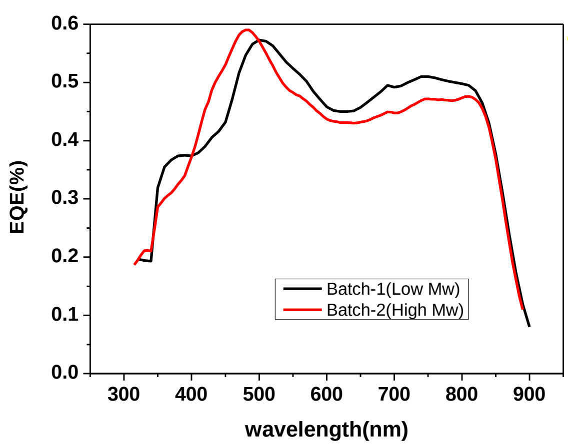
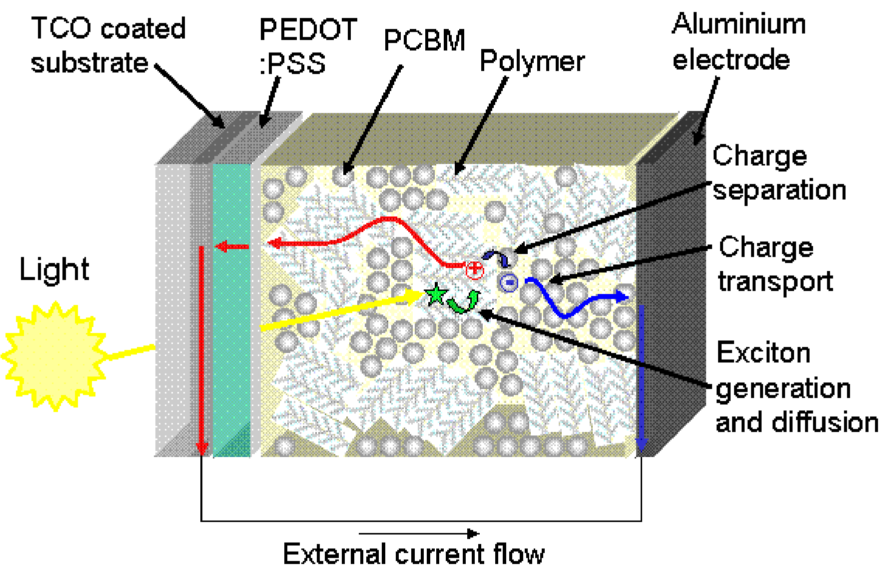
Organic solar cells

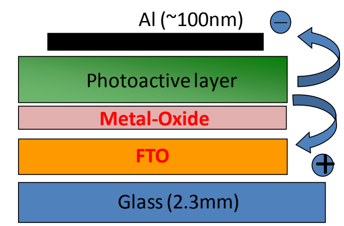
Photoactive layer: efficiency

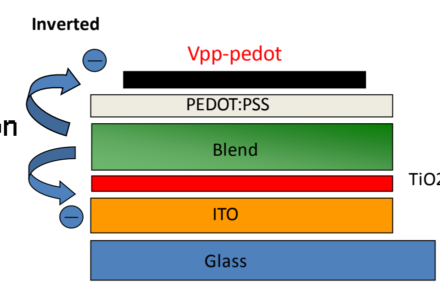
Electrodes: Cost and Stability

DPP-TTT









McCulloch et al JACS 2011

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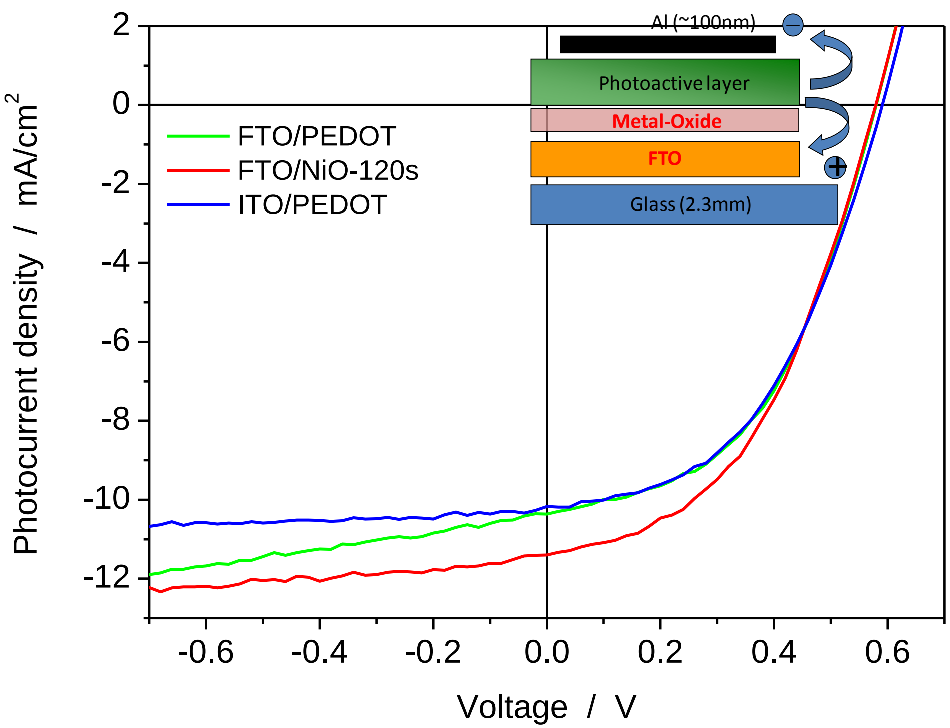
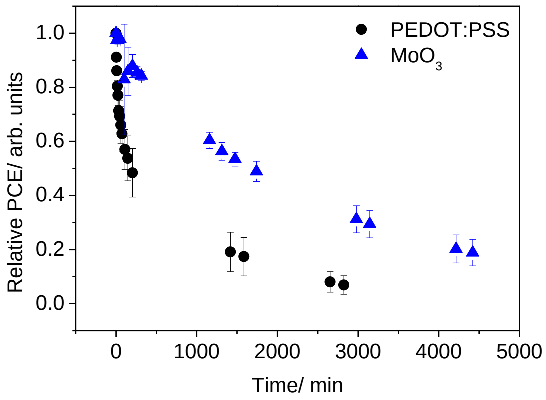
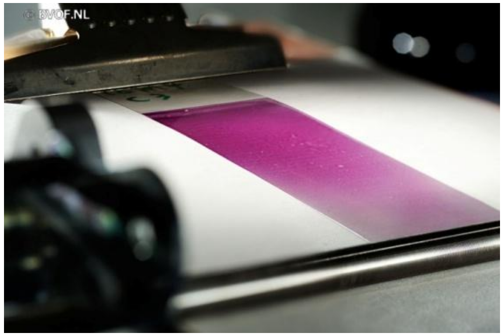
Processing, cost & stability



