# Solar Fuels and Artificial Photosynthesis

## Science and innovation to change our future energy options

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RSC | Advancing the Chemical Sciences

www.rsc.org/solar-fuels

## About this publication

This report is intended for an audience of policy makers with interests in the UK's future energy strategies, and in UK and EU research and innovation policy. It is a non-technical introduction to the potential of solar fuels to become a viable alternative in our future energy landscape.

The RSC is committed to raising awareness of the role of chemistry in addressing global challenges and it is hoped that the report will be of interest to the wider public.

## About the RSC

The Royal Society of Chemistry is the leading society and professional body for chemical scientists. We are committed to ensuring that an enthusiastic, innovative and thriving scientific community is in place to face the future.

The RSC has a global membership of over 47,500 and is actively involved in the spheres of education, qualifications and professional conduct. We run conferences and meetings for chemical scientists, industrialists and policy makers at both national and local levels.

We are a major publisher of scientific books and journals, the majority of which are held in the RSC Library and Information Centre.

In all our work, the RSC is objective and impartial, and we are recognised throughout the world as an authoritative voice for chemistry and chemists.

## The RSC and sustainable energy

This report is supported by a wide range of ongoing RSC activities to advance renewable energy technologies, through chemistry and other sciences.

For more information on the RSC's many activities in this area, including scientific publishing, international conferences and meetings, and policy activities, see Appendix C and the RSC's online portal for Sustainable Energy.

**www.rsc.org/sustainable-energy**

# TABLE OF CONTENTS

## FOREWORD

For previous generations, the idea that we could use solar energy to produce electricity or fuel may have appeared as a remote vision. But today, harnessing the power of the sun has become a reality; photovoltaic solar panels are an increasingly common sight.

Scientists are now working towards another great breakthrough: mimicking photosynthesis, nature's way of making fuel from sunlight, on a commercial scale.

This human achievement is testament to the determination, creativity and hard work of scientists and engineers, each generation building on the knowledge gained by their predecessors. It's a journey that began in the 19th century with the discovery of the 'photovoltaic effect', whereby an electric current is produced in a material when exposed to light.

During the 20th century, we have made completely unforeseeable breakthroughs, including the discoveries and development of conducting materials which are used in modern solar cells. This pace of progress continues as chemists work closely with physicists, materials scientists and, more recently, biologists, to lay the foundation for next-generation photovoltaic technologies.

Recent scientific breakthroughs mean that, in the laboratory, it is now possible to mimic photosynthesis and to use sunlight, water and carbon dioxide to produce fuels. Scientists in the UK have played a key role in these breakthroughs, most notably in developing materials to capture and channel sunlight; deepening our understanding of photosynthesis; and discovering new catalysts to make the chemistry possible.

This report represents an important step in raising awareness of the potential of producing fuels from sunlight, so that energy from the sun can be stored and used whenever and wherever it is needed.

A future where we could run our cars and factories on clean, sustainable fuel is not just a vision. There is increasing momentum in the global scientific and engineering community to develop the chemistry and technologies that will make fuels from sunlight to limit the impact we have on our planet.

The opportunity to contribute to this global effort by current and future world-leading scientists and innovators is one that no nation can afford to miss.

**Alan J Heeger**
Professor of Physics and of Materials
Department of Chemistry and Biochemistry
University of California at Santa Barbara
2000 Nobel Prize in Chemistry 'for the discovery and development of conductive polymers'

## EXECUTIVE SUMMARY

Harnessing and securing environmentally sustainable energy supplies is one of the key societal challenges the Royal Society of Chemistry has outlined in its roadmap, *Chemistry for Tomorrow's World*. The chemical sciences have a critical role to play in developing energy solutions that will support society's move from an economy based on fossil fuels to a more sustainable energy mix.

Scientists around the world are working towards the goal of developing technologies to harness energy from the sun to produce fuels for transport, industry and electricity generation. Fuels produced using solar energy would transform our energy options in the future by providing an alternative to fossil fuels. The United States, the Netherlands and South Korea have seen recent investment in dedicated programmes for solar fuels research and innovation, and there are also renewable energy research centres in China and Japan.

While each country is implementing a different strategy, important elements of the American, Dutch and Korean programmes are that they:

- foster interdisciplinary fundamental and applied research by bringing researchers from different subfields together to collaborate;
- aim to make advances using fundamental research in order to develop commercial prototypes;
- explicitly include the goals of engaging with established industry and innovation, and maximising business opportunities for each country.

Whilst there is considerable research strength in both solar fuels and solar photovoltaics in the UK, a coherent strategy for solar energy research and innovation is crucial if the UK is to maintain its position in light of international competition. This means that we need to invest in fundamental and applied interdisciplinary research; invest in mechanisms to support the next generation of researchers; protect our intellectual property; and, create a climate that supports innovation and engagement between academia and industry.

This report explains the concept of solar fuels and their potential to transform our future energy options. It sets out the opportunities for the UK to capitalise on its existing research capabilities and position itself to benefit, both environmentally and economically, from solar fuels innovation.

## INTRODUCTION

**Scientific breakthroughs and new technologies will play a key role in securing a sustainable supply of energy for the UK, and globally, and addressing the risks of climate change and ocean acidification.**

Sustainable, low carbon energy supplies are one of the most pressing challenges facing society. The need to take immediate action has been underscored by the International Energy Agency's *World Energy Outlook 2011*[2] which concluded that 'There are few signs that the urgently needed change in the direction of global energy trends is underway', and that 'We cannot afford to delay further action to tackle climate change'.

Scientists and engineers are needed not only to find more efficient ways of producing, refining and using fossil fuels, but also to develop renewable energy solutions. The RSC highlighted the major role of the chemical sciences in addressing global energy challenges in its roadmap *Chemistry for Tomorrow's World*.[3]

New and improved sustainable energy technologies will be one way in which nations will be able to deliver on important commitments to emissions targets, such as:

- the UN Framework Convention on Climate Change and recent agreements made at the UN Climate Change Conference, Durban 2011; and
- crucial near-term voluntary national pledges to reduce emissions.

The goal of this report is to raise awareness of the concept of solar fuels and show their potential to become an additional and significant new option in our longer-term energy future. The UK urgently needs a strategy to support the interdisciplinary research, entrepreneurship and industrial partnerships required to maintain a world-leading position. Only then will the UK be in a position to benefit both environmentally and economically from solar fuels in the long-term.

Other countries have made significant investment and strategic concentration of resources in solar fuels research and innovation. There is a risk that the UK will miss the opportunity to capitalise on its capability in this area.

***'Our sun is the champion of energy sources: delivering more energy to the earth in an hour than we currently use in a year from fossil, nuclear and all renewable sources combined. Its energy supply is inexhaustible in human terms, and its use is harmless to our environment and climate.'*[1]**

**Professor James Barber CChem FRSC FRS**
Ernst Chain Professor of Biochemistry
Imperial College London

## PART 1: THE POTENTIAL OF MAKING FUELS USING SUNLIGHT

### 1.1 What are solar fuels?

**The sun delivers more energy to the earth in one hour than we currently use from fossil fuels, nuclear power and all renewable energy sources combined in a year. Its potential as a renewable energy source, therefore, is vast. If we can develop systems to use solar energy to produce fuels on a large scale, this will transform our future energy options.**

There are various ways in which human beings are harnessing solar energy, such as for electricity and heating, and through biofuels and food. These are discussed in more detail in Appendix A. The focus of this report is solar fuels, or fuels produced directly using sunlight.

Currently, most fuels for transport, electricity generation and many raw materials for industry (feedstocks) are produced from coal, oil or natural gas. But an alternative route to producing liquid and gaseous fuels could be using technologies that harness sunlight. See Figure 1.

Solar energy can be captured and stored directly in the chemical bonds of a material, or 'fuel', and then used when needed. These chemical fuels, in which energy from the sun has deliberately been stored, are called solar fuels.

What is new here is not the fuels themselves, but the way that we can use energy from the sun to produce them. The word 'fuel' is used in a broad sense: it refers not only to fuel for transport and electricity generation, but also feedstocks used in industry.

This concept of making fuels using sunlight is the basis of photosynthesis, where sunlight is used to convert water and carbon dioxide into oxygen and sugars or other materials which can be thought of as fuels. See Figure 2.

