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Harnessing Solar Energy for the Production of Clean Fuel

Contents

Foreword

The quality of human life in the industrialized world has risen today to a level hitherto unachieved in human history. In Europe this development has been made possible through the recent period of political and economical stability and also because of an ever-growing abundance of energy derived primarily from fossil fuels.

The human population on this planet has risen from approximately 2.5 billion in 1950 to over 6 billion in 2005. In the same time period, the industrialized economies have expanded in terms of production and global trade. Automobile production increased from approximately 8 million cars per year in 1950 to over 80 million cars in 2007. These facts illustrate the increasing demand for energy and resources. Today almost all nations in South America, Africa and Asia strive to establish the same standard of living as in Europe and North America – most notably China and India with populations of over 1.3 and 1.1 billion respectively.

In this light it is increasingly evident that our fossil fuel consumption has become unsustainable and dangerous. It is posing serious threats to our human societies, for example, because of increasing CO_2 emissions and the related global climate change. Although European governments are implementing legislation to reduce greenhouse gas emissions, their quantity will still continue to grow over the next decades. Providing affordable energy in a sustainable manner and without inducing environmental damage is one of the toughest challenges in the 21st century as all regions of the world strive to reach the same high standard of living.

At present, in addition to creating closed-cycle zero- emission fossil fuel technologies, solar energy conversion and nuclear fusion appear to be the most favourable solutions to achieve clean energy production. Europe cannot afford not to lead the development of new technologies for clean energy. In order to improve environmental sustainability it is imperative for the world economies and for Europe, in particular, to conduct fundamental and applied research into the production of clean fuel.

Non-technical aspects of energy systems are also highly relevant in forging a sustainable energy future. Societal and ethical research is needed to understand the implications of energy security and safety issues and of new emerging environmental concerns on our economies and way of life. Energy research in the 21st century must relate the impact of science and technology on economic efficiency and long-term system stability. There is a need for greater engagement and cooperation of technical sciences with social sciences in the field of energy research.

The present ESF Science Policy Briefing is the outcome of a thinking process among leading European scientists in the field of solar-to-fuel energy conversion. It presents a common scientific view on technologies to harness solar energy and how to meet the challenges for Europe today. The document recommends the prioritized development of novel biosynthetic solar-to-fuel and biomimetic photosynthetic technologies for a sustainable energy economy if Europe is to become the leader in the field. The document has undergone external international peer review and has been approved by the ESF Standing Committees for Physical and Engineering Sciences (PESC), for Life, Earth and Environmental Sciences (LESC) and for Social Sciences (SCSS).

This Science Policy Briefing describes steps to a European action plan for Harnessing Solar Energy for the production of Clean Fuel. The report aims to contribute to a better understanding of challenges related to the clean fuel research and to initiate a debate among the relevant actors at national and European level on how to shape Europe's leadership in this domain.

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Executive Summary

- Solar energy is one of the major options for a sustainable fuel source that will allow a switch to a carbon neutral energy economy. Electricity generation from solar energy is rapidly spreading in our societies, but it needs transport and storage to balance production and demand. At present 70% of worldwide energy use is based on fuels. The efficient conversion of solar energy to a useful fuel requires more research and development. In particular finding a fuel for a smooth transition to a carbon neutral transport sector is a difficult challenge. This sector is responsible for 25% of our energy use and has the fastest growing emission profile.

- Potent novel technologies must be developed in order to be able to meet the challenge of mitigating climate change. This Science Policy Briefing proposes the implementation of large-scale integrated research programmes with two aims: 1) the production of biofuels from modified photosynthetic microorganisms, and 2) the development of chemical solar cells for fuel production. Both approaches have the potential to provide fuels with solar energy conversion efficiencies that are much better than those based on field crops or forestry. In consequence they could contribute substantially to sustainable economic growth and social stability in Europe. The ESF is asked to lead the implementation of the recommendations in this Policy Briefing and to use its portfolio of instruments to develop synergy, strengthen collaboration and coordinate with similar initiatives in other parts of the world.

- Photosynthetic microorganisms can be optimised for the production of hydrogen and other fuels (biodiesel etc.) with conversion efficiencies that are much better than the current biomass production methods. At the same time they can produce valuable ingredients for food and pharmaceuticals. Research done by European universities needs to be extended into prototype production through partnerships with the private sector. This needs to be paralleled with further research into the optimisation of the processes using systems biology and synthetic biology methods.