Stability test under 70% humdity, unsealed cells





Wire Bar coating

Fabrication of OPV devices without ITO (high cost) and PEDOT:PSS (unstable in air)

Natalie Singelin, Donal Bradley, Jenny Nelson, Saif Haque

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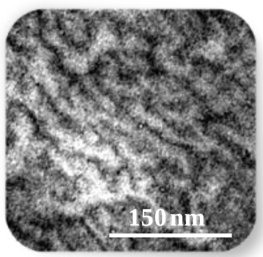
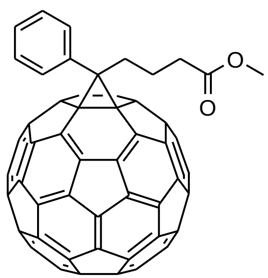
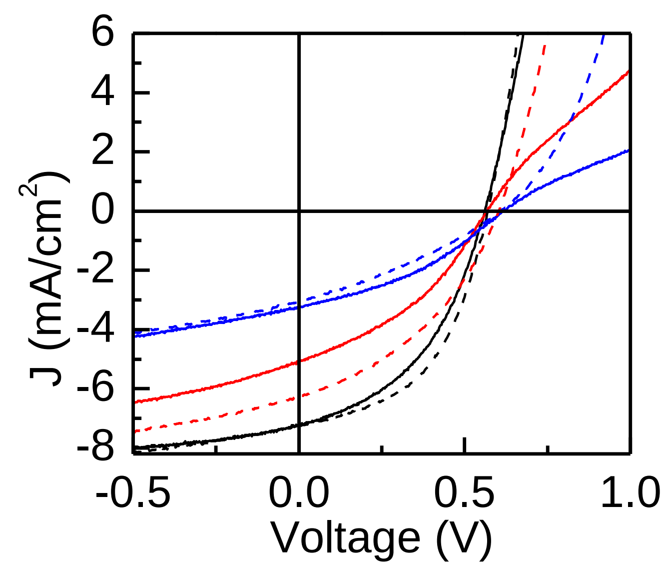
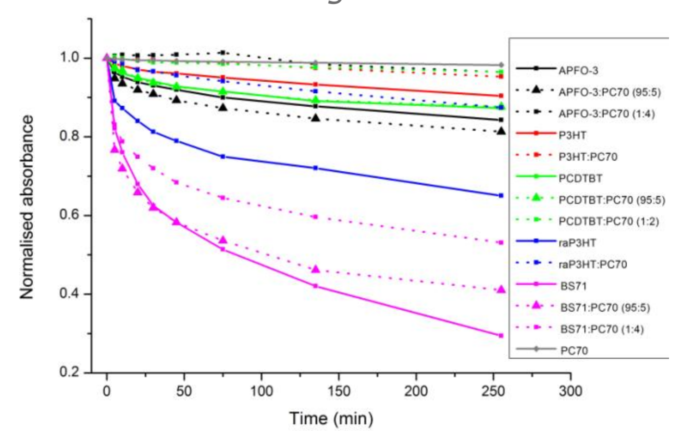
Photoactive Layer Challenge
Molecular Structure : Device Function Relationships



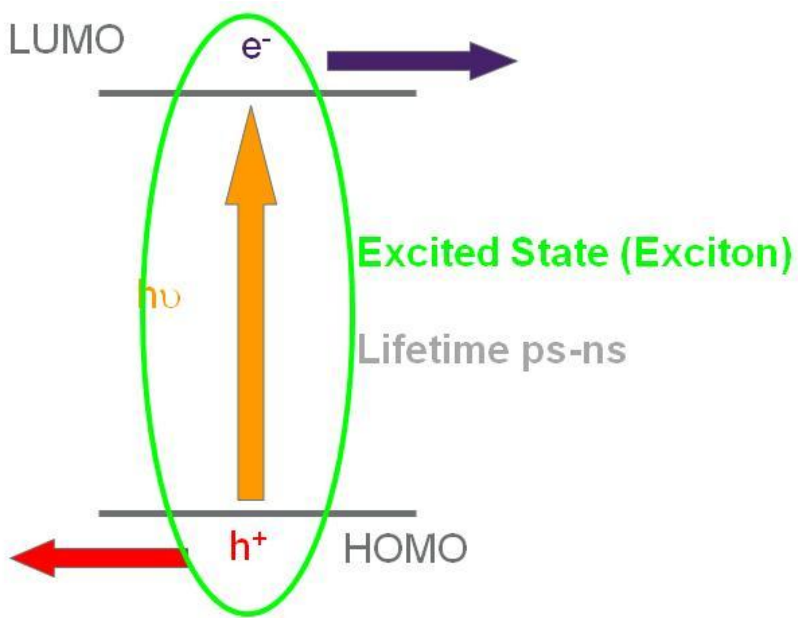




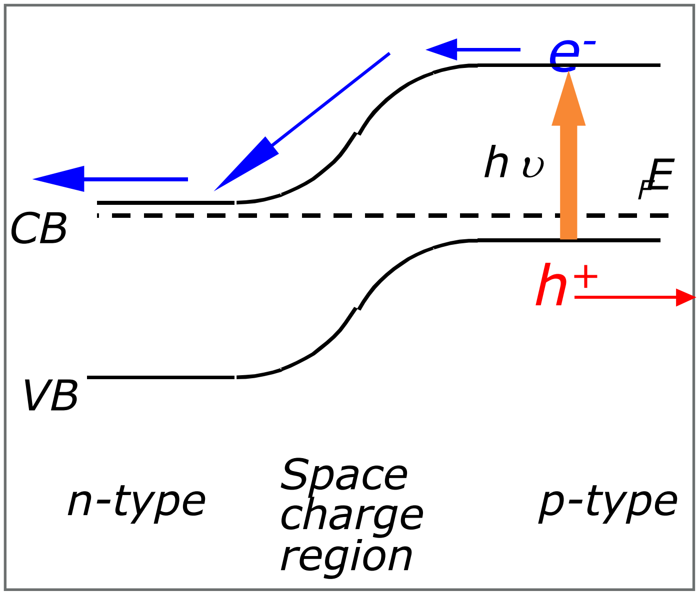
Accelerated degradation studies



Charge Photogeneration in Molecular Materials



silicon solar cell



Spatial separation of the photogenerated electrons and holes requires overcoming their coulomb attraction:

