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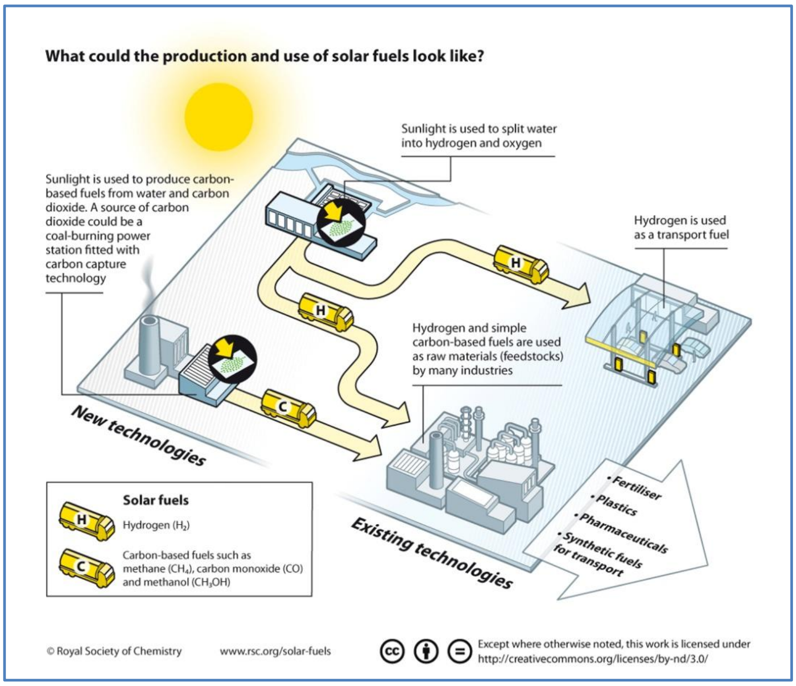
Solar Fuels and Artificial Photosynthesis: Global initiatives and opportunities May 17 2012, Chemistry Centre, London – Meeting Summary

This discussion meeting marked the launch of the Royal Society of Chemistry report *Solar Fuels and Artificial Photosynthesis: Science and innovation to change our future energy options.* A partnership between the Royal Society of Chemistry and the UK Global Science and Innovation Network, the invitation-only event was the first of its kind in the UK to focus on the possibility of using sunlight directly to produce fuels. Its goal was to bring together policymakers, industrialists and academic scientists to

- Discuss the potential of fuels produced using sunlight in future sustainable energy scenarios, as well as associated opportunities for wealth creation;
- Celebrate recent progress by UK and international scientists;
- Discuss important new solar fuels research and innovation initiatives internationally.

On May 18th there was an associated international scientific discussion meeting at Imperial College London chaired by Professor Jim Barber FRS and Professor James Durrant. With the exception of the webcast of the keynote lecture, the May 17th meeting was held under the Chatham House Rule. There were approximately 70 participants, from Australia, France, Germany, the Netherlands, Singapore, Spain, Sweden, the UK and the USA.

The following is a summary for participants of the talks, discussions and keynote lecture divided into: Examples, Views, Numbers and Links. These were all provided during the meeting – if you have any comments or corrections please send them to sciencepolicy@rsc.org and we will update the information on the RSC website at www.rsc.org/solar-fuels.



1. Examples

During the meeting the following examples were presented or discussed.

1.1 Examples of progress in solar fuels research

Nanostructuring in materials: Provides a new approach to simultaneously optimise the efficiency with which light can be captured and electrons utilised for fuel formation. Nanostructuring is also important for catalysis and for novel electrode design.

Photocatalytic materials: Benchmark work in 2006 demonstrating the feasibility of solar hydrogen production by an inorganic material using visible light. Previously this approach had only been feasible using ultraviolet light.

Understanding of natural photosynthesis: Fundamental insights into light harvesting and reaction centres (where "fuel" is produced) in photosynthesis in plants, algae and certain types of bacteria.

Molecular approaches to catalysis: Increases by several orders of magnitude in the efficiency of catalysts for different steps required for solar fuels production, as well as the discovery of catalysts based on inexpensive constituents such as nickel, cobalt and iron.