Figure 1

**What could the production and use of solar fuels look like?**

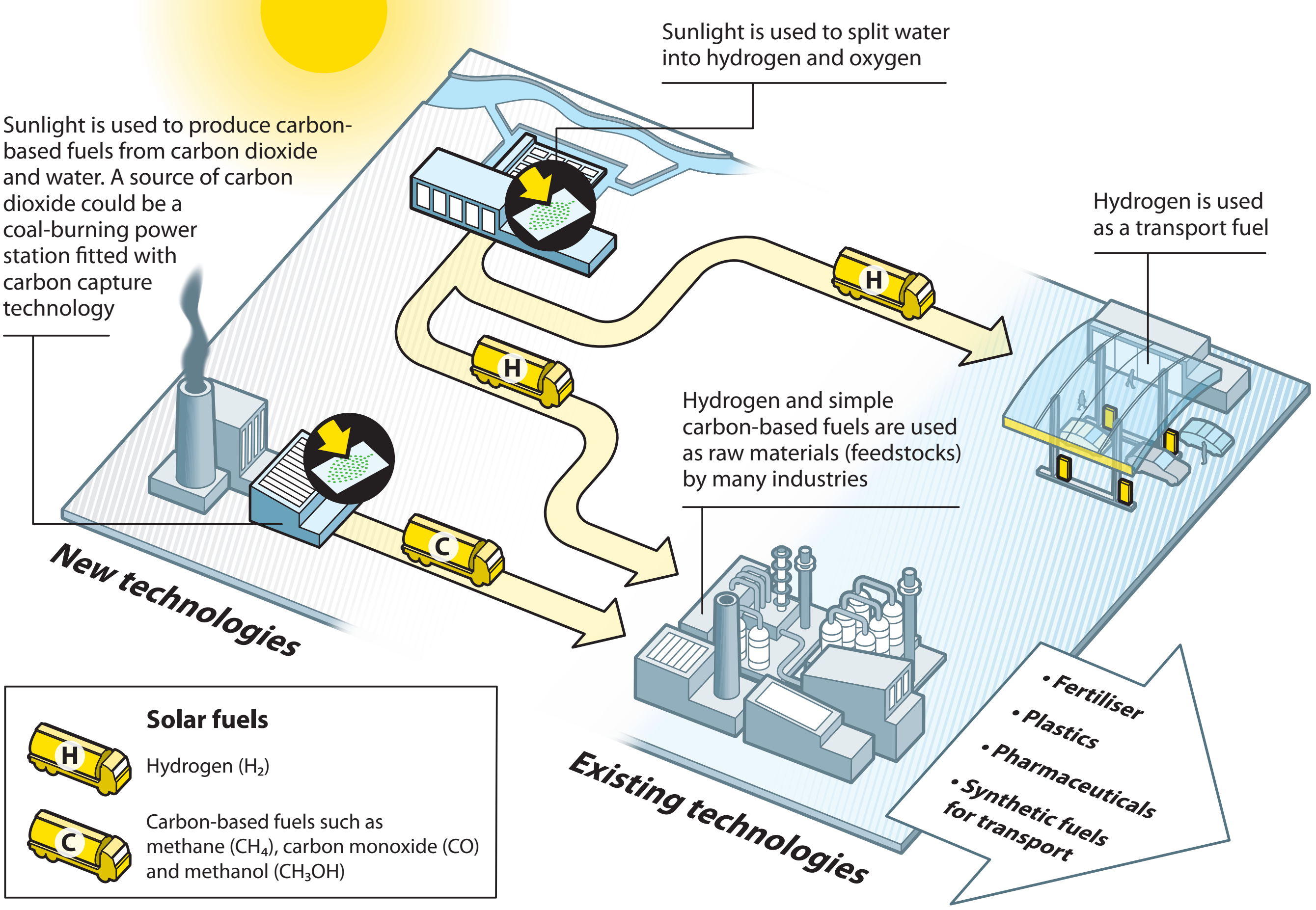
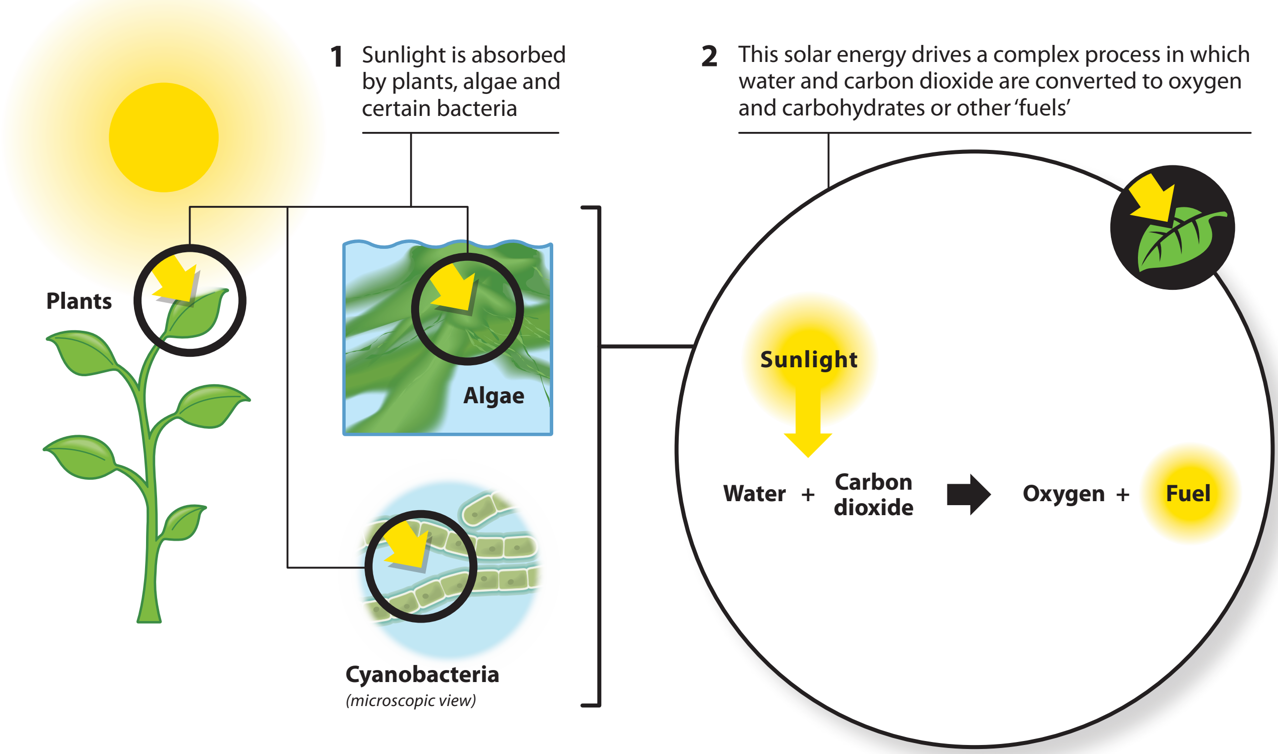


Figure 2

**Photosynthesis: Nature's way of making solar fuel**




For over half a century, scientists have pursued the possibility of producing solar fuels in the laboratory. There are three approaches:

- artificial photosynthesis in which systems made by human beings mimic the natural process;
- natural photosynthesis; and
- thermochemical approaches.

These processes to produce solar fuels are discussed in more detail in Part 2 and in Appendix B.

Over the last ten years the drive to develop systems to produce solar fuels on large scales has been an area of increasingly intense global research activity. It is also now attracting commercial interest.

Scientists have made significant progress in producing two very important types of fuels.

**Hydrogen** which can be used as a transport fuel and is an important feedstock for industry. Hydrogen can be produced by splitting water using sunlight. See Figure 3.

**Carbon-based fuels** such as methane or carbon monoxide.[i] These are key feedstocks for making a wide range of industrial products including fertilisers, pharmaceuticals, plastics and synthetic liquid fuels.

Carbon-based fuels can be produced using sunlight, carbon dioxide and, for example, water.