$$V = \frac{e^2}{4\pi\varepsilon_r\varepsilon_0 r}$$

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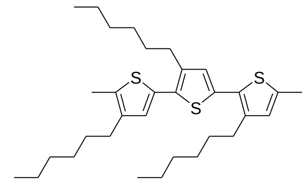
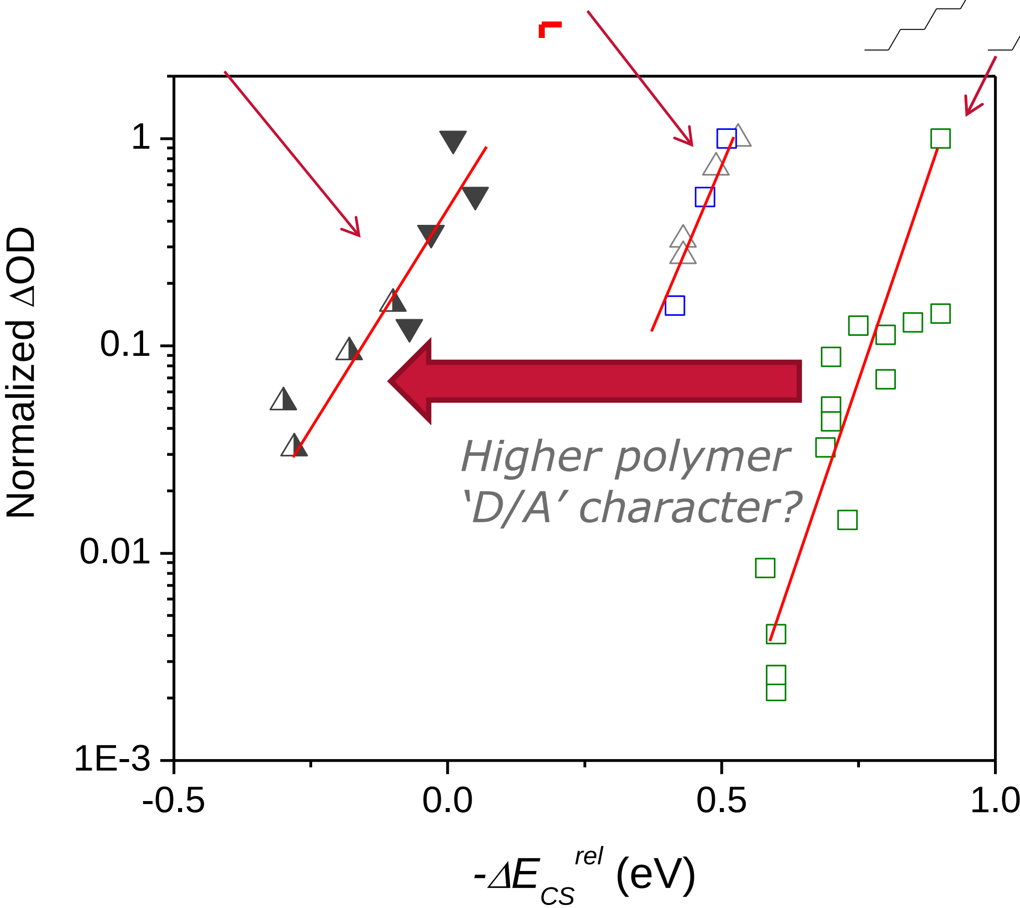
Charge separation: overcoming the coulomb binding energy

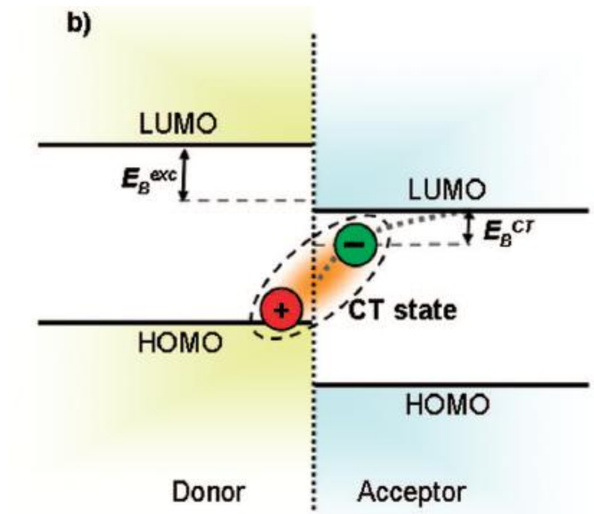
Safa Shoaee





Yield of Dissociated Charges

Energy offset driving charge separation



Key challenge:
How to avoid formation of bound interfacial charge transfer states