- The development of artificial solar-driven fuel production requires a series of fundamental and technological advances. Multi-electron redox catalysts must be developed; they must be coupled to photochemical elements, and all this in a material with surface areas sufficient to allow rapid access of substrate and removal of the fuel. This will require physical and chemical research often inspired by biological processes: biomimetic nanotechnology. Particular research efforts are required for finding new (photo) catalysts for 1) water splitting, 2) H_2 production, and 3) CO_2 reduction to produce liquid fuels such as methanol.

- The introduction of biology-inspired solar fuel as a source of sustainable energy will only be failure-tolerant when backed up with a thorough social science research programme that deals with the non-technological aspects of successfully establishing the new technology in society. In view of the urgency of current environmental challenges, time is critical and problems with combining innovation with the strengths of the energy incumbents – with their highly developed distribution systems and customer base – need to be overcome. At the same time the comprehensive dissemination of scientific advances along with a matching dialogue with the public should allow realistic expectations to be established. The social sciences must play a pivotal role in handling the complex interactions between governments, NGOs, industries, other stakeholders and the public.

Introduction

Europeans are urgently looking for a change to a sustainable energy future by more efficient production and use of energy, by boosting renewables, and by using domestic solar energy sources.[1] Vigorous action by all countries is needed if greenhouse gas concentrations are to be stabilised at a level that would prevent dangerous interference with the climate system. In response, European governments are implementing legislation to increase the contribution of renewables. Despite these efforts, there is evidence that even with current climate change mitigation policies and related sustainable development practices, global greenhouse gas emissions will continue to grow over the next few decades.[2]

Renewables address the problem of global warming through zero or near-zero net greenhouse gas emissions and can make major contributions to the security of energy supply and to economic development. Renewable energy technologies currently supply 13.1% of the world's primary energy supply, mostly in the form of hydropower, biomass and geothermal energy.[3] The prime scarcity is not of natural resources nor money, but time. The shares of biomass, solar photovoltaic(s) and wind are increasing, while ocean, geothermal and concentrated solar power are decreasing. This reflects the evolving consensus among early adapters as to where the greatest potential is. The use of solar energy, either directly or from wind, is by far the most popular option.[1] Decentralised energy from domestic sources directly addresses the need for energy security, economic prosperity and environmental protection.

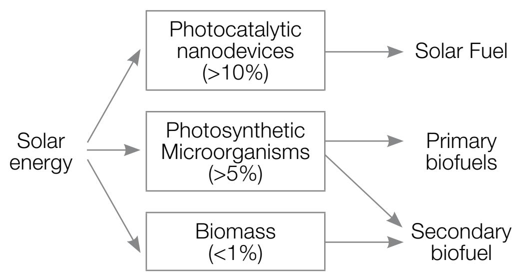

Figure 1. Microorganisms can provide primary and secondary biofuels with efficiencies >5%. The physical limit for artificial solar-to-fuel converters is above 10%.

A transition to a sustainable energy system will require exceptionally quick and unprecedented scientific and technological advances.[4] It is against this background that the ESF has decided to speak on the issue of clean solar fuel (Figure 1). It has assembled an interdisciplinary task force that has proceeded with a foresight exercise at the highest scientific level. In a recent White Paper, the task force assessed the research needs for clean solar fuels starting from recent scientific progress in basic research in photosynthesis, a range of natural solar-to-fuel conversion processes that evolved 2.5 billion years ago.[5] Photosynthesisers such as plants and bacteria are abundant in the biosphere (Figure 2) and use solar energy to make oxygen from water and convert atmospheric CO_2 into carbohydrates. They produced all the fossil fuels and fuel the current biosphere. Photosynthesis can also produce hydrogen.

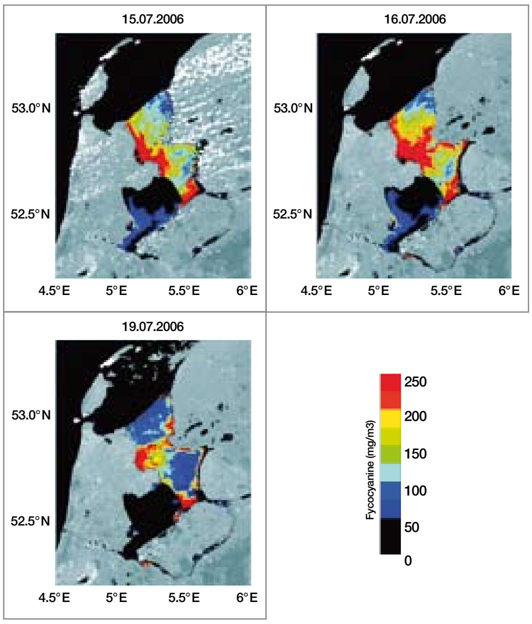

Figure 2. Photosynthetic microorganisms grow rapidly in the natural environment. The images have been obtained with the MERIS instrument of the ESA environmental satellite ENVISAT and show blooming of blue-green algae in the 1100 km² lake IJssel in the Netherlands between July 15 and 19, 2006. During a few hot summer days phycocyanine concentrations go up to 350 mg/m³ in waters that are rich in nutrients. (Source: MERIS/ENVISAT ESA, Netherlands Institute for Space Research)