[i] *used with hydrogen as synthesis gas.*

## 1.2 How would solar fuels change future energy options?

**The challenge of moving from laboratory prototype systems to commercial technologies is significant. However, if this new route to producing fuels is achieved on a large scale, it would transform our sustainable energy options by providing alternatives to oil, gas and coal as sources of fuel for transport, industry and electricity generation.**

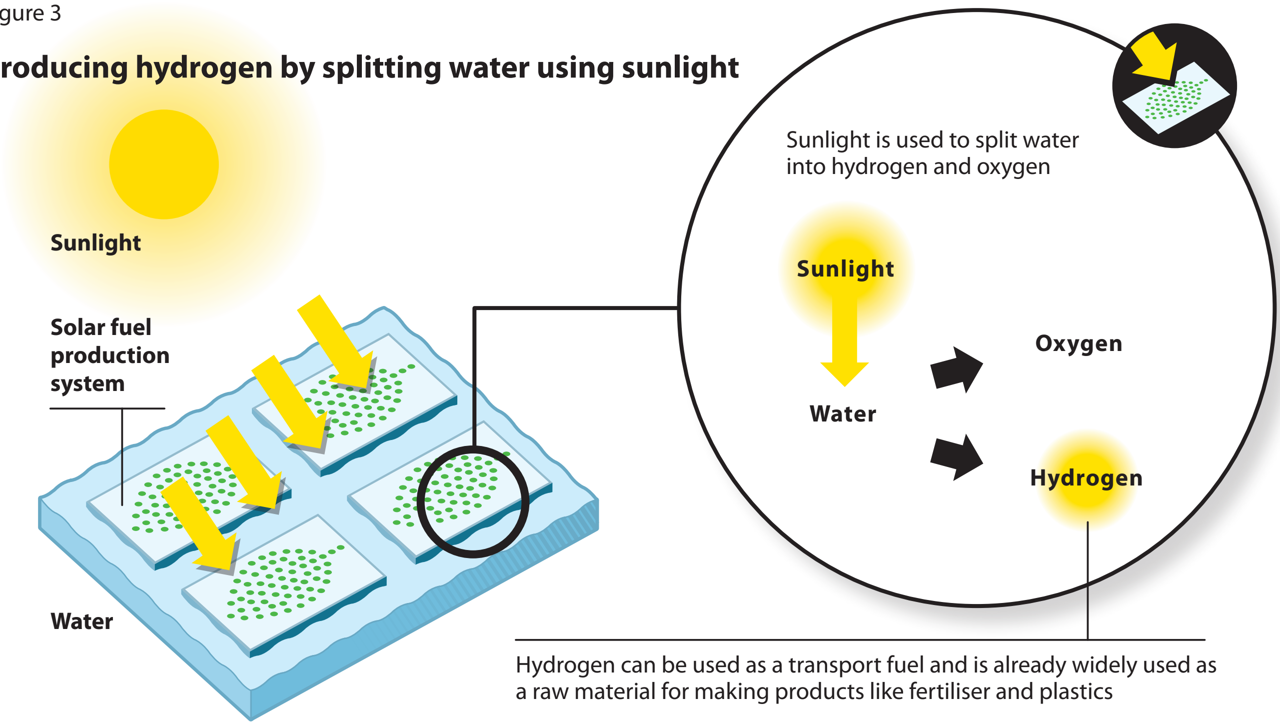
### 1.2.1 A way to store and transport solar energy

One of the challenges of solar and other intermittent renewable energy sources (like wind and wave power), is how to store the energy. For solar energy to become a practical and widespread component of our energy mix, new technologies to store it are vital so that solar power is available when there is little or no sunlight.

Solar fuels address this challenge as energy from the sun is stored in the chemical bonds of the fuels. The concept of producing and storing solar fuels is shown in Figure 4.

Figure 3

**Producing hydrogen by splitting water using sunlight**




Hydrogen can be used as a transport fuel and is already widely used as a raw material for making products like fertiliser and plastics

A second challenge for intermittent renewable energy sources is transporting energy from the place where it is captured to where it is needed. Solar fuels are easily transported using existing distribution networks by road, rail or sea. See Figure 1.

Solar fuels can also be combined with fuel cell technologies, which convert fuels to electricity, to power a building or small community. This is shown in Figure 4, where the solar fuel could be hydrogen or methane. An example of a demonstrator project in the UK where a building has been powered by a fuel cell is a leisure complex in Woking[4] (although the fuel in this case is not produced from sunlight).

### 1.2.2 A way of producing renewable liquid fuels for transport

Globally, just over 60% of world oil consumption is for transport[5] and, in affluent countries like the UK, transport typically accounts for about one third of the average energy consumption per person.[6]

Current UK policy analyses, such as the recent *Renewable Energy Review* by the Committee on Climate Change,[7] focus on biofuels, electric and hybrid electric vehicles as sustainable transport options. This report highlights that, in the longer term, solar fuels could be an important new option in addressing the issue of sustainable transport. These fuels could be used for light vehicles and, perhaps more significantly, for air and ocean transport, which are more challenging to electrify.

According to a large ongoing study[8] by the Committee on America's Energy Future, there are limited options for replacing or reducing the use of petroleum, at least in the United States, before 2020. In terms of cost, one of the report's conclusions is that producing liquid fuels from coal is the least expensive option but that there are important health and environmental issues associated with it. In contrast, liquid fuels produced directly using sunlight and abundant materials like water and carbon dioxide would avoid the need for coal.

There are two ways that solar fuels could be used to provide sustainable fuels for transport. The first is using hydrogen to power hydrogen vehicles. The second is using a combination of hydrogen and carbon monoxide (often referred to as synthesis gas, or syngas) to make liquid fuels for transport (often referred to as synthetic fuels). This conversion of hydrogen and carbon monoxide into synthetic fuels is called the Fischer-Tropsch process. Currently, synthetic liquid fuels are produced from coal and natural gas by a growing Fischer-Tropsch industry.[9]

### 1.2.3 A source of renewable fuels for established industries

Many of the products that we use, such as fertilisers, pharmaceuticals and plastics, are made, primarily, from feedstocks such as hydrogen and simple carbon-based molecules, which are derived from fossil fuels (see box overleaf). Producing these feedstocks also requires a lot of energy.

The capability to produce feedstocks using sunlight and abundant materials such as water and carbon dioxide would therefore be a major breakthrough in reducing our dependence on fossil fuels – both as feedstocks and energy sources.

An example is hydrogen which is widely used in industry as a feedstock, and is mainly produced in a process called 'natural gas steam reforming'. Concerns about the fossil fuel-derived energy required and the associated greenhouse gas emissions make alternative routes to producing hydrogen, such as producing it using sunlight, desirable.

## 1.3 Solar fuels, hydrogen transport and carbon capture

**Long-term, solar fuels could provide an alternative to fossil fuels. They would also play an important role in enabling or enhancing other sustainable energy technologies such as hydrogen transport and carbon capture, storage and use.**

### Hydrogen transport

Hydrogen vehicles operate either by combining hydrogen and oxygen in a fuel cell to produce water and electricity to power a motor (for example the Honda FX Clarity), or by burning hydrogen (for example the BMW Hydrogen 7).

Fuel-cell-grade hydrogen is currently produced in processes that require at least as much energy as natural gas steam reforming (see section 1.2.3).