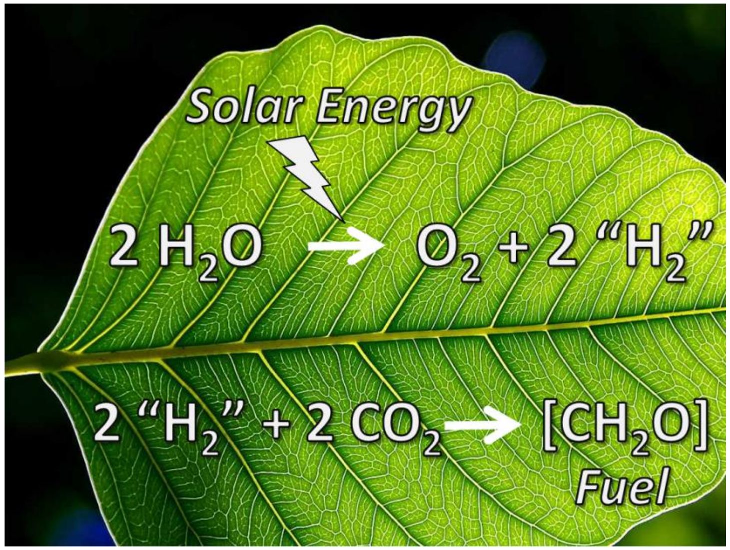
Clarke and Durrant Chem Rev 2010

Imperial College London

Solar to Fuels

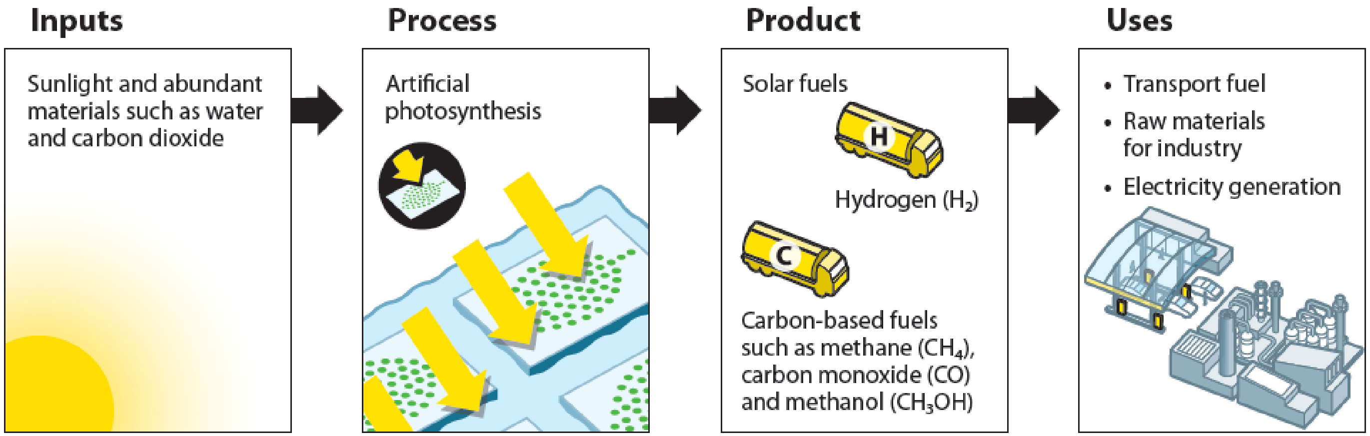
Renewable fuel synthesis

Storage of solar energy



www.rsc.org/solarfuels

Artificial photosynthesis pathway from sunlight to fuels



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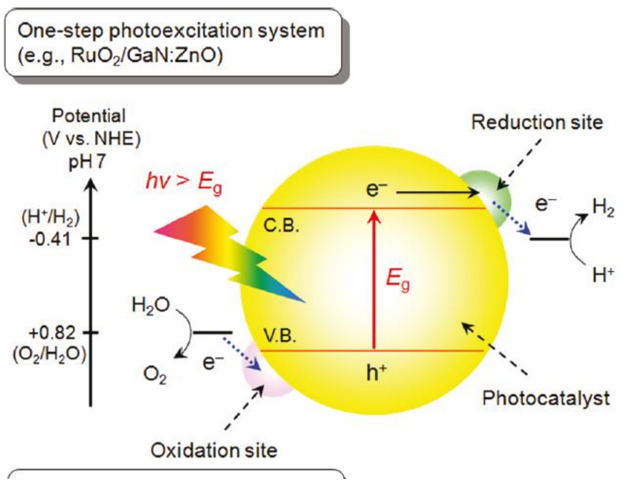
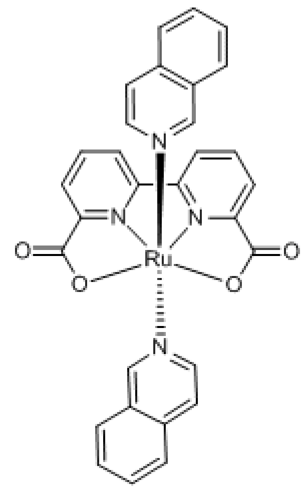
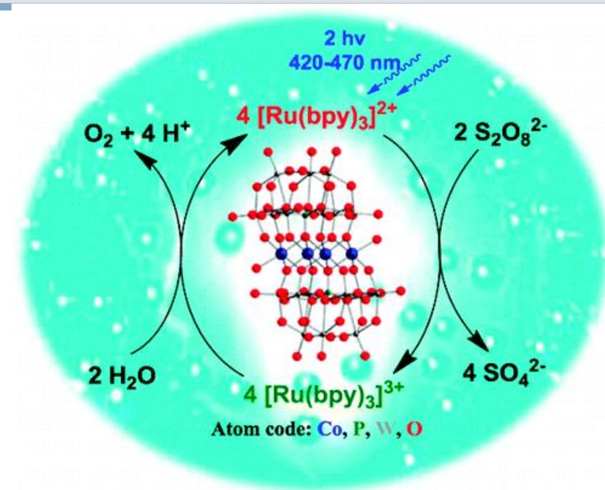
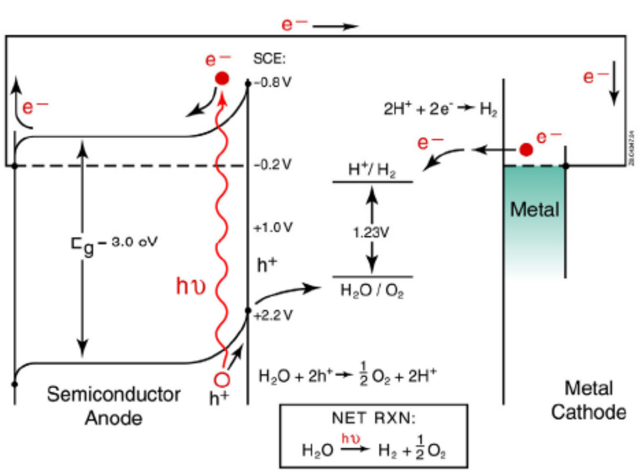
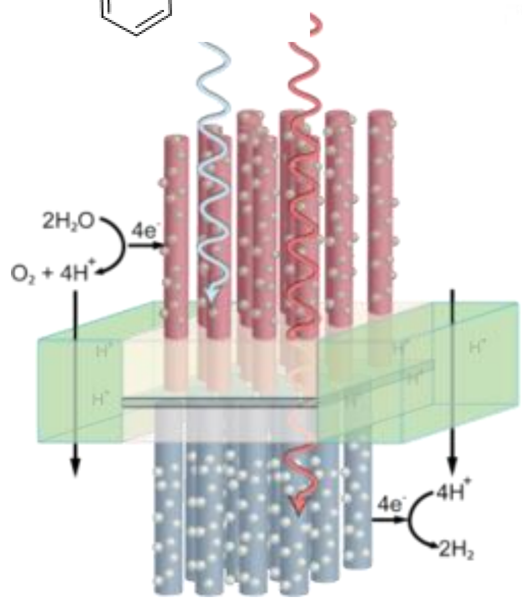
Artificial leaves for water photolysis.......