The ESF task force identified the most promising routes to eventual full-scale commercial solar energy conversion directly into fuels.[5] European scientists want to capitalise on the recent scientific breakthroughs to learn from Nature how to harness solar energy for sustainable production of primary energy carriers such as hydrogen from water or carbon-based fuels from CO_2 at an affordable cost and at much higher efficiency than is possible with biomass. The goal of this document is to outline workable science policies and implementation strategies for European scientific and economic leadership in solar fuels.

Current Status of Solar Fuel

Solar energy is plentiful: enough light reaches the Earth's surface every hour to meet the world's annual energy needs. The problem lies in harnessing it. Biomass represents the largest current source of renewable energy.[3] Molecules are easier to transport than electrons and a smooth transition to a carbon neutral transport sector without the need to change the existing infrastructure is most easily achieved by mixing in biofuels such as biodiesel and bioethanol. In 2010 our European societies will need to mix in 5.75% biofuels, which will increase to more than 20% in 2010.[6] The first and second generation biofuels cannot fulfil the need in a sustainable and societally acceptable manner. While bioethanol and biodiesel derived from plant material are economically competitive with gasoline at current oil prices, their total solar energy conversion efficiency in the production is less than 1% (Figure 1). Food demand competes with biofuels for existing arable and grazing land.

According to the UN projections, 650 million people will populate Europe by 2050.[7] If they succeed in reducing their energy use to the equivalent of 3-5 kW per person, down from the current 5-6 kW, they will need to harness in an economically profitable way ~ 2.5 Tera W of solar power, corresponding with ~ 0.2% of the solar irradiation that touches the European surface. With a system boasting 10% efficiency equipped with a distributed collector area corresponding to a square of ~200 km × 200 km, the equivalent of 0.5 Tera W in the form of solar fuel can be produced. This corresponds with Europe's estimated future need for transport and mobility.

In contrast, the conversion of light to fuel with current technologies is not very efficient. More than 10% of the European land surface must be used for every TW of fuel production using biomass from plants. This will be in competition with agriculture for food, and puts a burden on the environment. The economic cost of the R&D to implement and deploy novel solar fuel systems will be substantial, but it will be more than outweighed by the long-term social and economic benefits that will come from producing fuel more efficiently.

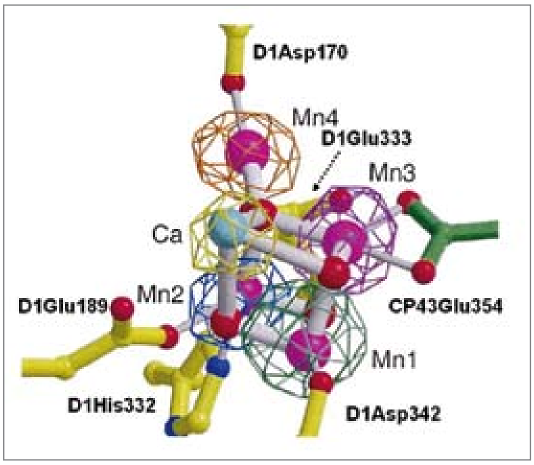

Figure 3. The manganese four-electron catalyst for water splitting in natural photosynthesis. The structure of the catalyst was resolved in 2004 by European scientists.[8,9] Recent scientific progress in determining the structures and mechanisms of the photosynthetic proteins and complexes paves the way for the development of smart matrices for solar to fuel conversion. (Figure supplied by J. Barber and is a modification of that which appeared in ref. 8.)

There is general consensus among scientists that there are no fundamental engineering and economic issues that would limit the technical feasibility of microalgal cultures for direct solar-to-fuel conversion, either in terms of net energy inputs, nutrient (e.g., CO_2) utilisation, water requirements, harvesting technologies, or general system designs. Present applications of microorganisms involve feeding the CO_2 exhaust of conventional fossil fuel power plants into microalgae cultures. These efforts are useful for CO_2 sequestration and will be valuable in stimulating the development of technology for solar-to-fuel conversion with high efficiency. However, they must be accompanied by efforts aiming for a transition to a renewable and scalable solar-based energy system.

Boosting the efficiency of solar-to-fuel conversion requires a fundamental technology transition, to direct conversion of solar energy into fuel.

