Energy beyond oil:
Mesoscopic photosystems for the generation of fuels from sunlight

Fuel Choices Conference – Panel Discussion Tel Aviv Israel December 4, 2014

The long term future, where is the technology taking us ?

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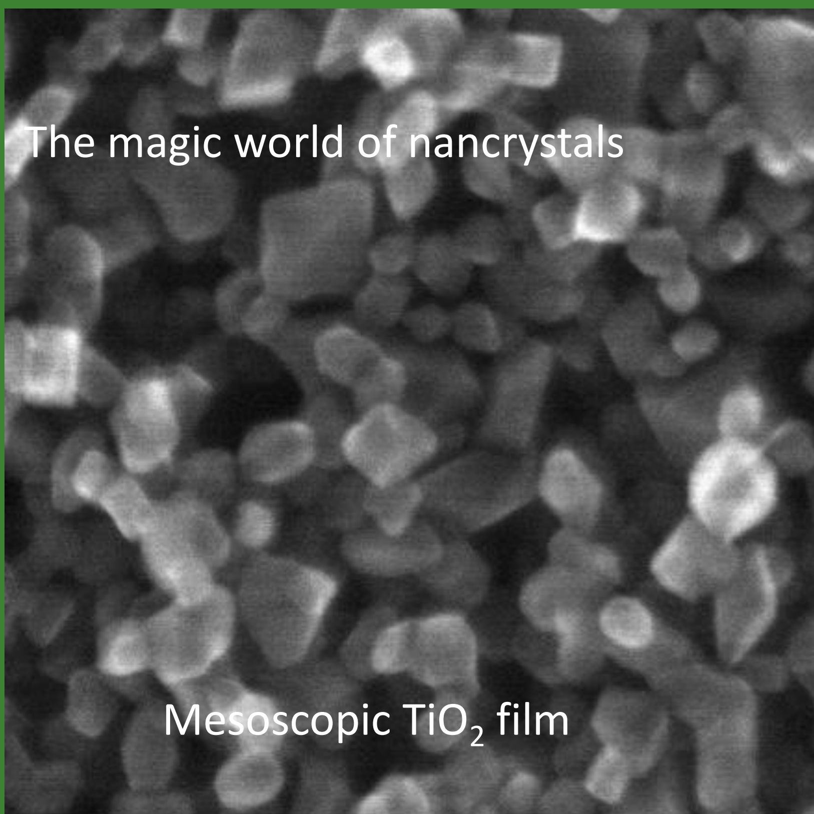
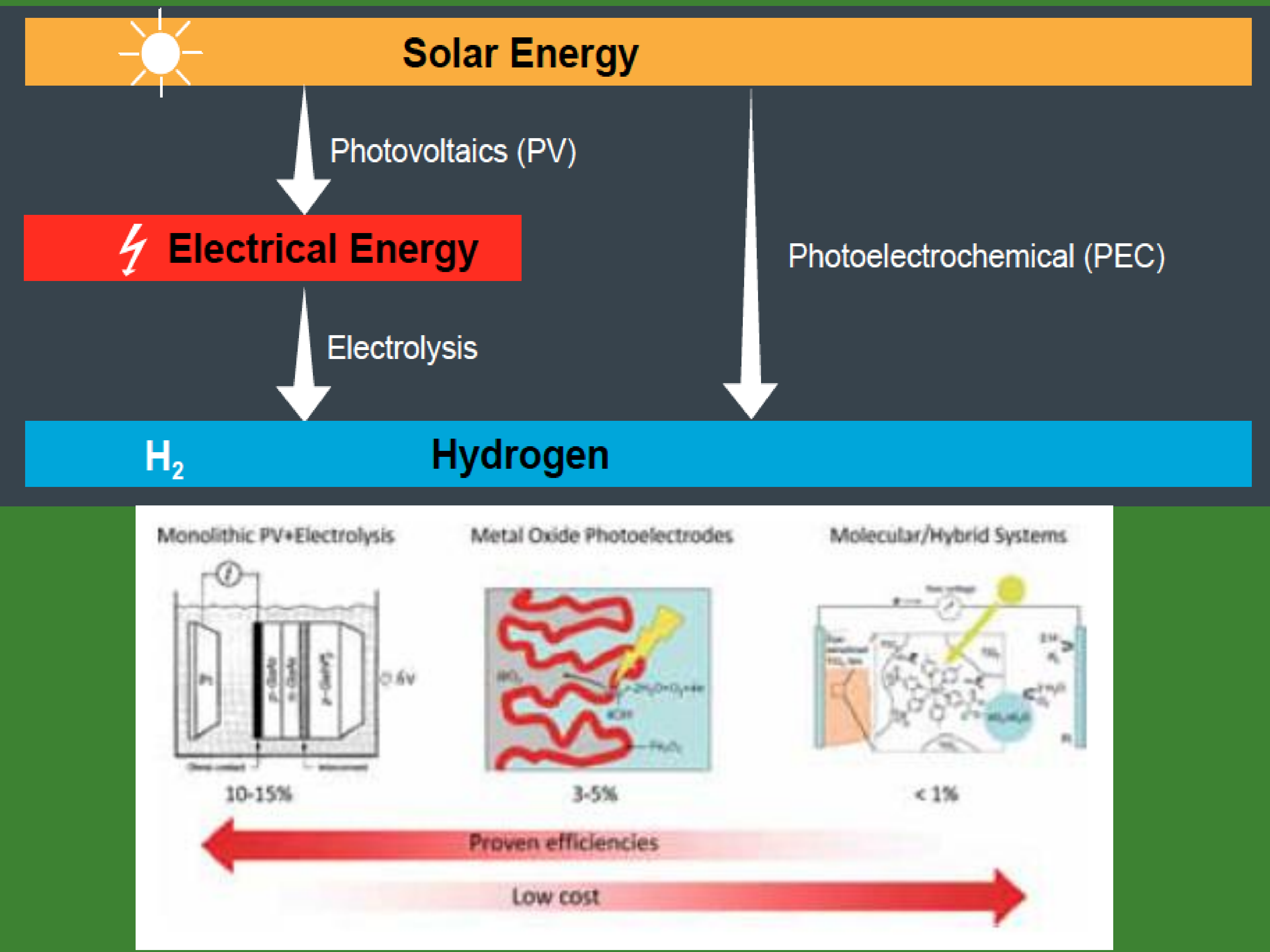
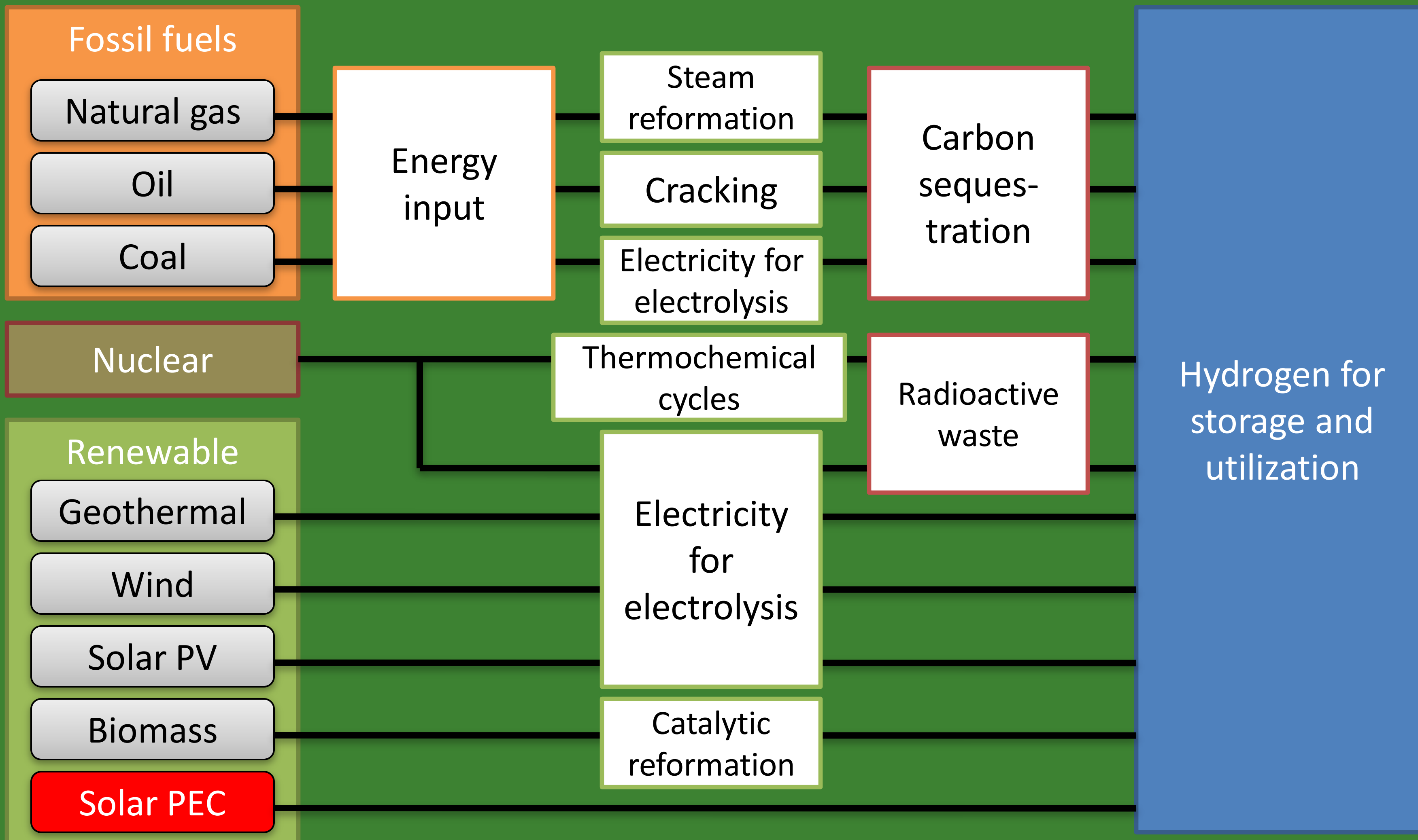