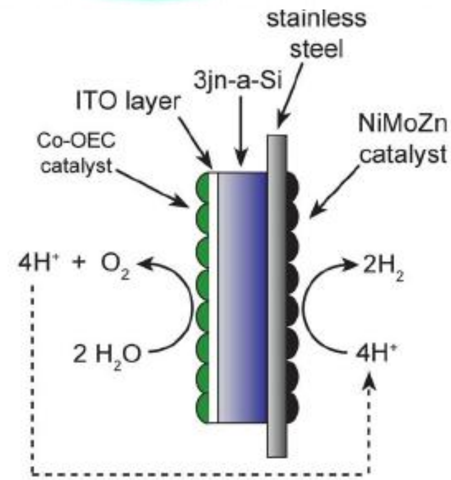












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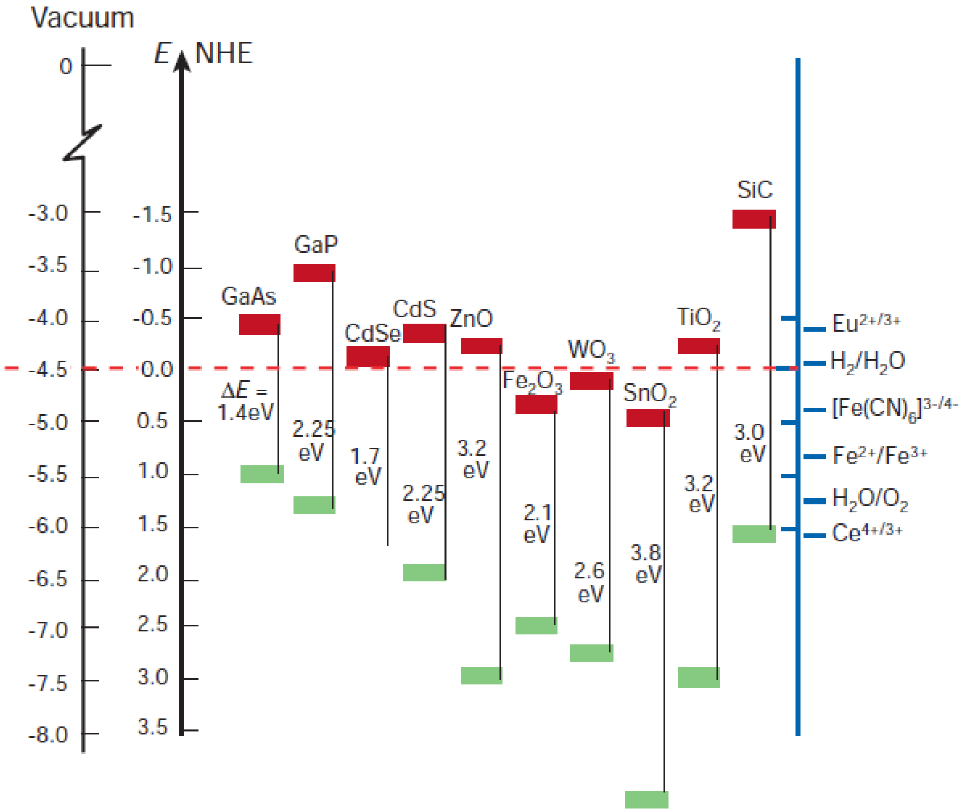
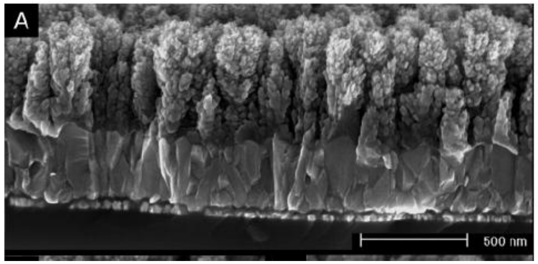
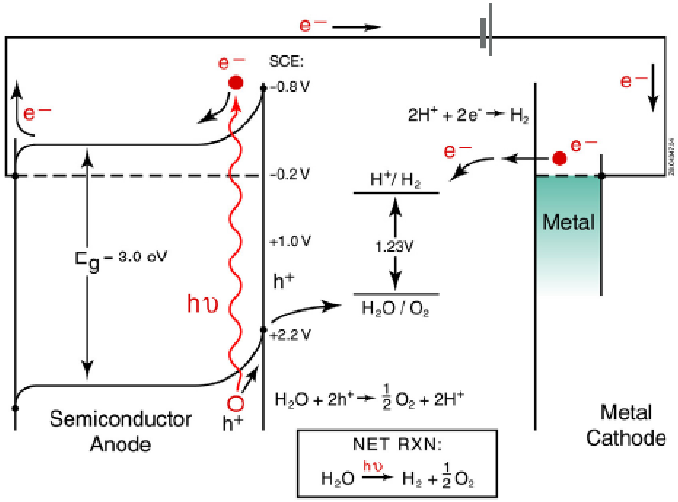
Nanostructured hematite photoelectrodes