Substantial progress has been made recently, particularly in Europe, to understand and mimic the natural solar-to-fuel conversion processes.[8-12] This is sufficient for scientists to be confident that it can be possible to produce fuels with solar energy from water on a commercial scale. While the barriers to the development of efficient and scalable solar fuel generation are known and have been studied for decades, today's emerging techniques in the life sciences and nanoscience provide new ways to overcome the limitations faced in years past. The capability exists to engineer and grow more efficient eukaryotic and prokaryotic microorganisms, to design materials optimising energy and charge transport control, and to study and learn from Nature to produce and use the most powerful catalysts (Figure 3). In the USA this effort has crystallised into the Helios Project (see reference 17), a new type of research facility that targets the development of efficient processes to produce transportation fuel from biomass or from light-driven electrochemistry. Parallel projects are currently being implemented in China and in Japan. Australia has a long-term interest in artificial photosynthesis. In Europe the Swedish consortium on biosolar energy conversion has pioneered an integrated approach on a national scale, while the French CEA has an ongoing programme on artificial water splitting, which is generally considered to be the most critical hurdle on the way to solar fuels. In addition, many European countries have excellent research groups, including Nobel laureates, that are active in the field of natural photosynthesis and are involved in European research consortia in FP6 and FP7 as a stepping stone to a sustainable and carbon neutral source of energy.[5,13,14]

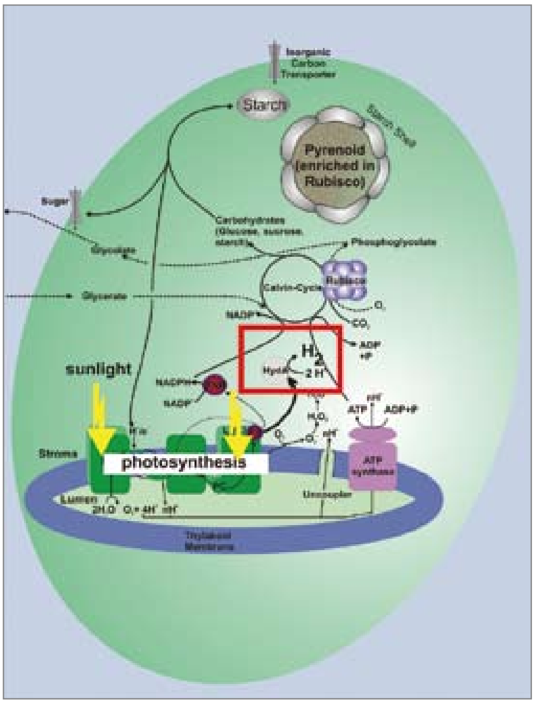

Figure 4. The biochemistry of solar powered H_2 production in the eukaryotic microorganism *Chlamydomonas reinhardtii.* European scientists are working on optimising electron pathways *in vivo*, to minimise metabolic losses and to optimise fuel production by small photosynthetic organisms. (Reproduced by permission of The Royal Society of Chemistry (RSC) on behalf of the European Society for Photobiology and the European Photochemistry Association)

Recommendations for Scientific Action

Conversion of solar energy into fuel can be realised either in autoregenerative systems, derived from photosynthetic organisms or in self-assembled integrated nanodevices that are durable, preferably on a time scale of several decades (the artificial leaf). Fundamental breakthroughs in these directions are expected on a time scale of 10 to 15 years and are recognised by the international science community as major milestones on the road to a renewable fuel.

Recommendation 1:
Solar-to-fuel Conversion in Microorganisms

It is recommended to capitalise on the capability of existing photosynthetic microorganisms to catalyse the light-driven oxidation of water and evolution of hydrogen and carbon-based fuels to develop a sustainable infrastructure for the efficient production of primary biofuels independent of the use of arable land mass.[10] In order to optimise the output, a combination of a systems approach coupled with the development of engineering to optimise sunlight driven biomass generation, to increase the efficiency of sunlight harvesting, to feed nutrients into the organisms and to collect the fuel produced by large areas of photobioreactors will be required. The biofuels yield can be improved at four levels, at the level of the primary processes as they occur in the thylakoid membrane, the cell or organism level, the biorefining and separation, and the sales and distribution. At all levels at least a 25% improvement needs to be realised in the next few years. This would lead to a total of a factor of 2.5 or better in synergy, which will be necessary for a secure and sustainable solar-to-fuel technology. The goal will be to achieve a photon conversion efficiency of >5% of the available solar energy within 5-10 years. Once the fuel evolution capacity of a batch of microorganisms has been exhausted, the resultant biomass can be used as a source for the production of secondary biomass to liquid fuels (such as sunfuel), biomethane, or biohydrogen, and for carbon enrichment of agricultural soil. It is recommended that existing laboratory-scale photobioreactors be rapidly used as templates to develop prototypes of outdoor pilot plants, initially in a range between 250L and 500L, where expected production costs will be less than 10€/m^2, in order that the engineering developments required for the scale-up and handling of large volumes of fuel can be achieved in parallel with molecular and biochemical improvements required to optimise the efficiency of production. This approach will allow production of primary biofuels and biomass to move rapidly into scaled-up production in public-private partnerships. In parallel, fundamental research into the systems biology of the direct solar-to-fuel conversion processes at the thylakoid membrane will guide metabolic engineering of the cells by modern synthetic biology methods, biobricks and biohybrid nanostructures. This will lead to advanced autoregenerative fuel production platforms adapted to a variety of environmental conditions with photon conversion efficiency >5%.