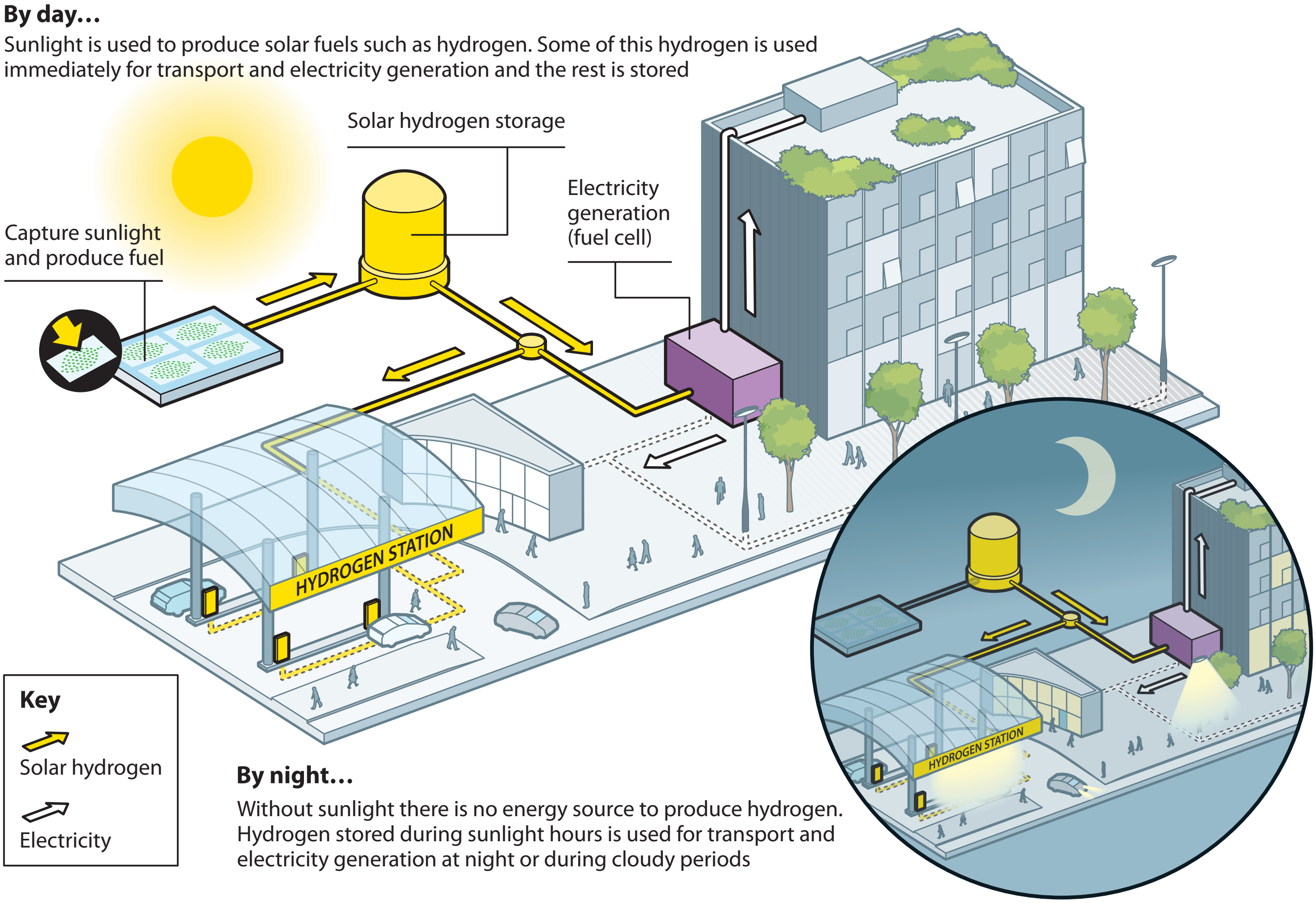
One of the challenges for hydrogen transport, therefore, is to find alternative ways to produce hydrogen.

Figure 4

**Solar energy around the clock**

**By day…**

Sunlight is used to produce solar fuels such as hydrogen. Some of this hydrogen is used immediately for transport and electricity generation and the rest is stored




**By night…**

Without sunlight there is no energy source to produce hydrogen. Hydrogen stored during sunlight hours is used for transport and electricity generation at night or during cloudy periods

**Hydrogen and carbon-based feedstocks are widely used in industry.**

### Fertilisers

Instrumental in increasing agricultural productivity worldwide, fertilisers will continue to play an important role in feeding the world's growing population. A key stage in fertiliser production is the Haber-Bosch process in which ammonia is produced from nitrogen and hydrogen. Fertiliser production, including the step of producing hydrogen by natural gas steam reforming, consumes around 1% of global energy supplies and around 4% of natural gas supplies.[10]

### Pharmaceuticals

Simple hydrogen and carbon-based feedstocks derived from fossil fuels are the starting point in many of the process chains in the pharmaceutical industry.

### Plastics

Hydrogen and carbon are the two primary constituents of many plastics. An example is polyethylene which consists of long chains of ethene ($C_2 H_4$). These are produced, predominantly, by the petrochemical industry, although bioplastics, derived from renewable sources, are becoming more widespread.

### Synthetic fuels

An area of increasing investment is the production of liquid fuels using the Fischer-Tropsch process which converts a mixture of carbon monoxide and hydrogen (CO and $H_2$), often called synthesis gas or syngas, to a liquid fuel.[9] Currently, this syngas is mainly produced from coal and natural gas.

**For all four types of products, if hydrogen or carbon-based feedstocks such as carbon monoxide and methane could be produced from sunlight, water and carbon dioxide, this would provide an alternative to natural gas, oil and coal as raw materials. Solar energy would also replace fossil fuel-derived energy in the production process.**

There are other challenges, such as storing hydrogen and improving fuel cell technologies, but if hydrogen were produced using sunlight, this would be a major step forward in enabling its use as a transport fuel on a large scale.

## Carbon capture, storage and use

According to the 2011 *World Energy Outlook*[2] coal accounts for nearly half of the increase in global energy use over the past decade, with the bulk of the growth coming from the power sector in emerging economies. Given the significant emissions associated with burning coal, technologies for capturing and storing carbon dioxide are being researched globally.[11] In the UK, the government has recently reaffirmed its £1 billion commitment to carbon capture and storage projects.[12]

But rather than long-term storage of carbon dioxide captured from fossil-fuel burning power stations (a major technological challenge in itself) an attractive prospect is to use some of it to produce fuels and feedstocks.[11] This is one area of interest to the CO2Chem network[13] in the UK. According to a recent review by a group of UK chemical scientists, 'the biggest obstacle for establishing industrial processes based on $CO_2$ is the large energy input which is required to reduce it in order to use it.'[14]

Sunlight could provide the energy needed to produce fuels from carbon dioxide. Figure 1 shows how carbon capture technology could provide a source of carbon dioxide which, combined with water and solar energy, would be used to produce useful carbon-based fuels such as carbon monoxide (combined with hydrogen as syngas), methane or even methanol. These are used as feedstocks by established industries as described in 1.2.3.

# PART 2: SOLAR FUELS: SCIENCE AND INNOVATION

**UK scientists are making world-class research contributions towards developing systems to produce solar fuels on a commercial scale. But in comparison with the level of activity internationally, there is a concern that the UK will not be able to compete in the long-term without a coherent strategy for research and innovation in solar energy.**

This section surveys the approaches to, and challenges in, producing solar fuels on commercial scales. It also gives an overview of research and innovation in the UK and internationally.

Recently, there have been major scientific breakthroughs in developing systems that produce fuels from sunlight.

These include:

- significant breakthroughs in our understanding of the molecular mechanisms in natural photosynthesis and in catalysis;
- developing new materials that harvest sunlight and channel it to produce electricity and fuels; and
- developments in nanotechnology.

There have also been advances in other new energy technologies such as fuel cells and carbon capture.

These breakthroughs, along with concerns about energy security and climate change, have led to increased efforts to produce solar fuels. Many nations are increasing their investment in dedicated interdisciplinary solar fuels research programmes, particularly the US, the Netherlands and South Korea.

These national programmes aim to support solar fuels research: from fundamental research, through development, to commercial solar fuel production systems. There are real opportunities for the UK to take its place at the forefront of this international effort.

## 2.1 Scientific approaches to producing solar fuels

**Scientists are exploring three main approaches to using sunlight to make fuels. Some of these are interrelated, where advances in one area often support progress in others.**

Nature has developed a highly sophisticated system to convert solar energy into fuel. In photosynthesis, plants, algae and some types of bacteria absorb sunlight and channel it to convert water and carbon dioxide into oxygen and carbohydrates. These carbohydrates (sugars and starches) can be thought of as 'fuels' that provide the energy that enables plants and animals to live, grow and reproduce (see Figure 2).