Swiss Tech Convention Center in Lausanne with a glass façade made of dye sensitized solar cells


Solar Energy
Photovoltaics (PV)
Electrical Energy
Photoelectrochemical (PEC)
Electrolysis
H2
Hydrogen
Monolithic PV+Electrolysis
Metal Oxide Photoelectrodes
Molecular/Hybrid Systems
10-15%
3-5%
< 1%
Proven efficiencies
Low cost

PEC (photo-electrochemistry) offers a direct path from solar energy to transportation fuels



Source: Toyota Motor Corporation

Our research has introduced mesoscopic structures for energy conversion. These systems are now applied in electrochemical devices for solar generation of chemical fuels, dye sensitized - and perovskite solar cells as well as lithium ions batteries.

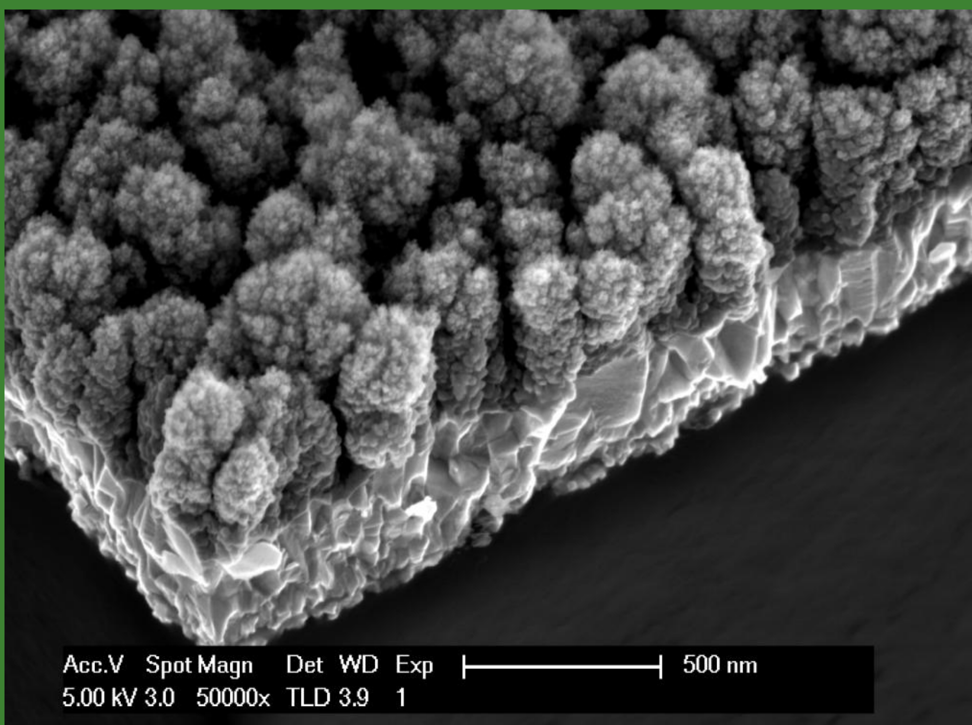
ARTICLES
PUBLISHED ONLINE: 7 JULY 2013 | DOI: 10.1038/NMAT3684
nature materials

Identifying champion nanostructures for solar water-splitting

Scott C. Warren[1*†], Kislon Voïtchovsky[2], Hen Dotan[3], Celine M. Leroy[1], Maurin Cornuz[1], Francesco Stellacci[2], Cécile Hébert[4], Avner Rothschild[3] and Michael Grätzel[1]