Recommendation 2: The Artificial Leaf

It is recommended that detailed information on how photosynthetic organisms are able to use solar energy to extract electrons from water to produce a range of fuels such as hydrogen or reduced carbon compounds is used to design novel catalysts capable of using solar energy to produce fuels.[12] The research into solar-driven electrochemistry uses the information obtained from the biological process, which has been honed by evolution, in order to short-circuit the time required to develop durable *de novo* catalysts for the production of solar fuels. This approach is more long term than that outlined in recommendation 1 and will initially require substantial public funding. However, it represents a very important strategy. When combined with highly efficient systems for charge separation, such as quantum dot devices, this can lead to solutions that are significantly more efficient, >10% photon conversion efficiency over the entire solar spectrum into fuel, than those which rely on the use of intact photosynthetic organisms.

The development of efficient and durable photocatalysis energy technologies is impeded by bottlenecks that require the development and application of basic science and cross-cutting technologies. The biological system involves not only catalytic centres but uses smart matrices (proteins) in which these centres are embedded and which actively promote the desired chemical reactions. Advanced biomimetic analogs must thus start to design not only the catalytic centres but also the matrices in which these are embedded (Figure 5).[12] Such matrices should be durable. Starting from excited-state life times of 10^{-9} s for molecular light absorbers they allow for the generation and storage of multiple electrons for the time scale of catalysis, 10^{-3} s, by a proper implementation of electron tunnelling barriers in conjunction with efficient light-induced charge separation properties. They should provide sufficient photocurrent to allow for driving the catalytic converters at maximum throughput, independent of light conditions. Finally, they should actively engage in the catalytic reactions by dynamic optimisation of their physical and chemical structure to maintain the balance for electrons and protons required for optimal catalysis by multielectron reactions. Little work has been done on solar-driven fuel production using bio-inspired supramolecular chemical complexes within the matrices that might be appropriate for future devices. Existing knowledge and technology from nanosciences, supramolecular chemistry and biology can be combined with future developments to produce more complex assemblies for solar-driven fuel production. Metal-organic frameworks and hydrogen bonded donor-acceptor arrays may be useful as they should allow multi-electron catalysts based on Ru, Mn, Fe or Co to be combined with donor and acceptor systems, with quantum dots or stable organic molecules in a smart matrix. This recommendation aims at ensuring a genuine chance for ‘emerging ideas’ to be explored based

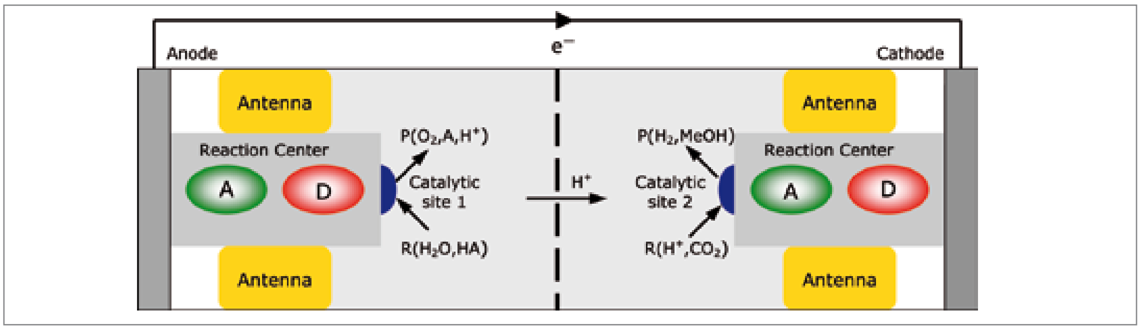

Figure 5. Solar energy driven electrochemistry for production of hydrogen or methanol with high efficiency. Future integrated nanodevices may combine a light harvesting antenna system and photochemical reaction centre containing a donor (D) and an acceptor (A) to produce a stable photocurrent, that drives novel catalysts for multielectron reactions (R→P). Such artificial leaves can extract electrons from water and produce fuel from protons or CO_2.

on the strategic need to use the creative spirit in European research, and mediated by the Framework Programmes of the European Commission. It should enable 'high risk/high impact' science and vigorously promote multidisciplinarity on a European collaborative basis.