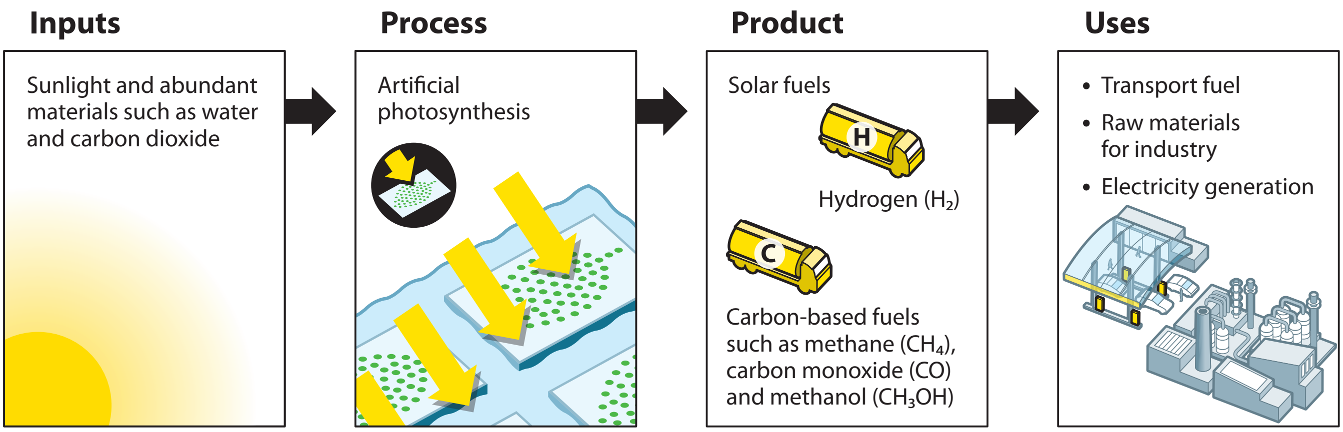
Scientists are currently pursuing three main approaches to produce solar fuels.

### Artificial photosynthesis

This is a term that has emerged to describe processes which use a broad range of systems to mimic natural photosynthesis: sunlight is harvested and the energy is used to chemically convert water and carbon dioxide into fuels.[1] Artificial photosynthesis is the process and solar fuels are the products. See Figure 5.

Figure 5

**Artificial photosynthesis pathway from sunlight to fuels**



### Photosynthesis

There is significant research activity exploring how to produce hydrogen and more complicated fuels directly from the photosynthetic reactions of living organisms such as algae and bacteria.[15]

Researchers at the University of Cambridge demonstrated this concept to the public at the 2010 Royal Society Summer Science Exhibition.[16]

There is a natural interplay between research in artificial photosynthesis and natural photosynthesis. For instance, by advancing our understanding of the natural process, scientists can generate ideas for how to mimic aspects of it.

Some large-scale research programmes are pursuing both approaches to solar fuels production, such as the Towards Biosolar Cells[17] consortium in the Netherlands, discussed in section 2.4.

### Thermochemical production

These approaches are based on using sunlight to heat substances to very high temperatures so that they react with steam or carbon dioxide to produce carbon monoxide or hydrogen.

A European example is a series of EU-funded Hydrosol projects, the latest of which is Hydrosol 3D[18] which aims to lead to a demonstration plant. In the US, both Sandia National Laboratory and the US Airforce have active programmes in this area.[19]

## 2.2 Challenges in large-scale production of solar fuels

**Scientists and engineers are working together on significant scientific and technological challenges to successfully scale up laboratory prototypes to a commercial scale.[20]**

If solar fuels are to become part of our sustainable energy mix, the systems to produce them must be:

- **Efficient**, so that they harness as much of the sunlight hitting them as possible to produce fuels. The larger the fraction of sunlight that can be converted to chemical energy, the less materials and land would be needed. A target efficiency of about 10%, which is about ten times the efficiency of natural photosynthesis[21], would be an initial goal.[ii]
- **Durable**, so that they can convert a lot of energy in their lifetime relative to the energy required to install them. This is a significant challenge because some materials degrade quickly when exposed to sunlight.
- **Cost effective**, so that solar fuels are commercially viable.

If we are to successfully develop efficient, long-lasting and commercially viable solar fuels production systems, we need to support diverse areas of fundamental and applied research in chemistry, other sciences and engineering.

Artificial photosynthesis requires the expertise of all of these communities working together to address some of the key challenges such as:

- integrating the different processes and materials involved, from capturing and channelling sunlight through to producing a chemical fuel;
- identifying inexpensive catalysts to drive different aspects of the process;
- developing ways to avoid the system degrading quickly because of exposure to sunlight.

Since the 1950s scientists have been developing systems to produce solar fuels using artificial photosynthesis, natural photosynthesis and thermochemical routes. An overview of scientific advances in artificial photosynthesis is given in Appendix B.

## 2.3 Research and innovation in the UK

**The UK has considerable research capability in solar energy, both in solar fuels and photovoltaics. UK researchers have also demonstrated entrepreneurial initiatives and industrial partnerships in next-generation photovoltaics. There are significant opportunities for the UK to build on its position through a coherent strategic approach to solar fuels research and innovation.**

This section gives some examples of current research projects related to solar fuels funded by UK research councils and European sources, and discusses potential or related innovation. There is some overlap between solar fuels and photovoltaics research and innovation because, in both cases, scientists need to understand and develop systems that harvest and channel the sun's energy.

[ii] *There are really two challenges here – to convert as much of the solar radiation spectrum as possible, from infrared to ultraviolet, and to convert a large fraction of the light at each frequency (or colour) into chemical energy.*

### 2.3.1 UK research

There are many examples of current research projects related to solar fuels.

**The Engineering and Physical Sciences Research Council (EPSRC)** supports several projects through the Towards a Sustainable Energy Economy programme.[22]

- New and Renewable Solar Routes to Hydrogen is led by Imperial College London and is targeting both artificial and natural photosynthetic routes to solar-derived hydrogen (£4 million);
- Artificial Photosynthesis: Solar Fuels is led by the University of Glasgow (£1.6 million);
- The SolarCAP consortium of researchers are based at the Universities of East Anglia, Manchester, Nottingham and York; they are working to develop solar nanocells for the production of carbon-based solar fuels (£1.7 million).

**EPSRC SUPERGEN** programmes also focus on photovoltaics, and the EPSRC recently announced a call for applications for a new Solar Energy Hub, with funding of up to £4 million. One feature of the new hub will be that: 'The institutions involved in the successful application will be expected to take a leadership role in the solar energy research community.'[23]

**The Biotechnology and Biological Sciences Research Council (BBSRC)** recently announced a highlight notice for research proposals on the generation of hydrocarbons from living organisms.[24] This is part of its Bioenergy and Biotechnology Priority Area.

The BBSRC is also a partner in the European Science Foundation's EuroSolarFuels programme[25] which has funded projects led by the University of Glasgow and Imperial College London.

**The Research Councils UK (RCUK)** supports a cross-council programme, Nanoscience: through Engineering to Application. This has three complementary research projects (at UCL, Imperial College London, and the Universities of Bath, Bristol and the West of England) with a total investment of £4 million to turn carbon from a pollutant into useful products.[26]

**The Christian Doppler Laboratory for Sustainable Syngas Research** will be launched at the University of Cambridge in 2012, funded by the Christian Doppler Society (Republic of Austria) and OMV, the Austrian oil company.

Continued support for this kind of fundamental research across a range of subfields in the chemical and other sciences will play a key role in achieving the kinds of breakthroughs that are needed to produce practical technologies to produce solar fuels.

Examples of key research areas include:

- the photocatalytic and electrochemical properties of organic and inorganic materials;
- catalysis;
- molecular mechanisms for light harvesting and transport;
- nanomaterials;
- the structure and properties of surfaces.

### 2.3.2 UK innovation and industry

The RSC is not aware of any UK university start-up companies that have been established to develop technologies aimed at solar fuels production.

There are, however, several university spin-out companies (Eight19, g24i, Molecular Photovoltaics, Ossila, Oxford Photovolatics, Solar Press) already working to commercialise next-generation photovoltaic technologies.

Companies from established industrial sectors - such as the automotive, catalysis, construction and energy sectors - are engaged with developments in solar fuels research in a variety of ways.

For example, Johnson Matthey is actively monitoring technologies that would require catalysis in the overall conversion of sunlight into useful chemicals, but believes that there has to be a clear business advantage for making products this way over conventional chemical routes.

Companies such as Merck, Pilkington and CristalGlobal are also engaged with research in next-generation applications using both photovoltaic and photocatalytic technologies.

OMV, the Austrian oil company, has recently partnered with the Christian Doppler Society to fund a seven-year project at the University of Cambridge. This will focus on using sunlight to produce syngas from carbon dioxide and water, as described in section 2.3.1.