Fe_2O_3

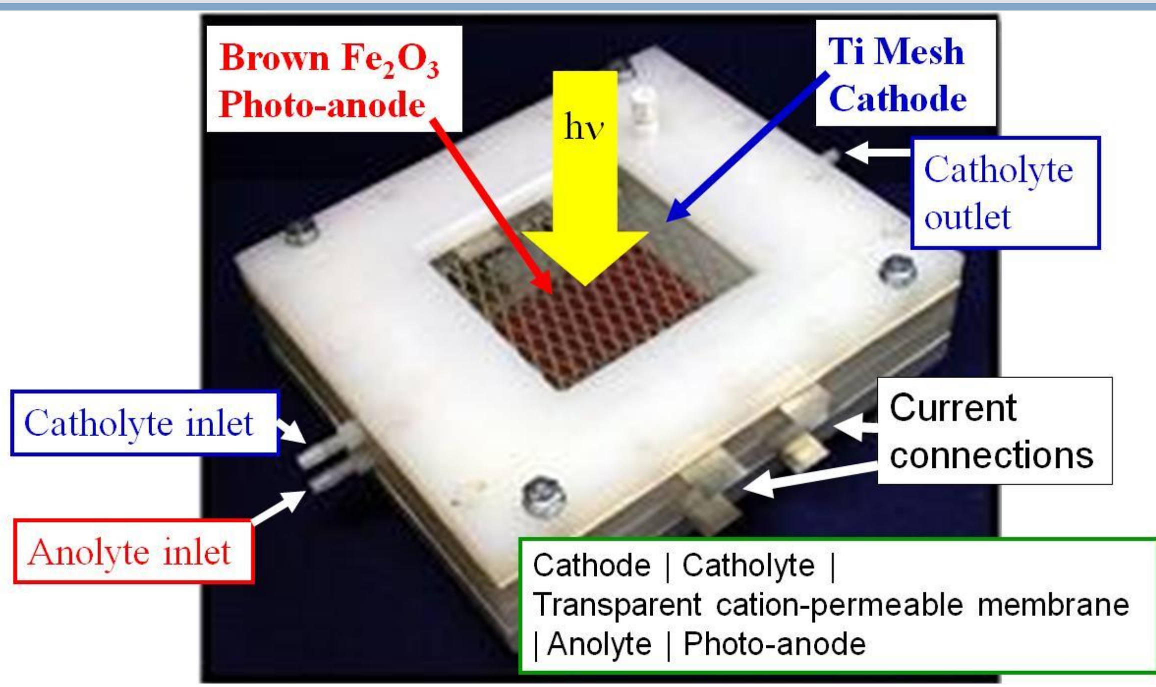


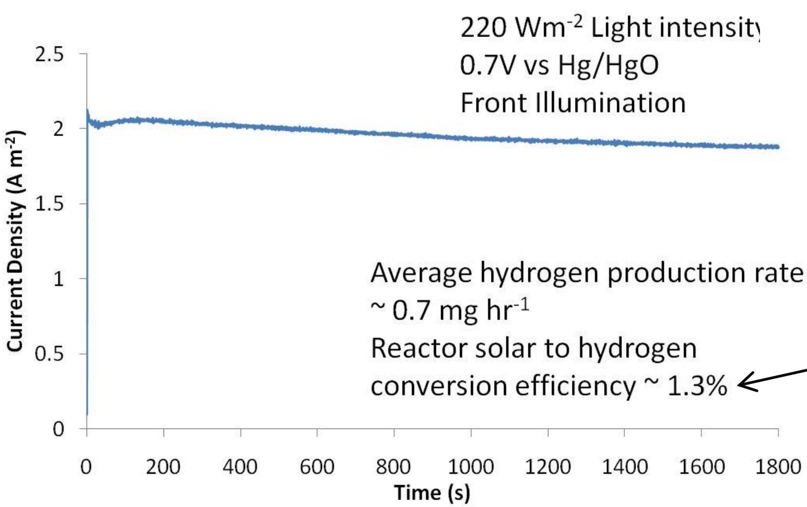
Gratzel et al. JACS 2006



Photoreactor design and scaleup

- 100 cm^2 Fe_2O_3 photoanode on steel deposited by spray pyrolysis
- Key issues: Optimisation of performance (especially miminisation of electrical bias); stability





Assumes tandem cell provides electrical bias

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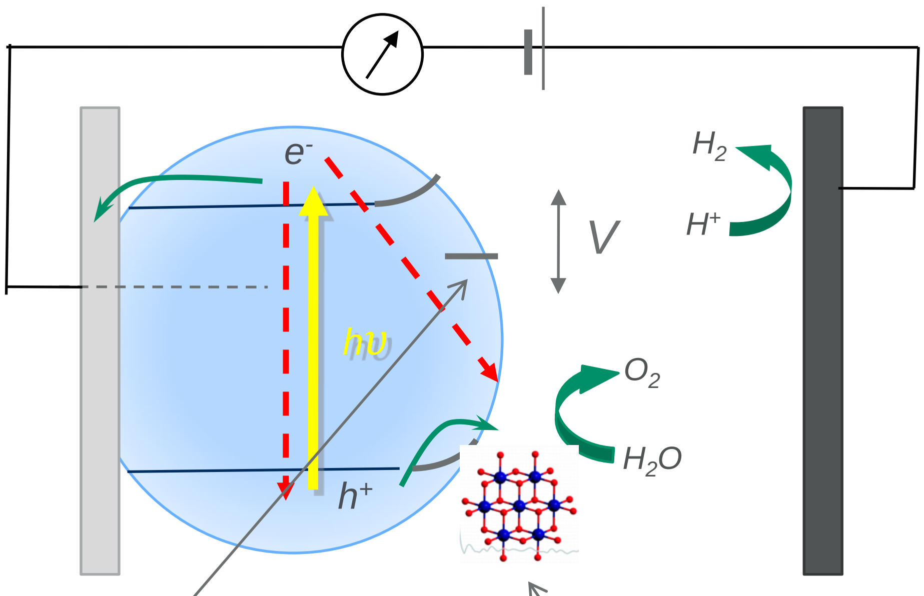
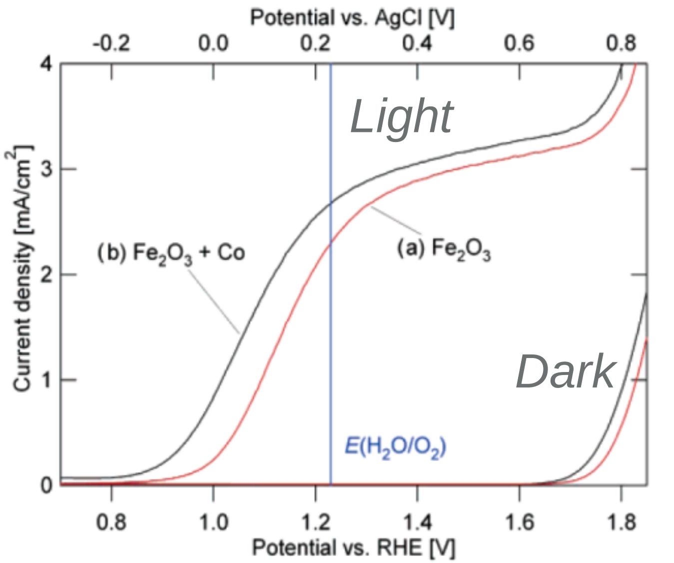
Questions for photoelectrode function