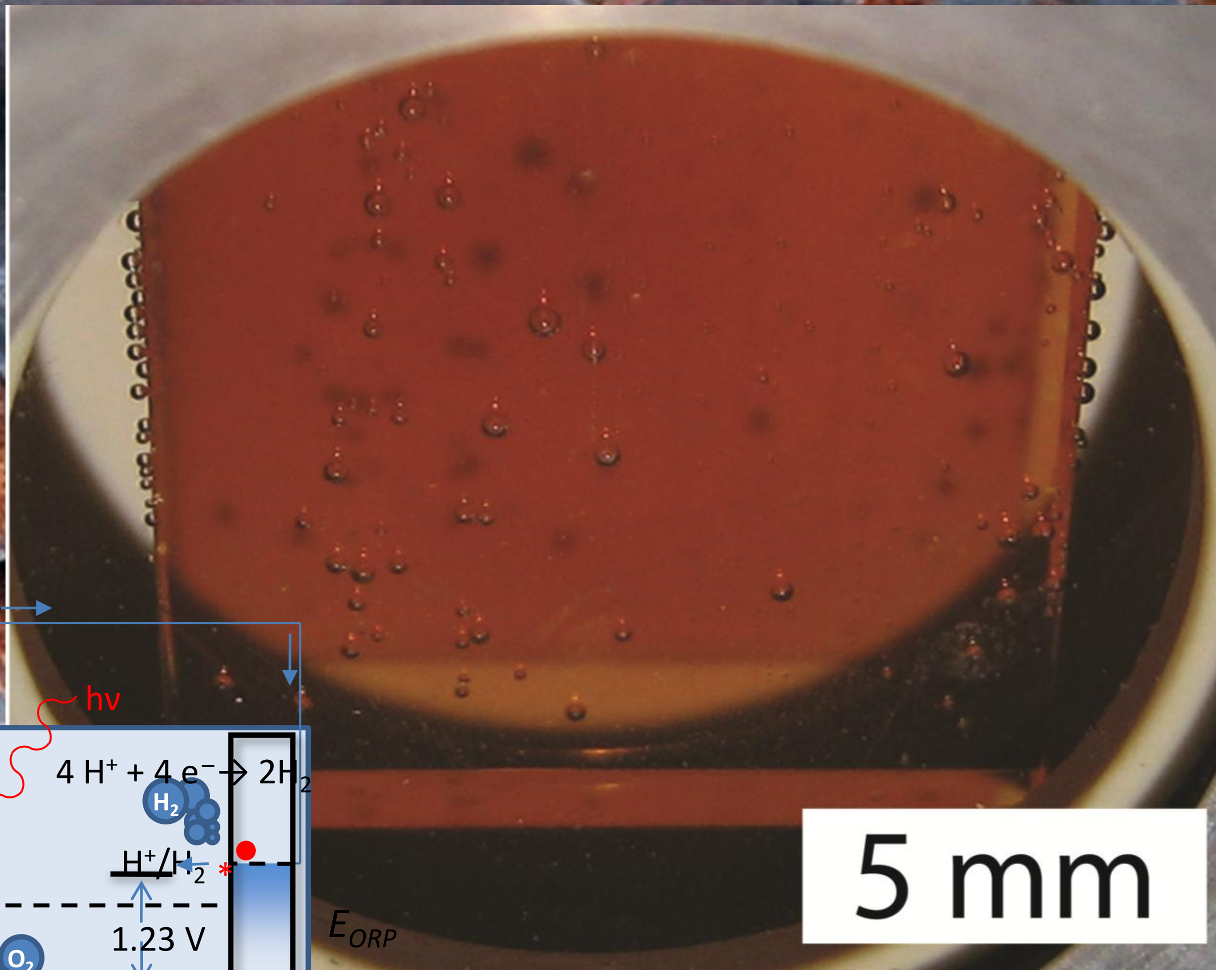
$$\eta_{coll} = (1 + (d/L_D)^2)^{-1}$$

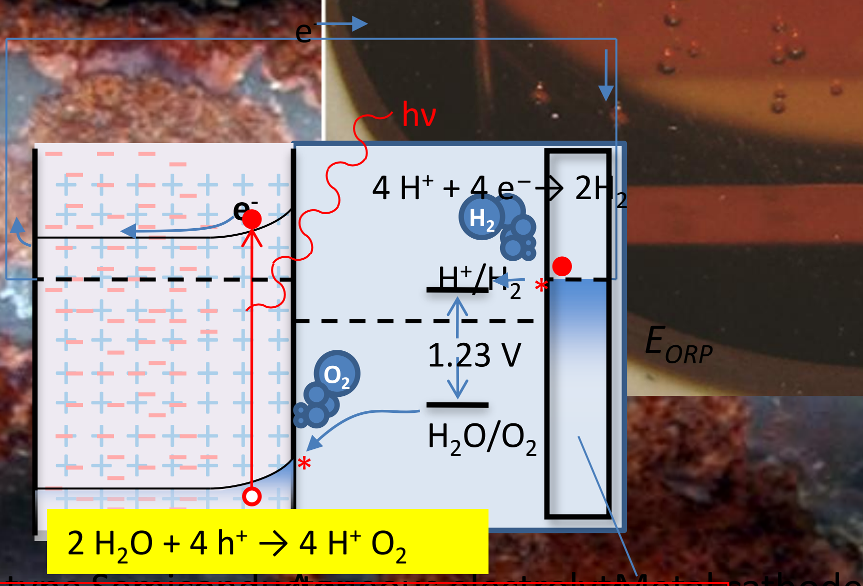
$$\eta_{coll} = 1/(1+ \tau_{trans}/\tau_{rec})$$



The key advantage of mesoscopic over planar semiconductor architectures is that they can **achieve near quantitative collection of the photo-generated charge carriers** even for materials where the charge-carrier diffusion length is much shorter than the light absorption length. In photo-electrochemical cells **the electrons and holes are used to generate hydrogen and oxygen from water,**

The power of the mesoscopic architecture; visible light induced oxygen evolution on Fe_2O_3 (iron oxide ,rust)





Rust is inactive !

Net Reaction: $2 H_2O + h\nu \rightarrow 2H_2 + O_2$

nature photonics

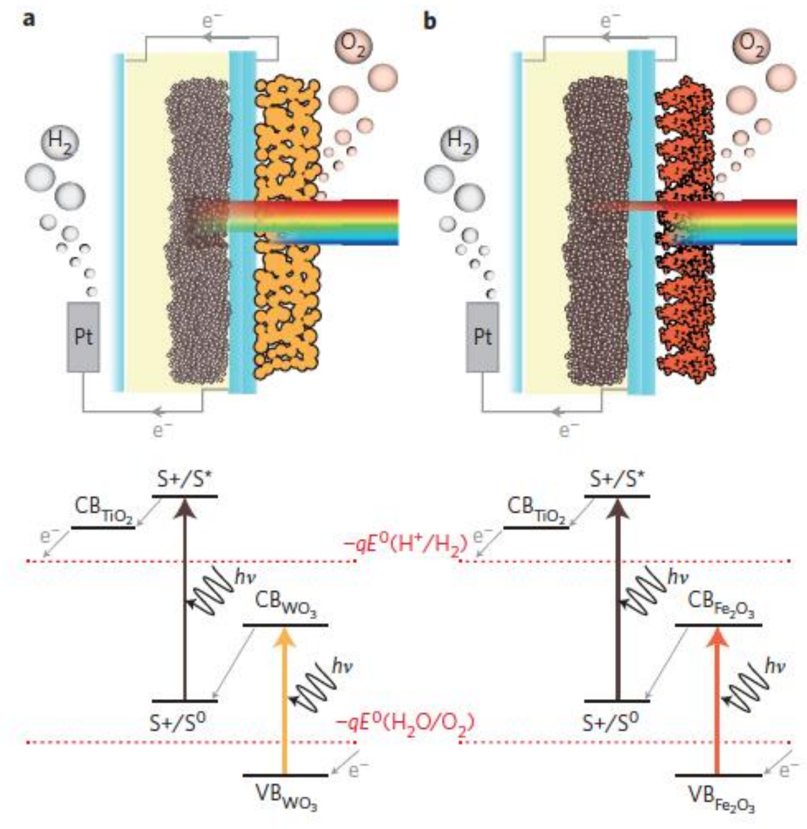
LETTERS

PUBLISHED ONLINE: 11 NOVEMBER 2012 | DOI: 10.1038/NPHOTON.2012.265

Highly efficient water splitting by a dual-absorber tandem cell

Jeremie Brillet[1], Jun-Ho Yum[1], Maurin Cornuz[1], Takashi Hisatomi[1], Renata Solarska[2], Jan Augustynski[2], Michael Graetzel[1] and Kevin Sivula[1]*