Tata Steel has invested in the Sustainable Building Envelope Centre in collaboration with the Welsh Assembly Government and the Low Carbon Research Institute, and has expanded its photovoltaics development project with Dyesol, also in Wales.[27]

Swansea University and Tata Steel are also leading on an Innovation and Knowledge Centre – the Sustainable Product Engineering Centre for Functional Industrial Coatings. This has funding from the Technology Strategy Board and the EPSRC.

The UK also has significant research activity in fuel cells. For example, the AIM-quoted company Ceres Power, based in the UK, produces fuel cells that can generate both electricity and heat from fuel and air. Its products are based on unique UK-owned technologies.[28]

## 2.4 Research and innovation globally

**Internationally, there is a trend towards investing in large coherent interdisciplinary programmes for energy research and innovation.**

There are programmes dedicated to solar fuels research and innovation in the United States, the Netherlands and South Korea, as well as renewable energy research centres in China and Japan. There is also evidence of some industries investing in solar fuels research and innovation.

The UK should consider similar strategies to ensure that UK science and innovation are major players in this emerging field.

> ***'The end goal of JCAP, the Joint Center for Artificial Photosynthesis, a DOE Energy Innovation Hub, is to develop and ultimately enable the deployment at scale of an artificial photosynthesis technology that will directly produce fuels from sunlight, and which simultaneously is cheap, robust, and efficient. This would truly revolutionize our clean energy choices in unprecedented ways. Because the prize is so great, the effort must be pursued as an imperative to achieve a truly sustainable, clean, affordable, and scalable global clean energy system.'***
>
> **Nathan S. Lewis,**
> Director, Joint Center for Artificial Photosynthesis
> George L. Argyros Professor of Chemistry
> California Institute of Technology

### United States

There has been a renewed focus in funding and political support for solar fuels in the US with the announcement of a new Department of Energy (DOE) Energy Innovation Hub which President Obama referred to in his January 2011 State of the Union address.[29] This hub is in addition to other projects funded by the DOE and the US National Science Foundation.

The hub, called the Joint Center for Artificial Photosynthesis (JCAP),[30] will receive $122 million of funding over a period of five years. It is being led by the California Institute of Technology in partnership with Lawrence Berkeley National Laboratory and SLAC National Accelerator Laboratory. A select group of universities are also involved. The premise of the centre is that by bringing scientists and engineers together under one roof, they can accomplish more, and faster, than working separately.

There are also examples of early stage solar fuels innovation in the US such as the MIT spin-out, Sun Catalytix,[31] (which completed its $9.5 million Series B Funding Round, led by Tata Limited in 2010), and the Princeton University spin-out, Liquid Light.[32]

### Europe

The largest single national investment in a solar fuels research project has been by the Dutch government in a €25 million project, Towards BioSolar Cells.[17] This interdisciplinary consortium of six universities is working on solar fuels production by both natural and artificial photosynthesis. It is explicitly set up to build links with existing industry to develop an incubation structure for new business.

Other projects include the European Science Foundation's EuroSolarFuels programme (referred to in 2.3.1) and SOLARH2, led by Uppsala University in Sweden, which received approximately €4 million under the European Commission's Seventh Framework Programme (FP7) for research.

Two other projects funded as part of FP7 are Nanostructured Photoelectrodes for Energy Conversion (NANOPEC), at €3.94 million, and Nanodesigned Electrochemical Convertor of Solar Energy in Hydrogen Hosting Natural Enzymes or their Mimics (SOLHYDROMICS), at €3.65 million.

## South Korea

The Korean Centre for Artificial Photosynthesis (KCAP) was launched at Sogang University in 2009[33] and, the following year, signed a memorandum of understanding on international research with the Solar Energy Research Centre (SERC) of the Lawrence Berkeley National Laboratory in the US. In 2011, the centre made a cooperation agreement with steel company POSCO to undertake joint research on the commercialisation of artificial photosynthesis. POSCO is constructing a dedicated building, due to be completed in 2012, for this research programme.

## China

In China, the Institute for Clean Energy was recently inaugurated and forms part of the Chinese Academy Institute of Chemical Physics in Dalian.

## Japan

In 2007, the Japanese government launched its World Premier International Research Center Initiative.[34] Each multidisciplinary basic research area receives around ¥1.4 billion per year over a 10 to 15 year period to create centres for research.

The most recent centre to be announced is the International Institute for Carbon-Neutral Energy Research in Kyushu. Two other projects within the initiative – the International Center for Materials Nanoarchitectronics and the Advanced Institute for Materials Research[35] – also include research related to artificial photosynthesis.

Japanese automotive companies are involved in solar fuels research and development. There is an active research programme in artificial photosynthesis at Toyota Central R&D Labs[36] and, last year, Honda announced plans to build a second station to produce hydrogen from sunlight and water in Saitama Prefecture by the end of March 2012.[37]

# PART 3: OPPORTUNITIES FOR THE UK

**Renewable energy industries can develop very rapidly once commercially viable – the growth we have seen in the silicon photovoltaics industry is a prime case. The UK has the opportunity to position itself among the front-runners if new solar energy industries develop. The UK needs to develop a strategy now to build skills for the future, invest in research, protect intellectual property, and foster entrepreneurship and partnerships with industry.**

Scientists and engineers around the world have developed systems to produce fuels, such as hydrogen and simple carbon-based fuels, using water, carbon dioxide and the sun's energy.

Significant challenges remain in moving from these research prototypes to commercial systems. If these challenges can be overcome, however, it will transform our energy options in the future by providing a way to store and transport solar energy for use anywhere and anytime, and by providing a source of sustainable fuels for transport. It will also provide an alternative to fossil fuels as feedstocks for industry.

There are opportunities for the UK to build on its strengths in solar fuels research and position itself to benefit economically and environmentally from potential new technologies.

The RSC has identified two interrelated areas where the UK should consider how to maximise the potential benefits of a solar fuels industry: research and innovation, and capacity building.

## 3.1 Research and innovation

**The UK has many world-leading scientists who are working on solar fuels. So that the UK can retain its position, we need strategies for future investment in research and innovation in this field, particularly in light of international competition.**

The United States, the Netherlands and South Korea, have invested in large-scale, interdisciplinary research programmes specifically in solar fuels. China and Japan have dedicated centres for renewable energy research, where solar fuels are an area of substantial effort.

While each country is implementing a different strategy, important common elements of the American, Dutch and Korean programmes are that they:

- foster interdisciplinary research by bringing researchers from different subfields together to collaborate on projects;
- aim to make advances using fundamental research in order to develop commercial prototypes;
- explicitly include the goal of innovation and maximising commercial opportunities for each country.

There is some overlap between research in light harvesting materials for solar fuels and for photovoltaics, discussed in Section 2.3. Given the UK's existing strengths in this area, a UK strategy could build on this and potentially be part of a broader initiative focused on solar energy.

### 3.1.1 Research and innovation supporters

In the UK there is already support for research in solar energy and for university spin-outs in photovoltaics, as well as initiatives such as the Sustainable Building Envelope Centre (funded by Tata Steel) and the SPECIFIC Innovation and Knowledge Centre. This is provided by the UK Research Councils, especially the EPSRC and the BBSRC, along with the Technology Strategy Board, and the Carbon Trust. These organisations are likely to be very important in developing any strategy specifically targeting solar fuels.

There are also opportunities for research programmes to build links with, and draw investment from, existing industrial sectors with interests in fuels and sustainable energy technologies. The energy sector, automotive and catalysis sectors, and the sustainable building sector are all potential partners.

The UK should also explore opportunities to link with initiatives at a European level, for example, as part of the €80 billion Horizon 2020 programme for investment in research and innovation,[38] proposed recently by the European Commission.

### 3.1.2 Intellectual property

Whilst not the only way the UK could benefit from technologies that are eventually commercialised, the issue of protecting early intellectual property is important. There is evidence, however, that this is not currently a UK strength.

The UK Intellectual Property Office recently carried out an analysis of published worldwide patent documents related to graphene, which causes some concern. Graphene is an area of research that has seen a recent surge of activity towards innovation. The data shows that less than 2% of these patent documents belong to UK-based applicants and less than 2.5% belong to UK resident inventors. This suggests that, despite considerable strengths in fundamental graphene research, 'the UK is falling behind other high-tech nations such as the USA, Japan, Korea and Germany when it comes to research in graphene and its potential commercial applications.'[39]

With this in mind, any UK strategy for solar energy research programmes should consider how to protect intellectual property and associated commercial opportunities.