In addition, it is recommended that this research should aim to produce not only hydrogen but also a range of reduced carbon-based fuels, such as methanol and other fuels, from atmospheric and concentrated CO_2. This recommendation is both timely and appropriate since scientists in Europe are world leaders in both the molecular understanding of the underlying photosynthetic reactions and in the underpinning sciences, including multiscale theoretical modelling that will be required to achieve technological breakthroughs to translate this understanding into novel materials concepts.[8,9,11] In the long run these novel concepts can lead to biohybrids that help to improve the autoregenerative systems that result from the biotechnology and synthetic biology efforts.

Recommendation 3: A Comprehensive Systems Approach

Processes of technological innovation and decision making in relation to the energy challenges are shaped by a host of social, economic and political factors.[15] The solar-based energy system that is proposed has the distinct characteristic of being scalable. It should be secure, sustainable and profitable at every scale, both from the producers' and the users' points of view. Improving the efficiency for solar fuel can induce a paradigm shift where energy becomes a distributed proprietary source of sustainable economic growth for large numbers of citizens, favouring an equitable distribution of income. This new dimension should be addressed in a socio-technical systems approach by the social sciences. A prime issue is how to overcome the incumbent opposition to innovation we are currently experiencing, since fossil fuel corporations are defending their positions with oil, gas and coal-to-liquid technologies. The social sciences should be drawn upon for the following questions:

- What would the markets for innovation look like?
- If the private sector is to play a large role, does this mean incumbents or new firms that need adequate access to financial resources?
- If new market entrants are to play an important role, how will they secure funding?
- If incumbents are to play an important role, how can problems of combining innovation with incumbent strength be overcome to prevent delaying the innovation process and its dissemination?
- By what means (regulations, market designs, tax regimes) could the new technologies become a sustained proprietary source of energy for Europeans?

Second, the production factor energy, in a physical-technical sense, presupposes the existence of technical systems that are, by their very nature, socio-technical systems developed and operated by people. In addition, they are embedded within economic, political, social and cultural systems. The intended and unintended consequences of the production, distribution and use of energy reveal themselves in an analysis of the interactions within these socio-technical systems. Decisions concerning the design and further development of socio-technical energy systems are societal matters. Thus, the analysis of socio-technical systems and the formulation of design recommendations for them fall directly within the purview of the social sciences. While the availability of energy is enabled by technology, social and economic aspects predominantly determine energy security and access.[15] To cope efficiently with environmental impacts requires a long-term learning period. Combining the partially opposing goals of short-term economic efficiency and long-term stability will be a challenge. The complexity of the social and technical choices involved and the difficulties in forecasting the developments due to uncertainties creates a need for a systems approach to analyse the societal context of solar-to-fuel conversion, to outline different pathways to the future and to allow for more adaptive and interactive planning instruments. These methods also have the capability of responding to the need for a more enlightened and integrative public dialogue, as expert regimes and political choices alone are not satisfactory for handling the possible alternatives and their implications. Whether the perspective is to improve the basis for policy, to create a basis for exploring the possibilities for consensus, or directly to involve the public and create new social, economic and educational structures to facilitate rapid dissemination of technology supported by democratic decision making, the role of public understanding and engagement is crucial and has to go hand in hand with foresight activities and methods. Scenario techniques focusing on how technologies and societal developments are intertwined and point to important choices to be made to prepare for the consequences of continuing existing paths of development are part of this field of research. So are improvements in the analytical methods, stepping up from the elemental analysis to the description and formation of the system as a whole, in analysing and developing solutions in the field of behaviour, social practices and trends, institutional and industrial cultures, lifestyles and economic arrangements and institutions. For instance, mapping out pathways of change and predicting long-term stability and consensus among European citizens may benefit from the analysis of the short-term fluctuations and time lags in the complex dynamic networks of social interactions.[16]

Implementation

Direct conversion of solar energy to fuel is not yet widely demonstrated nor commercialised. The research, development and demonstration (RD&D) programmes of governments will therefore play a vital pioneering role in overcoming incumbent opposition to innovation and provide the necessary means for new firms to grow. More R&D into solar fuel in the private sector is also critical. The private sector is best equipped to tailor ongoing applied research, prototyping and learning in response to the market's needs in a competitive environment shaped by government regulations derived from public dialogue and based on societal acceptability.