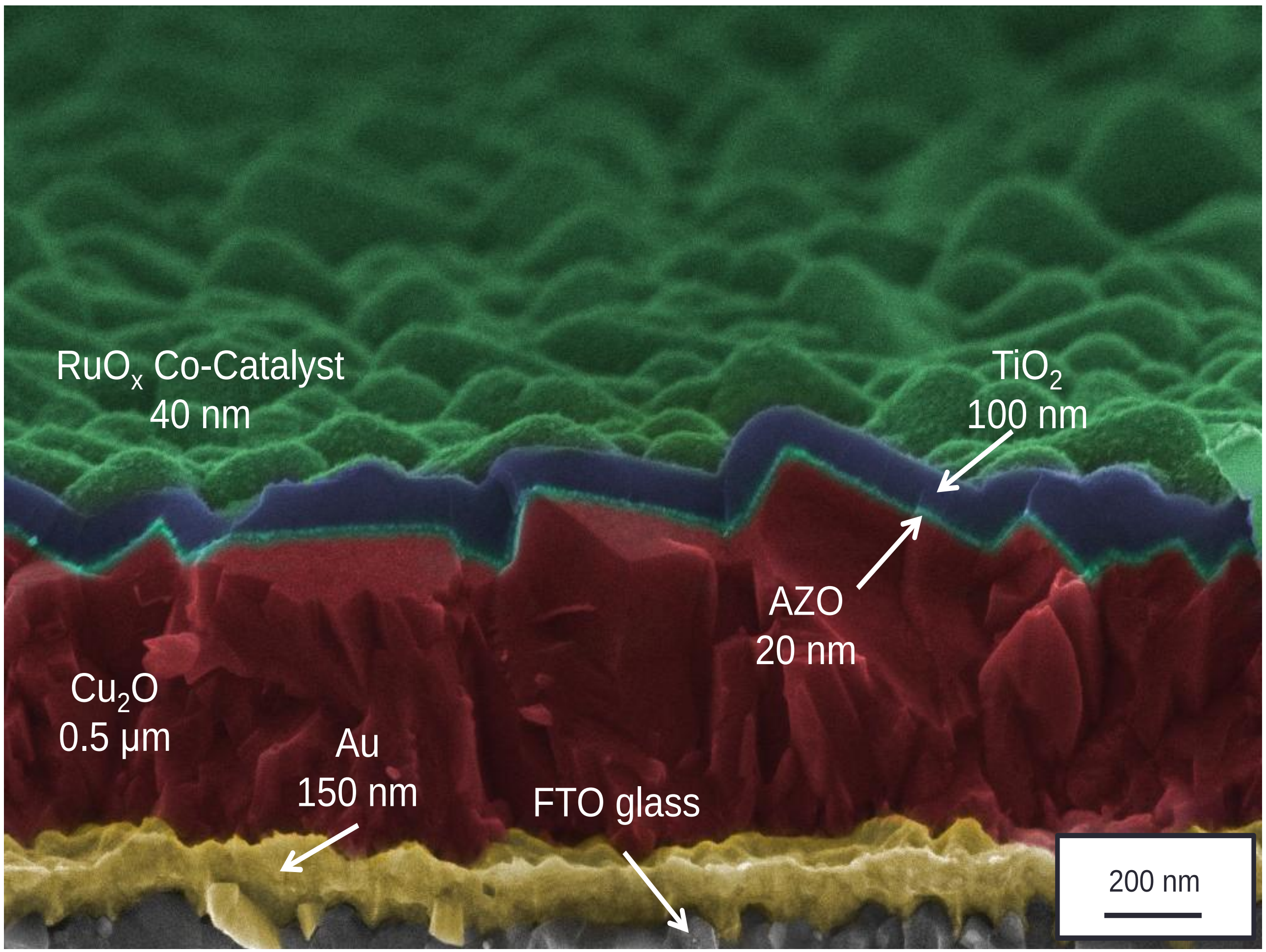
Photoelectrochemical water-splitting devices, which use solar energy to convert water into hydrogen and oxygen, have been investigated for decades. Multijunction designs are most efficient, as they can absorb enough solar energy and provide sufficient free energy for water cleavage. However, a balance exists between device complexity, cost and efficiency. Water splitters fabricated using triple-junction amorphous silicon[1,2] or III–V[3] semiconductors have demonstrated reasonable efficiencies, but at high cost and high device complexity. Simpler approaches using oxide-based semiconductors in a dual-absorber tandem approach[4,5] have reported solar-to-hydrogen (STH) conversion efficiencies only up to 0.3% (ref. 4). Here, we present a device based on an oxide photoanode and a dye-sensitized solar cell, which performs unassisted water splitting with an efficiency of up to 3.1% STH. The design relies on carefully selected redox mediators for the dye-sensitized solar cell[6,7] and surface passivation techniques[8] and catalysts[9] for the oxide-based photoanodes.