## 3.2 Capacity building

**The UK needs to develop strategies for investing in the next generation of solar energy researchers, entrepreneurs and industrialists.**

### 3.2.1 Higher education and research

As well as supporting the UK's current world-class researchers and innovators, the UK needs to consider those who will be the UK's solar energy experts in the future. These include PhD students, postdoctoral researchers and university faculty members who are progressing towards leadership positions. It also includes undergraduate students in chemistry and other sciences who may pursue solar energy-related careers in industry, academia and policy.

In spring 2012, the RSC will publish a report setting out visions and recommendations for the future chemistry landscape. It will include potential strategies to support future generations of researchers, entrepreneurs and industrialists.

### 3.2.2 A framework for chemistry education

At an even earlier stage, those involved in teaching and communicating science – and chemistry in particular – must inspire and equip the next generation of scientists with the knowledge and skills needed as a foundation for further study.

The UK needs a science curriculum that is relevant to the challenges we face as a society, and that emphasises the crucial role of chemistry in tackling these challenges through fundamental and applied research.

In 2011, the RSC launched a report setting out a context-based framework for the curriculum for age ranges 11-14 and 14-16. *Developing a Global Framework for Chemistry Education*[40] links learning outcomes to the fundamental science behind solving societal challenges, such as sustainable energy, as identified in the RSC's roadmap.[3]

# APPENDICES

## APPENDIX A: OTHER METHODS OF HARNESSING SOLAR ENERGY

**There are several ways in which sunlight is already being turned into useful power.**

### Solar electricity

#### Photovoltaics

The main technology in the UK is photovoltaics, where homeowners have solar panels installed on their property. There are also examples, such as the 40 MW Waldpolenz Solar Park near Leipzig in Germany, where there are large arrays of photovoltaic panels, or solar farms, which generate electricity on much larger scales.

The vast majority of current photovoltaic technology in use is based on crystalline silicon. This industry has undergone significant growth, globally, in recent years. There are other photovoltaic technologies which are used for specialised applications, as well as many new technologies, such as organic and dye-sensitised solar cells, emerging from very active research and development in the UK and elsewhere.

#### Concentrating solar power

Another approach to large-scale solar electricity generation involves concentrating solar energy using mirrors and lenses to produce heat. These technologies heat oils and molten salts to high temperatures, and the stored heat can then be later used for electricity generation, day and night. A recent example is the new 20 MW Gemasolar plant in Spain, based on molten salt heat storage technology.[41]

The European Academies Science Advisory Council highlighted in a recent report the potential of concentrating solar energy for electricity, both in Southern Europe and as a component of a larger grid in the region of Europe, the Middle East and North Africa (EU-MENA).[42]

#### Other solar electricity

There are other ways in which electricity can be generated using sunlight which are not at a commercialised stage. These include using living organisms such as algae or using solar fuels in an electrochemical fuel cell.

### Solar heating

The simplest solar heating technology is a panel that heats water which can be used to provide heating and hot water for a home or larger premises.[43] There are also systems where solar energy is stored as heat in a material and combined with heat pump technology. This system is used by UK company, ICAX.[44]

These systems can provide 24-hour heating to a home or community, and can also store energy from the sun during the summer to provide heating for buildings during the winter.

### Biofuels and food crops

Biofuels are produced by harvesting and then processing plants and algae. And crops are grown and harvested for food. In both cases, sunlight is the source of energy, converted naturally by photosynthesis.

## APPENDIX B: SCIENTIFIC ADVANCES IN ARTIFICIAL PHOTOSYNTHESIS

**Artificial photosynthesis is a term that has emerged to describe processes that, like natural photosynthesis, harvest sunlight and use this energy to chemically convert water and carbon dioxide into fuels.[1]**

Research in artificial photosynthesis is highly interdisciplinary – its challenges span the physical sciences, biological sciences and engineering. Subfields of the chemical sciences such as photochemistry, electrochemistry, materials chemistry, catalysis, organic chemistry and chemical biology will continue to play a crucial role in pursuing the artificial photosynthesis approach to producing solar fuels.

In the last decade there has been a huge increase in momentum in this field, mainly in the scientific research community. The two main avenues being explored are water-splitting and carbon dioxide reduction. Progress in these areas is summarised here.

### Water-splitting

Scientists first successfully produced hydrogen and oxygen by splitting water (see Figure 3) using artificial photosynthesis in the 1950s when there were many breakthroughs using both biological and physical systems. However, these early systems were cost-prohibitive and not efficient or durable enough for large-scale use.[45]

Over the past ten years, there has been a revival of research into water-splitting[46] which has attracted some initial commercial investment. In 1998, scientists at the National Renewable Energy Laboratory in Colorado produced a solar hydrogen generator that is four times as efficient as photosynthesis. This system was, however, too costly to develop commercially as it used platinum electrodes and gallium-indium-based photovoltaic cells.[45]

There are now many laboratory prototypes of systems that use sunlight to split water to produce hydrogen. Some examples that have been demonstrated to the public are the exhibition by scientists from the UK SolarCAP consortium at the Royal Society Summer 2011 exhibition,[47] and a video demonstration by the Energy Institute at the University of Texas at Austin.[48]

In March 2011, scientists in the US announced they had developed an inexpensive and efficient prototype 'artificial leaf',[49] although the issue of the long-term stability of this system has yet to be fully explored.

The field of water-splitting is at the stage where there is a need for standardisation so that test results are quoted at a neutral water pH, for example, and efficiencies are calculated based on illumination using a standard solar lamp.[50]

In January 2010, Japanese car manufacturer Honda announced that they had begun operating a solar hydrogen station prototype at their R&D centre in Los Angeles,[51] although it is too costly to scale-up commercially.

Entrepreneurial initiatives include the SunHydro chain of solar hydrogen fuelling stations between Maine and Florida.[52] These hydrogen stations, like the 1998 National Renewable Energy Laboratory prototype, are based on a system where solar photovoltaic electricity is used to split water into hydrogen and oxygen by electrolysis.

It is not yet clear which process will emerge as the most commercially viable in terms of efficiency, durability and cost: photo-electrochemical artificial leaf-type cells, or photovoltaic cells combined with electrolysers.

## Reducing carbon dioxide

Sunlight can be used to produce fuels from carbon dioxide combined with other materials such as water. The fuel products include carbon monoxide, formic acid, methanol and methane. The process is called carbon dioxide reduction, and it can either be achieved directly in a photoreactor or indirectly using solar-derived hydrogen as a 'reductant'.

The multielectron chemistry involved in these processes makes this a particularly challenging technology.

One strategy is to use approaches inspired by photosynthesis to reduce carbon dioxide. Scientists are also exploring other enzymes from microorganisms, such as carbon monoxide dehydrogenase.

Early photocatalysts required ultra-violet radiation rather than visible light to reduce carbon dioxide to carbon monoxide. But chemists are now developing these to work with light in the visible range. For example, a collaboration between the Universities of Oxford and Michigan recently reported on a system that produces carbon monoxide from carbon dioxide using visible light and an electron source.[53]

Scientists are also developing catalysts that can be used to generate methanol or methane. Researchers are also combining photochemical and electrochemical methods so that the reaction of carbon dioxide at an electrode is light-assisted.

## APPENDIX C: THE RSC AND SOLAR FUELS

**The RSC organises and supports a wide range of activities to advance renewable energy technologies, through chemistry and other sciences. These include scientific publishing, international conferences and meetings, and policy activities.**

RSC books and many RSC journals are publishing research related to solar fuels, reflecting the high level of international research activity in this field across the chemical sciences and other related disciplines. The RSC's interdisciplinary journal *Energy and Environmental Science* is playing a key role in disseminating the latest advances in solar fuels research globally.

The RSC carries out its activities to support science with the guidance of experts in the chemical science community. The RSC's scientific Divisions, governed by RSC members, include:

- the Faraday Division (physical chemistry);
- the Dalton Division (inorganic chemistry);
- the Materials Chemistry Division; and
- the Environment, Sustainability and Energy Division.