- Well focused R&D into solar fuels by national governments will remain essential, especially for basic science that is pre-competitive. Sustainable solar-to-fuel conversion cannot be realised by incremental scientific progress alone, and scientific revolutions will be necessary, leading to novel devices and bioprocesses, and inspired by scientific revolutions in the life sciences and the nanosciences. The national agencies will have to implement programmes in this direction, open to research groups and consortia. This document recommends scientific priorities for this vitally important effort.

- Leadership of the European Commission is critical, because the current incentives for companies to make early investments are weak. Prototyping and learning stages require considerably more resources than the initial R&D phase. While most solar fuel-related investments will have to come from the private sector, the Commission has a key role in creating the appropriate transnational investment environment to bridge the gap between basic research and application in a European perspective.

- Ultimately, the private sector will have to deliver the solar fuel to the market. Innovations by small firms that are ready for prototyping need government backing in the form of public-private partnerships. National, regional and local governing bodies can help to overcome the hurdle of reducing costs by technology learning, for instance by operating as guaranteed customers at prices that are fully competitive with traditional fuels. Early adaptors among the public sector are important in analysing and fostering the interface of science and society in the introduction of new technologies and the transition to a sustainable and resilient European energy system.

- Renewable fuels technologies promise to develop into key multibillion Euro biotechnology and chemical industries within several decades. It is of utmost importance that the governments of the European Union will provide sufficient financial means for their research infrastructure to make appropriate and targeted research efforts that will pay back at a later time by allowing our countries to hold the technological leadership in this future technology which has fundamental importance for the future of the industrial societies.

- The task force recommends that ESF takes the lead in implementing the recommendations in this Policy Briefing. A first step would be bringing together the programmes funded by its Member Organisations, together with key national programmes funded by others in order to develop synergy. A second step would be ESF actively promoting the use of its portfolio of instruments for strengthening collaboration (Research Networking Programmes), dissemination (ESF Research Conferences) and research (EUROCORES). It makes sense that ESF should initiate a global coordination with similar initiatives in other parts of the world.

Making Choices

The choice the ESF task force has made on scientific grounds is to recommend scalable solar energy for fuelling economic growth that leads to social stability and well-being of our European populations. Now there are other real choices that need to be made. First, the public RD&D budgets have remained stable at 60% of their peak level during the 1970s for the past decades. The need to increase these budgets is now becoming widely recognised. Second, the share of renewable energy technologies in the RD&D has remained low at ~7-8%. In parallel, massive public investments are made in RD&D for non-renewable energy infrastructure, prolonging the lifetime of the current fossil fuel-based energy system. This is the 'prisoners' dilemma' in our energy policies. Oil companies' exploration costs are surging to meet demand for fossil fuels. Students who are going to study mining in our technical universities are offered excellent career prospects, while students in the basic sciences that are necessary for overcoming the barriers for a renewable energy system experience many more hurdles. Public and private support will be essential to focus valuable human resources for a smooth transition to solar fuel before a less efficient chain of biofuels and a new fossil fuel supply infrastructure are locked into place. Third, European research into the direct conversion of solar energy into fuel with high efficiency is lagging behind with respect to international competition, mainly from the USA.[17] Budgets for public energy R&D need to be reviewed and focused on areas with the greatest potential for a scalable energy system. Scientific breakthroughs that profoundly change the way we produce energy will almost certainly take decades and significant investments. These difficulties do not justify inaction or delay, which would raise the long-term economic, security and environmental costs. It will be inevitable to make choices and reallocate funding to solar fuel. The sooner a start is made, the quicker a new generation of more efficient and low- or zero-carbon energy systems can be put into place. In practice, it may take considerable political will to push these policies through, as making choices is bound to encounter resistance from established research communities working on other energy technologies and short-term interests of industries.

The *European Commission* has already adopted a pioneering role by establishing calls for proposals in the area of solar fuel in the FP7 to promote cross-disciplinary and transnational collaborations. In addition, several European countries have already started to direct resources towards solar fuel. Examples are:

Finland has strongly invested in bioenergy, and clean solar fuels have attracted great interest also from the public. Both major research-funding agencies, the Academy of Finland and TEKES, have launched new research programmes for renewable, sustainable and clean energy production.

In *France* the life science division of the Atomic Energy Commission (CEA) has a programme on biological and solar hydrogen production. Several research teams form a collaborative network for basic research in solar fuel production with emphasis on bio-inspired catalysts, photocatalysts for water oxidation and microbial hydrogen production. The CEA has also interests in conventional biomass approaches, hydrogen technologies and fuel cells. The National Centre for Scientific Research (CNRS) has a biohydrogen research group.