1.2 Examples of large research initiatives

Joint Center for Artificial Photosynthesis (JCAP): One of three new US Energy Innovation Hubs launched in 2010, styled after directed research efforts such as Bell Labs. The hub, directed by Professor Nathan Lewis of the California Institute of Technology, has $122 million in funding over five years, and the possibility, subject to performance, of renewal for two further five year periods. Described in the 2011 State of the Union Address by President Obama as one of the "Apollo projects of our time", the mission of JCAP is to demonstrate a scalable, manufacturable solar-fuels generator using Earth-abundant elements, that, with no wires, robustly produces fuel from the sun ten times more efficiently than (current) crops. The hub brings together, at two purpose-built facilities, about two hundred scientists, engineers, technologists and designers from diverse subfields. JCAP operates parallel research projects ranging across the spectrum from fundamental research on individual sub-challenges, to systems integration and scale up, to product design and prototype development. Its goals include maximising commercial opportunities for the United States associated with both solar fuels devices and likely spin-off developments in catalysis, photovoltaic technology and reactor design. JCAP Website: http://solarfuelshub.org/

Biosolar Cells: A five-year research project, which started in 2010, involving nine Dutch universities and over 30 companies in an open innovation environment. The project is a public-private partnership with funding totalling €42 million from the Dutch Government, the Netherlands Organisation for Scientific Research, industry and Dutch universities and research institutes. The project is organised around three clusters of research topics: (i) Artificial systems, (ii) Research at Cell level: Synthetic Biology for fuel production from living organisms and (iii) Research at Plant level: Whole genome reprogramming for cross-species improvement. The goals for 2016 in each of these areas include respectively (i) two nanostructured artificial leaf laboratory prototypes that directly convert solar energy into hydrogen gas and/or methanol; (ii) production of *algae or bacteria* that can convert sunlight into biofuel at an overall efficiency of 5%, production of biofuel from algae on a semi-industrial scale and development of fatty-acid producing algae with improved growth characteristics, (iii) a programme on the genetic aspects of photosynthesis in various plant species with the goal of improving the efficiency of photosynthesis in plants. Biosolar Cells website: http://www.biosolarcells.nl/en/

1.3 **Examples of industrial interest in solar fuels**

It is beyond the scope of this document to provide an exhaustive list, but some examples of interest in, or awareness by, companies in diverse industrial sectors are: BASF; industrial partners in the Biosolar Cells project; BP; General Electric (GE); Honda; Lotus Cars;

Panasonic Corporation; Toyota Central R&D Labs. Links are given in section 4 below.

1.4 UK research institutions engaged in solar fuels research: Participants at the meeting included researchers from Bristol University, Imperial College London, Loughborough University, Newcastle University, Queen Mary University of London, Queen's University Belfast, University of Bath, University of Cambridge, University College London, University of East Anglia, University of Glasgow, University of Manchester, University of Nottingham, University of Oxford, University of Sheffield, University of York.

1.4 European research institutions engaged in solar fuels research: It is beyond the scope of this document to give an exhaustive list. Participants in the meetings also included researchers from the Catalonia Institute for Energy Research; Free University of Berlin; Institute of Chemical Research of Catalonia; KTH Royal Institute of Technology, Stockholm; Max Planck Institute for Bioinorganic Chemistry, Mülheim; Université Paris-Sud; CEA Saclay; University of Kiel; University of Leiden.

1.5 European networks and initiatives: The following joint initiatives were represented at the meeting:

- European Cooperation in Science and Technology (COST) collaborative network on *Supramolecular photocatalytic water splitting (PERSPECT-H2O).* See http://www.cost.eu/domains_actions/cmst/Actions/CM1202.
- European Energy Research Alliance *Joint Programme on Advanced Materials and Processes for Energy Applications*, Artificial Photosynthesis Network. See http://www.eera-set.eu/index.php?index=78.
- The European Chemical Industry Council (CEFIC) and the European Association for the Chemical and Molecular Sciences (EuCheMS), working on a joint initiative to embed support for artificial photosynthesis research and innovation in plans at European Union level for a coherent approach.