The role of applied bias? Band bending and energetics versus lifetime





Gratzel et al. JACS 200

Kinetics of electron / hole recombination versus water oxidation?

Charge trapping and surface states

The role of 'co-catalysts' Multi-electron (hole) chemistry?

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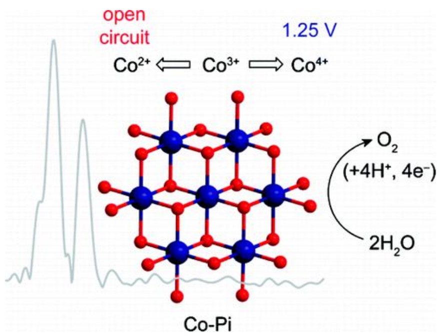
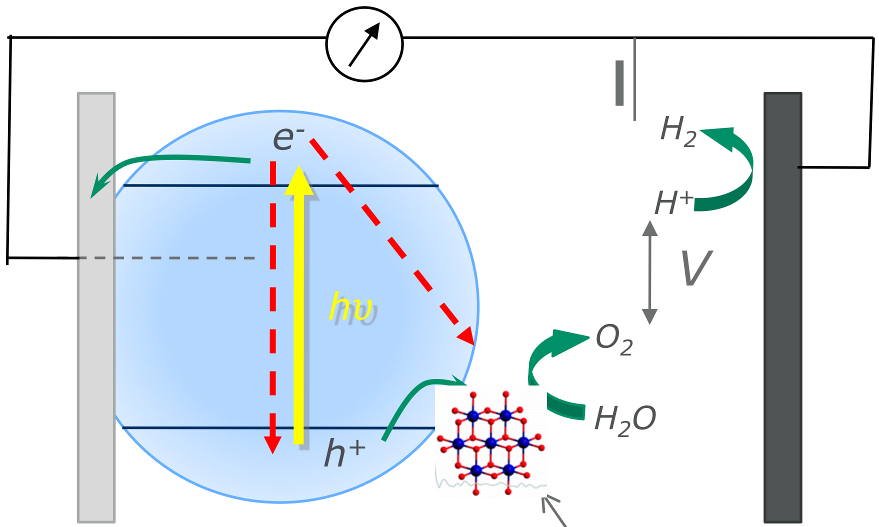
Inorganic catalyst: Cobalt phosphate (Co-Pi)

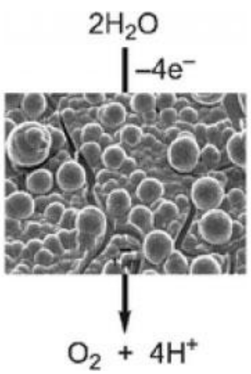
Cobalt Phosphate treatment:

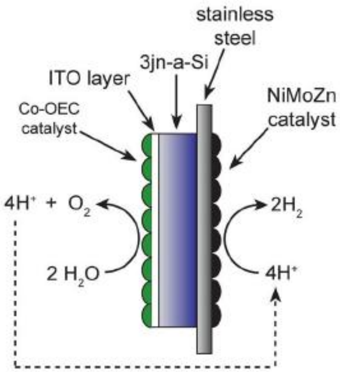


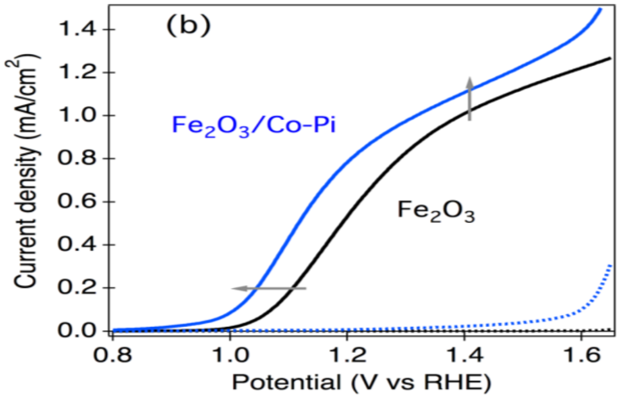


Nocera et al. Science 2008 & 2012

The role of 'co-catalysts'