Germany is among the biggest spenders on energy R&D in the world, together with the USA and Japan. Most of the research in renewables is currently in third generation photovoltaic and wind energy. Recently, the Federal Ministry of Science & Technology (BMBF) launched a programme on 'Solar technology of the next generation'. Other budget plans for solar fuels research are under discussion, with a focus on basic research through the Max Planck Society (MPG), the German Research Foundation (DFG) and other funding bodies.

In *Hungary* high quality research targeted on understanding the mechanism of photosynthetic water oxidation and hydrogen production has been ongoing in the last 15 years, mainly in the large research centres of the Hungarian Academy of Sciences. The Hungarian National Research Fund (OTKA) supports basic research. Recently a substantial amount of support has been provided by the National Research and Technology Agency (NKTH) to deal with applied aspects of hydrogen production.

The Netherlands is among the countries spending the largest amount per capita on energy RD&D and its long-term energy policy is focused on sustainable, competitive and secure energy. The Dutch government is contemplating a substantial increase of the basic energy research, coordinated through the Netherlands Organisation for Scientific Research (NWO). This organisation is working on a national programme. Upon approval by the government clear choices will be made for the theme of energy transition against other societal needs. Private parties are reluctant to invest and need incentives. Local governments with strong economic power are open to explore early public-private partnerships for solar fuel prototyping by startups.

The *Swedish* Consortium for Artificial Photosynthesis was started in 1994 by a group of Swedish scientists located at three different universities around the common goal to produce a fuel from solar energy and water. The Consortium has evolved over the years, to become a large project on a national scale directly involving approximately 50 researchers in five different groups funded by mainly Swedish funds both from state and private foundations. The Consortium has been concentrated at one site in Uppsala University. The Consortium comprises groups in chemical physics, organic chemistry, biochemistry and molecular biology working in close collaboration. The research is focused on both biomimetic and photobiological routes to solar fuels. In addition the Consortium is coordinating the SOLAR-H and SOLAR-H2 consortia financed by the European Commission.

In the *United Kingdom* forward-looking energy industry is increasing investments in solar fuel in the form of public-private partnerships, but this needs to continue and broaden, since major research spending is diverted to the USA and Canada where public funding has adapted more rapidly to the shift in basic research needs for future energy supply. The Engineering and Physical Sciences Research Council (EPSRC) and the Biotechnology and Biological Sciences Research Council (BBSRC) are looking into possibilities to reverse this trend. The BBSRC already has a Special Initiative on Climate Change that includes research into biofuels. They are currently also considering what research topics to commission in the area of harnessing solar energy.

Other European economies are urged to follow up rapidly, in order to benefit from the opportunity to focus their budgets for basic energy research in a newly established area of research with high potential for their societies.

Final Overview

It is clear that solar fuels will be produced. The timely transition to renewable fuel from solar energy critically depends on scientific progress in three areas, which are:

- *Biotechnology:* Biofuels from modified photosynthetic organisms, including biomimetic routes aiming for biological/chemical hybrid systems;
- *Photocatalysis:* Development of chemical/physical solar-to-fuel cells (the artificial leaf); and
- *Social sciences:* Problems with incumbent opposition to innovation, improvement of scenario techniques and understanding complex networks of social interactions with respective public involvement.

Efficient conversion of solar energy into fuels at diverse scales without risk of disruption and proneness to large hazards addresses the two energy-related threats simultaneously: that of not having adequate and secure supplies at affordable prices and that of anthropogenic changes of the environment by consuming too much of it. The financial system needs to support a long-term research and innovation programme ensuring that emerging ideas that are explored are based on societal needs. It has the capacity to fund the required investments but needs active steering in the right direction. This requires a strong political will.

Preconditions for an accelerated development for industrial applications will be:
- *government regulations* shaping a competitive environment for the private sector
- *public-private partnerships* for prototyping of new processes
- *an educational infrastructure* to accumulate the best possible human resources

When vigorously pursued, direct conversion of solar energy into fuel represents one of the very few major options that humankind has to provide socially, economically and environmentally robust and resilient renewable fuel with energy security that is guaranteed in a humanitarian instead of confrontational manner. With scalable solar-to-fuel conversion technology, European countries can become producers and exporters at the level of regions, cities, communities and individual citizens. This may well give rise to a paradigm shift, from the current model where fuel is provided at the lowest possible cost by large-scale industries to an energy system where fuel is a sustainable source of economic growth for the European public that principally owns its source of energy and the benefits that come with it.

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