ARTICLES
PUBLISHED ONLINE: 8 MAY 2011 | DOI: 10.1038/NMAT3017
nature materials

Highly active oxide photocathode for photoelectrochemical water reduction

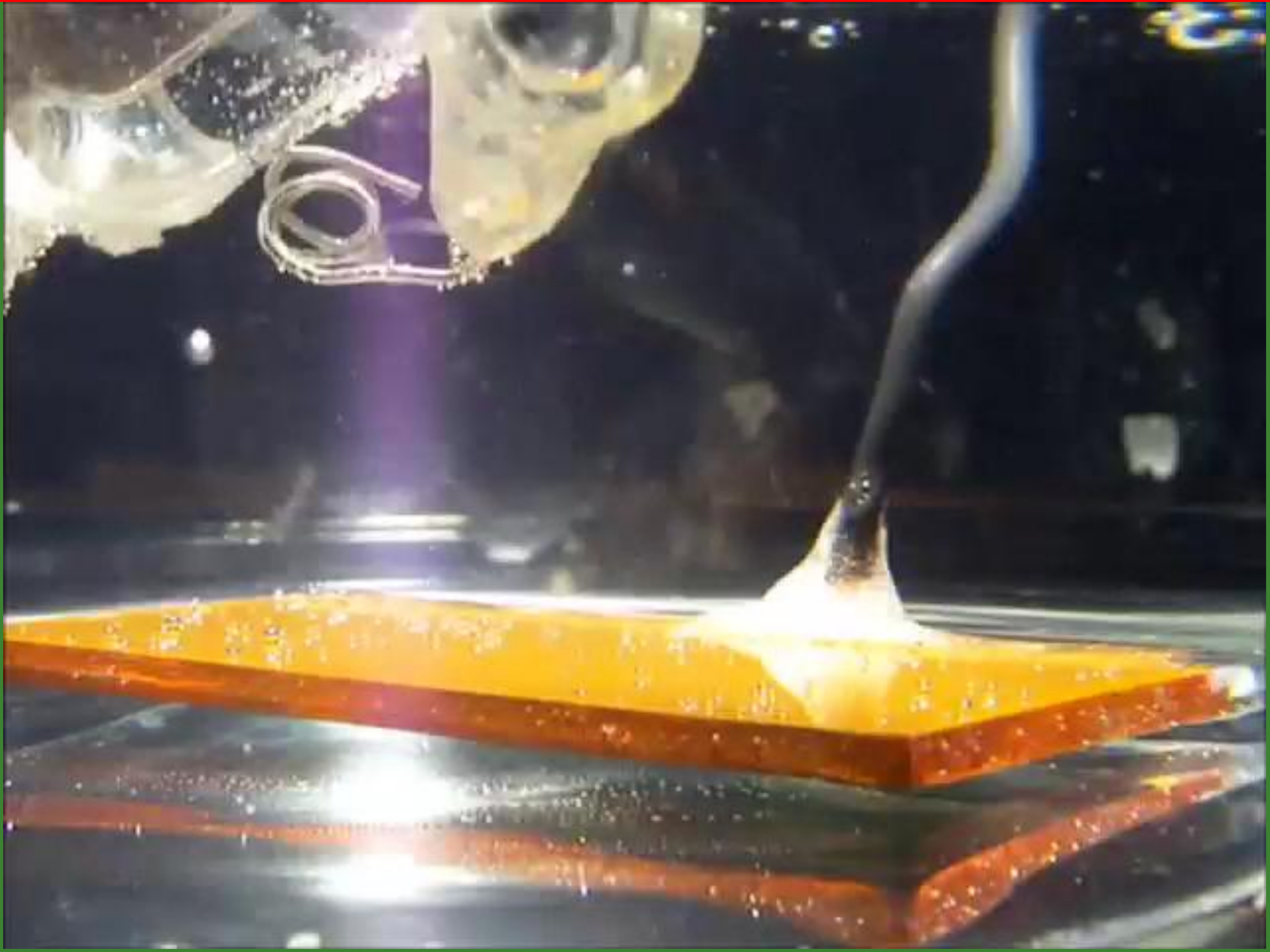
Adriana Paracchino[1], Vincent Laporte[2], Kevin Sivula[1], Michael Grätzel[1] and Elijah Thimsen[1*†]



Build-in Cu_2O/ZnO (AZO) p/n junction
and TiO_2 overlayer
protect the Cu_2O film
Against photo-corrosion

Nc

The Holy Grail of photocatalysis: solar splitting of water into hydrogen and oxygen on Cu_2O films protected by TiO_2



REPORT

Science **345**, 1593 (2014)