These and other RSC Divisions and networks represent some of the communities who are contributing to solar fuels research. With their support, the RSC has organised important international conferences and satellite meetings, including:

- 1st International Symposium on Renewable Energy, at the Institute for Clean Energy in Dalian, China, 2011
- Faraday Discussion on Artificial Photosynthesis, Edinburgh, 2011
- ISACS, Challenges in Renewable Energy Symposium, Boston, 2011, including a pre-symposium discussion for early career researchers on solar fuels.

Meetings for 2012 include:

- 1st UK Solar to Fuels Symposium, London, January 2012
- Materials Chemistry Division joint Symposium on Organic and Molecular Materials for Light Harvesting, China, April 2012
- Dalton Discussion on Inorganic Photochemistry and Photophysics, Sheffield, September 2012.

The RSC has a strong record of bringing together interdisciplinary communities of researchers at all stages of their careers, along with stakeholders from industry, policy makers and funding agencies.

Following the release of this report the RSC will continue to develop a series of initiatives to raise awareness of the potential of solar fuels, as well as the associated opportunities for the UK, in parallel with related broader RSC projects in capacity building.

## REFERENCES


1 *Photosynthetic energy conversion: natural and artificial*, J. Barber, Chemical Society Review, 2009, **38**, 185-196

2 *World Energy Outlook 2011*, International Energy Agency http://www.iea.org/weo/

3 *Chemistry for Tomorrow's World: A roadmap for the chemical sciences*, Royal Society of Chemistry, www.rsc.org/roadmap, July 2009

4 http://www.woking.gov.uk/environment/greeninitiatives/sustainablewoking/fuelcell.pdf

5 International Energy Agency, Key World Energy Statistics 2011 www.iea.org/publications/free_new_desc.asp?pubs_ID=1199

6 *Sustainable Energy – Without the Hot Air*, David JC MacKay, UIT Cambridge Ltd., p104, 2009

7 www.theccc.org.uk/reports/renewable-energy-review, 2011

8 *America's Energy Future: Technology and Transformation, Summary Edition*, US National Academies, National Academies Press, 2009

9 *Liquid Assets*, Chemistry World, May 2011 www.rsc.org/chemistryworld/restricted/2011/May/LiquidAssets.asp

10 *Agro-Chemistry: new directions, new challenges?* Minutes of meeting of the UK All-Party Parliamentary Group on Science & Technology in Agriculture, www.appg-agscience.org.uk/linkedfiles/MEETING%20NOTES%20-%20 31%20OCT%202011.pdf, October 2011

11 *Rehabilitating captured $CO_2$*, Chemistry World, www.rsc.org/chemistryworld/Issues/2011/February/ RehabilitatingCapturedCO2.asp, Feburary 2011

12 www.decc.gov.uk/en/content/cms/news/pn_1184/pn_1184.aspx, October 2011

13 CO2Chem network: http://co2chem.co.uk/

14 Section 3.2 of *An overview of $CO_2$ capture technologies*, N. MacDowell et al, Energy and Environmental Science, 3 1645-1669, 2010

15 A very recent scientific review of the use of photosynthesis in organisms to produce fuels is *Photosynthesis to Fuels: From hydrogen to isoprene and botryococcene production*, A. Melis, Energy and Environmental Science, DOI: 10.1039/C1EE02514G

16 Royal Society Summer Science 2010 exhibition, University of Cambridge: Meet the algae: diversity, biology and energy
http://seefurtherfestival.org/exhibition/view/meet-algae-diversity-biology-and-energy

17 Towards Biosolar Cells, www.wur.nl/NR/rdonlyres/553F9FF7-78F0-43DE-8471-586D565EBB0F/87524/ Biosolarflyer.pdf

18 Hydrosol 3D www.hydrosol3d.org

19 *Reverse Combustion: Can $CO_2$ Be Turned Back into Fuel?* D. Biello, Scientific American, September 23 2010 www.scientificamerican.com/article.cfm?id=turning-carbon-dioxide-back-into-fuel&page=2

20 *Powering the planet: Chemical challenges in solar energy utilization*, N. S. Lewis and D. G. Nocera, PNAS **vol 103**, no 43, 15729, 2006

21 *Comparing Photosynthetic and Photovoltaic Efficiencies and Recognizing the Potential for Improvement*, R. E. Blankenship et al, Science, Vol. 332, p805, 2011

22 EPSRC *Towards a Sustainable Energy Economy*: http://gow.epsrc.ac.uk/ViewPSP.aspx?PSPId=879

23 EPSRC SUPERGEN Solar Energy Hub Call
www.epsrc.ac.uk/funding/calls/2011/Pages/supergensolarenergyhub.aspx

24 BBSRC Highlight Notice 1: www.bbsrc.ac.uk/funding/opportunities/2012/indbiotech-bioenergy-1.aspx

25 ESF EuroSolarFuels www.esf.org/activities/eurocores/running-programmes/eurosolarfuels.html

26 www.rcuk.ac.uk/research/xrcprogrammes/prevprogs/nano/Pages/ProgrammeHighlights.aspx

27 www.sbec.eu.com/en/information_centre/2011_lcri_invest_green_buildings

28 www.cerespower.com

29 See around time-point 20:20 in www.whitehouse.gov/state-of-the-union-2011

30 Joint Center for Artificial Photosynthesis www.solarfuelshub.org

31 Sun Catalytix www.suncatalytix.com

32 Liquid Light www.liquidlightinc.com

33 www.k-cap.or.kr/eng/info/index.html?sidx=2

34 www.jsps.go.jp/english/e-toplevel/11_gaiyo.html

35 World Premier Institutes Research Centers: International Center for Materials Nanoarchitectonics, www.nims.go.jp/mana/, International Institute for Carbon-Neutral Energy Research http://i2cner.kyushu-u.ac.jp/en/ and the Advanced Institute for Materials Research, www.wpi-aimr.tohoku.ac.jp/en/index.php

36 www.tytlabs.co.jp/english/news/press/20110920_epress.pdf

37 http://world.honda.com/news/2011/c110420Solar-Hydrogen-Station/index.html

38 Horizon 2020 press releases (November 2011) http://ec.europa.eu/research/horizon2020/index_en.cfm?pg=press

39 *A Brief Analysis of Worldwide Patent Filings Related to Graphene by UK Resident Applicants and Inventors*, UK Intellectual Property Office, www.ipo.gov.uk/informatic-graphene-uk.pdf, November 2011

40 http://www.rsc.org/ScienceAndTechnology/Policy/EducationPolicy/global-framework-education-project.asp

41 Gemasolar concentrating solar power plant: http://www.torresolenergy.com/TORRESOL/gemasolar-plant/en

42 *Concentrating solar power: its potential contribution to a sustainable energy future*, European Academies Science Advisory Council, November 2011
http://www.easac.eu/fileadmin/Reports/Easac CSP Web-Final.pdf

43 Chapter 6 *Sustainable Energy – Without the Hot Air*, David JC MacKay, UIT Cambridge Ltd, 2009
www.withouthotair.com

44 www.icax.co.uk

45 H B Gray, Engineering & Science No. 2, pp 26 – 31, 2008

46 A detailed scientific review of solar water splitting is given in *Solar Water Splitting Cells*, M. G. Walter et al, Chem Rev 2010, **110**, 6446-6473

47 Royal Society Summer Science 2011 exhibition: *Solar nanotech: Putting sunshine in the tank – using nanotechnology to make solar fuel* (SolarCap consortium, UK), http://royalsociety.org/summer-science/2011/solar-nanotech/

48 Learn about Sunlight to Fuel and see a functioning device in a video from the Energy Institute at the University of Texas at Austin at: www.energy.utexas.edu/index.php?option=com_content&view=article&id=52&Item id=159

49 www.rsc.org/chemistryworld/news/2011/March/31031101.asp

50 Pre-symposium discussion, *Challenges in Renewable Energy (ISACS4)*, MIT, Boston, July 2011

51 http://world.honda.com/news/2010/c100127New-Solar-Hydrogen-Station

52 www.sunhydro.com

53 *$CO_2$ photoreduction at enzyme-modified metal oxide nanoparticles*, T. Woolerton et al, Energy and Environmental Science, DOI: 10.1039/c0ee00780c

Links active at the time of going to print.

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