2. Views

Case for Pursuing Solar Fuels:
The case for pursuing a solar fuels technology is a compelling one because of the:

- urgency of the need to address climate change
- momentum created by recent scientific progress
- need to think long-term about wealth creation.

Production at scale of solar fuels such as hydrogen or carbon-based fuels - such as methanol, methane and carbon monoxide (syngas) - by technologies requiring just sunlight, carbon dioxide and water as their inputs would simultaneously address two key unresolved challenges in sustainable energy:

- Large scale storage of solar energy
- A source of renewable fuels for transport.

Solar fuels could also be renewable feedstocks for key industrial sectors.

Current status of research: For a solar fuels technology to be deployed widely it must be efficient, cost-effective and robust (durable). Currently there are research prototypes which satisfy any two of these criteria, but none that satisfy all three.

Research investment globally: There are examples of significant recent investments in dedicated solar fuels research initiatives. However, these do not cover all promising routes or approaches to solar fuels production and there is a need for increased investment in solar fuels globally.

Multidisciplinary research: The multidisciplinary nature of the challenges in developing a solar fuels technology makes the creation of research programmes designed to bring together academics and industrialists from a range of different backgrounds on long-term projects an important priority.

Timescales: Recent scientific breakthroughs and laboratory prototypes mean that an efficient, affordable, durable technology to harness solar energy to produce chemical fuels from water and carbon dioxide is a realistic goal.

The likely timescale to market (at least 10-15 years) means that it is probably not realistic to rely on private sector investment to drive research in the short term. It is however clear that there is interest in solar fuels in various industrial sectors, including the energy and automotive sectors and chemical industry and that, in the long-term disruptive solar fuels technologies would bring significant business opportunities.

This timescale also means that any research programme needs to be long-term, including mechanisms for review and continued support.

An end-state: It is important, if there are to be large investments in research, to articulate clearly-defined goals or end-states for a research programme.

Support for solar fuels research: The level of investment in solar fuels research in the UK and, on average, in Europe needs to be increased.

UK position: There is considerable UK research expertise in key areas, including solar photovoltaics, photosynthesis, nanostructured materials, catalysis, reactor engineering and biochemical approaches. There is a real opportunity to build on this by developing and implementing a long-term UK strategy in this area, integrating increased support for inter-disciplinary research and for innovation.

European position: There are world-class solar fuels research communities in several European countries, in some cases, such as in The Netherlands and Germany, supported by significant programmes. There are also some recently established pan-European research networks. There is a tremendous opportunity, perhaps as part of Horizon 2020, to make the most of this combined expertise within the European Research Area. Enabling European researchers to contribute to the solar fuels effort to their full potential, bringing associated environmental and economic benefits, will require a coordinated initiative or initiatives.

3. Numbers

Public funding for Joint Center for Artificial Photosynthesis, US Energy Innovation Hub	$122 million over 5 years
Public and Private funding for BioSolar Cells, The Netherlands	€42 million over 5 years (approx €2.50 per capita)
US Energy Frontiers Research Centers	$777million (approx $2.50 per capita)
Investment in R&D as a percentage of revenue: • Energy • Information Technology • Pharmaceuticals	 0.1% 12-14% 12%
Total world primary power (2009)[1]	16TW
Projected total world primary power (2050) – International Panel on Climate Change “Business as Usual” scenario	28TW
Projected carbon-free primary power (2050) - “Business as Usual” scenario	10TW
Projected carbon-free primary power (2050) – WRE 550 atmospheric CO_2 stabilization path[2]	15TW
Percentage of energy demand for transportation that cannot be electrified (heavy duty vehicles, ships, aeroplanes)	40%
Number of UK Universities where solar fuels research is being done	At least 16

For detailed analyses of nuclear power, carbon sequestration and renewable energy see transcript at http://nsl.caltech.edu/energy.

[1] *Key World Energy Statistics* - International Energy Agency (2011)

[2] *Energy implications of future stabilization of atmospheric CO_2 content*, M Hoffert et al, Nature, 395, p 881 (1998). See Figure 2.