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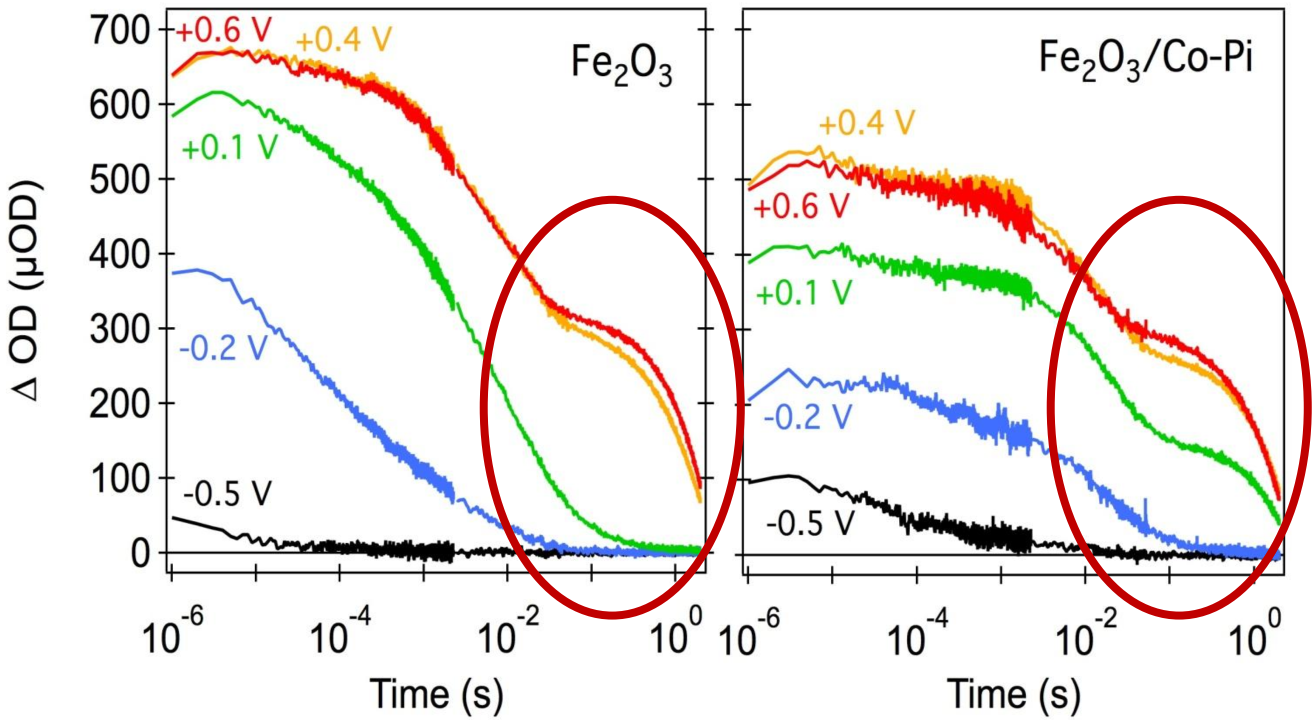
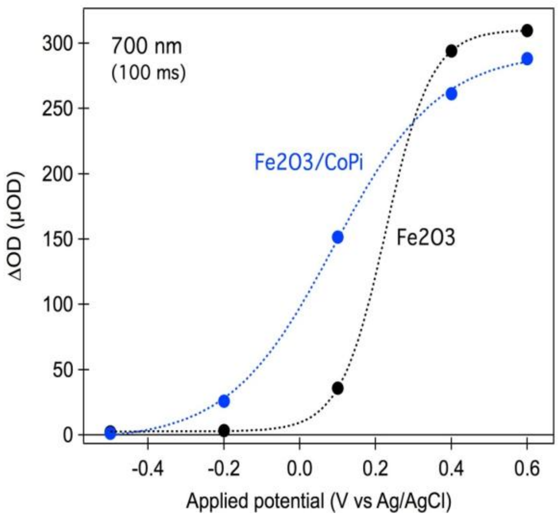
Fe_2O_3 Hole Dynamics

Monica Barosso

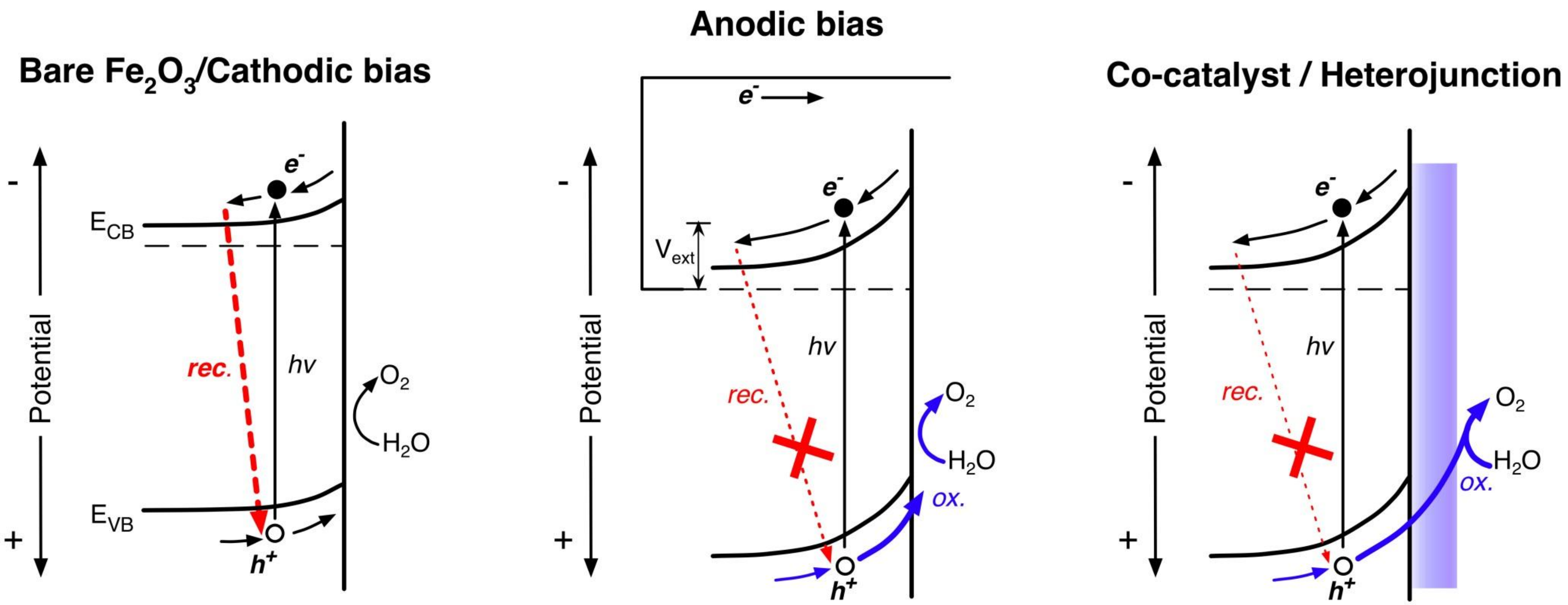




CoPi treatment:

- Doesn’t change kinetics of water *oxidation*
- Does retard recomb*ination dynamics at a given applied bias*

Fe_2O_3 / CoO_x heterojunctions



- *CoO_x* deposition causes electron depletion of Fe_2O_3 surface
- Slows down electron / hole recombination – so less requirement for positive bias
- No evidence for CoO_x being directly involved in the water oxidation process

Barroso et al. JACS 2011 & PNAS 2012

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Acknowledgements

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energy futures lab

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