Science
AAAS

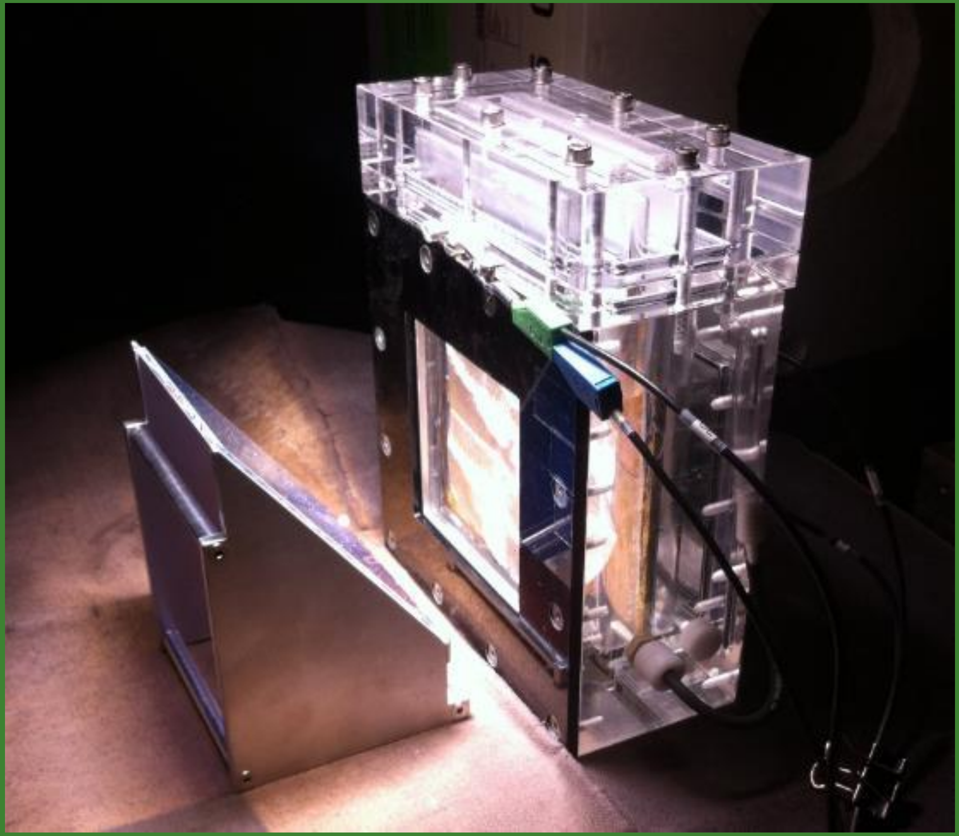
WATER SPLITTING

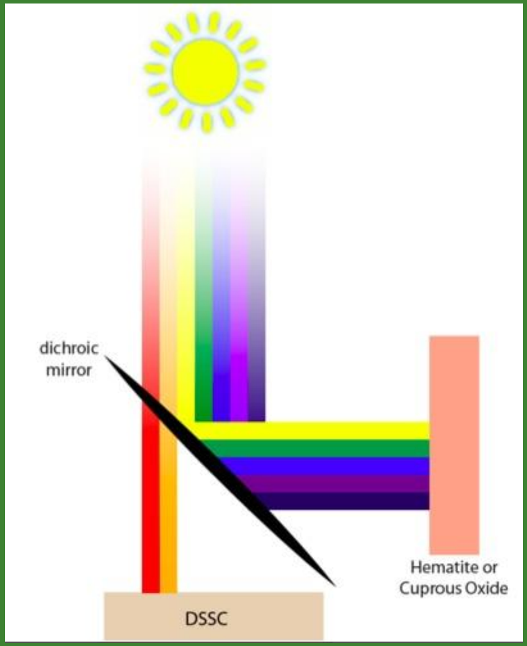
Water photolysis at 12.3% efficiency via perovskite photovoltaics and Earth-abundant catalysts

Jingshan Luo,[1,2] Jeong-Hyeok Im,[1,3] Matthew T. Mayer,[1] Marcel Schreier,[1] Mohammad Khaja Nazeeruddin,[1] Nam-Gyu Park,[3] S. David Tilley,[1] Hong Jin Fan,[2] Michael Grätzel[1]*

Present status of research and development

- Large electrode tandem (100 cm^2)
- 10% unassisted water splitting in AM1.5 sunlight.





Future practical implementation: PECDEMO -EU project sunlight to hydrogen

Fuel Cells and Hydrogen Joint Undertaking (FCH JU)

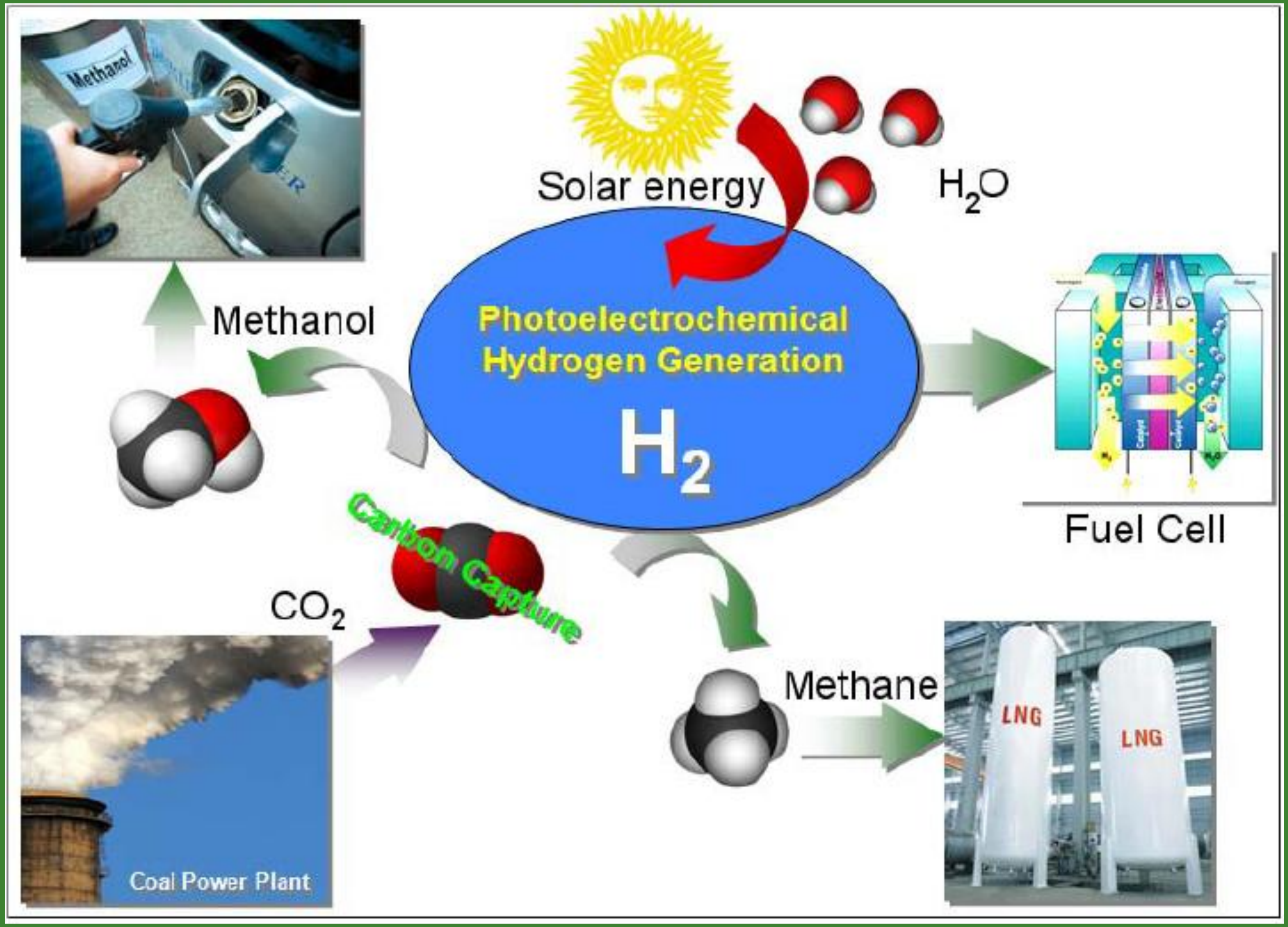
- Stand-alone hybrid PEC-PV devices will be constructed and tested for performance and stability,
- fabrication of large scale demonstration modules that will be tested in the field under real-world conditions.
- Price target for hydrogen: 5€/kg