4. Resources and Links

Solar Fuels and Artificial Photosynthesis: Science and innovation to change our future energy options
Royal Society of Chemistry report
www.rsc.org/solar-fuels

Harnessing Solar Energy for the Production of Clean Fuel,
European Science Foundation Science Policy Briefing SPB34 (2008)
www.esf.org/publications/science-policy-briefings.html

Welcome and introductory remarks on Solar Fuels by Professor David Phillips CBE, RSC President 2010-2012
http://www.rsc.org/solar-fuels

Webcast of *Global Energy Perspectives* keynote lecture by Professor Nathan S Lewis and excerpts from the Question & Answer session, May 17th London
http://www.rsc.org/chemistryworld/Webinar/Global_Energy_Perspectives.asp.

Slides for *Powering the Planet / Global Energy Perspectives* lecture by Professor Nathan S Lewis
http://nsl.caltech.edu/energy

BBC Radio 4 Frontiers episode on *Artificial Photosynthesis*, June 2012, including excerpts from talks by Nathan S Lewis and interviews with other participants at the 17/18th May meetings in London
http://www.bbc.co.uk/programmes/b01jrknf#synopsis

G. Ciamician, Science, Vol. XXXVI, 926 p 385 (1912)
http://www.sciencemag.org/content/36/926/385.extract

RSC Solar Fuels Centenary collection of articles, reviews and commentaries about solar fuels (September 2012)
http://blogs.rsc.org/cs/2012/09/25/a-centenary-for-solar-fuels/

Examples of Industrial Interest in Solar Fuels

BASF press release (2012) http://www.basf.com/group/pressrelease/P-10-221
Industrial partners in Biosolar Cells http://www.biosolarcells.nl/en/over-biosolar-cells/bedrijven.html
British Petroleum http://ccisolar.caltech.edu/webpage/98
GE Ecomagination (2011) http://www.ecomagination.com/artificial-photosynthesis
Honda news release (2012) http://www.solarfeeds.com/honda-introduces-solar-hydrogen-station/
Lotus cars, proActive magazine, 44 p 20-31 (2012) http://issuu.com/lotuscars/docs/proactive_issue_44_spring_2012
Panasonic press release (2012) http://panasonic.co.jp/corp/news/official.data/data.dir/2012/07/en120730-5/en120730-5.html
Toyota CRDL, Inc press release (2011) http://www.tytlabs.co.jp/english/news/press/20110920_epress.pdf

Next Steps for the RSC

The RSC will continue to raise awareness of the environmental and economic potential of solar fuels among UK policymakers. We will also use communications with our members, authors, educators and young people to continue to raise general awareness of solar fuels.

The RSC will work together with the UK chemical sciences research community and other stakeholders to explore and articulate concrete options for a UK solar fuels research programme. The Environment Sustainability and Energy Division will support a 2nd UK Solar to Fuels community-building scientific meeting in 2013.

In Europe, the RSC will support EuCheMS and work with sister societies in efforts to raise awareness of the environmental and economic potential of solar fuels.

We will also explore opportunities to work in partnership with other international stakeholders to facilitate knowledge exchange and research collaboration between Europe and Asia.

May 17th Meeting Programme

Session 1	Scientific Perspectives on Solar Fuels
	Welcome and Introduction Professor David Phillips (Royal Society of Chemistry)
	Solar fuels and Artificial Photosynthesis Professor James Barber FRS (Imperial College London)
	Solar water splitting Professor Ivan Parkin (University College London)
	The Joint Centre for Artificial Photosynthesis Professor Nathan S Lewis (California Institute of Technology)
	The Towards Biosolar Cells Programme Professor Huub deGroot (University of Leiden)
Session 2	Panel Discussion: Routes to Solar Fuels Innovation Chair: Professor Laurie Peter (University of Bath)
	Dr Raymond L Orbach (University of Texas at Austin) Otto Bernsen (Agentschap NL, Dutch Ministry of Economic Affairs, Agriculture and Innovation) Dr Gernot Klotz (European Chemical Industry Council) Professor Anthony J Ryan (University of Sheffield)
Keynote Lecture	Chair: Prof David Phillips (Royal Society of Chemistry)
	Global Energy Perspectives Professor Nathan S Lewis (California Institute of Technology)