Prof. Roel van de Krol

Participant no.	Participant organisation name	Country
1 (Coordinator)	Helmholtz-Zentrum Berlin für Materialien und Energie GmbH **Prof. Roel van de Krol**	Germany
2	Ecole Polytechnique Fédérale de Lausanne **Prof. Michael Grätzel**	Switzerland
3	Technion – Israel Institute of Technology **Prof. Avner Rothschild**	Israel
4	Deutsches Zentrum für Luft - und Raumfahrt **Dr. Christian Jung** **Dr. Martin Roeb**	Germany
5	Universidade do Porto **Prof. Adélio Mendes**	Portugal
6	Evonik Industries AG **Dr. Matthias Blug**	Germany
7	Solaronix SA **Dr. Toby Meyer**	Switzerland

H_2 is a key future energy vector and fuel

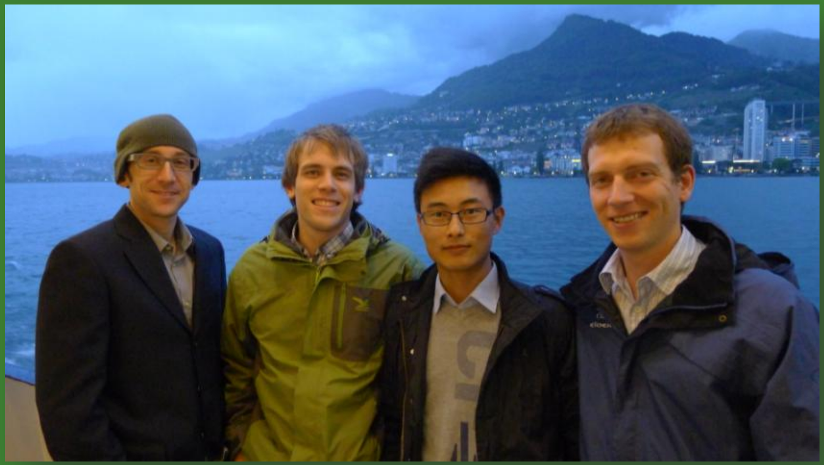
- Provides environmental, economic and national security
- Can be easily converted to methane or methanol
- Price target for renewable hydrogen 5 €/kg
- By 2050, H_2 is expected to comprise 50% of transportation fuels.




EPFL
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

LPI-SolarFuels group members

• Ludmilla Steier	Fe_2O_3 photo-anodes for solar water splitting
• David Tilley	Group leader, now Professor at the University of Zurich
• Marcel Schreier	CO_2 reduction on photocathodes, gas chromatography
• Jingshan Luo	copper oxide-and CIGS based photocathodes, tandems, earth-abundant electrocatalysts
• Matt Mayer	present solar fuels group leader, photocathodes, metal oxides, mesocopic photoelectrodes
• Min-Kyu Son	Cu_2O tandems, scale-up of water splitting systems



Cooperations with Israeli groups

Academic

- Professor Efrat Lifshitz Technion Haifa
- Professor Avner Rothschild Technion Haifa
- Dr. Hen Dotan Technion Haifa
- Professor Doron Aurbach Bar-Ilan University
- Professor Ariel Zaban Bar-Ilan University
- Professor Lioz Etgar Hebrew University
- Professor Gary Hodes Weizman Institute
- Professor David Cahen Weizman Institute

Industrial

3GSolar Jerusalem

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Confederaziun svizra

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MARIE CURIE ACTIONS

SEVENTH FRAMEWORK PROGRAMME

We thank our corporate sponsors

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