

Does the World Need a Global Project on Artificial Photosynthesis?

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Summary

This paper introduces a special edition of *Interface Focus* derived from papers presented at the Royal Society supported meeting ‘Do We Need a Global Project on Artificial Photosynthesis?’ held at Chicheley Hall in July 2014. At that meeting, leaders of national solar fuels and chemicals projects and research presented ‘state-of-the-art’ on artificial photosynthesis in the context of the policy challenges for globalising a practical technology to address climate change and energy security concerns. The discussions included contributions from many experts with legal and policy skills and uniquely focused on producing principles for prioritising and specialising work while enhancing the funding and attendant public policy profile. To this end, representatives of major public, philanthropic and private potential stakeholders in such a project (such as the Wellcome Trust, the Moore Foundation, Shell, the Leighty Foundation, the EPSRC and Deutsche Alternative Asset Management) were invited to provide feedback at various points in the meeting.

For this *Interface Focus* edition, speakers at the Chicheley Hall meeting were required to present a snapshot of their cutting edge research related to artificial photosynthesis (AP) and then draw upon the Chicheley Hall discussions to innovatively analyse how their research could best be advanced by a global AP project. Such multidisciplinary policy analysis was not a task many of these researchers were experienced or trained in. Nonetheless their efforts here represent one of the first published collections to attempt such a significant task. This introduction contains a brief summary of those papers, focusing particularly on their policy aspects. It then summarises the core discussions that took place at the Chicheley Hall meeting and sets out some of the central ethical principles that were considered during those discussions.

Keywords: artificial photosynthesis, solar fuels, carbon dioxide fixation, nitrogen fixation, ammonia, hydrogen, food and fuel security, environmental sustainability, Sustainocene

1. Introduction

This unique collection of interdisciplinary papers in artificial photosynthesis (AP) science and policy are derived from presentations at the Royal Society Chicheley Hall meeting in July 2014 on the theme 'Do We Need a Global Project in Artificial Photosynthesis. They explore the vision that there is a growing ethical responsibility on humanity in general to ensure that every road, pavement, building and vehicle on the earth's surface performs photosynthesis. A common theme is that a global AP project is not just an issue of enhancing AP technological capacity but of thereby facilitating an expansion of moral sympathy; the promoted good intention being not just to make renewable human fuel and food, but help sustain the biosphere.

A billion years ago cyanobacteria began a revolution- to oxygenate the earth's atmosphere by using sunlight to split water, but also to use the reductive acetyl-CoA pathway to make food and energy through the formate dehydrogenase-catalyzed reduction of CO₂ to formate and CO dehydrogenase-catalyzed reduction of CO₂ to CO.¹ Since then, biology has slowly evolved other approaches to CO₂ fixation including the pentose phosphate (Calvin-Benson-Bassham) cycle utilising the key enzyme ribulose biphosphate carboxylase/oxygenase (RuBisCO) to catalyze carboxylation of the five-carbon sugar 1,5-ribulose biphosphate to form the six- carbon sugar fructose-1,6-bisphosphate. Those dominant and ecologically damaging sources of human energy, coal, petroleum and natural gas, are ancient remnants of such components of the natural photosynthetic process that, over a billion years, has evolved to utilise large (i.e., trees) and small (i.e., grass, bacteria) structures over the earth's land and sea mass.² Life on this world remains critically dependent on the 385×10^9 tons of carbon dioxide fixed annually through biological photosynthesis.³ Part of the vision shared at the Chicheley Hall meeting is that humanity, through a global project on AP, must urgently develop through a fully functional global artificial photosynthetic system that achieves not only a more efficient system of solar-driven water splitting but of atmospheric CO₂ and nitrogen fixation.^{4 5}

The idea of a global Project on AP had first been raised at an international conference held at Lord Howe Island in August 2011. The purpose of the Chicheley Hall global AP project meeting, was to encourage key scientists in the AP field to turn their minds in greater detail to how their cutting edge research in AP could best be advanced by the creation of basic governance structures behind a global project on artificial photosynthesis. It was expected that such discussion would focus at some point on the composition of a global AP project's board of directors, its advisory councils, its property and funding arrangements. To this end, representatives of major potential public, philanthropic and private stakeholders in such a project (such as the Wellcome Trust, the Moore Foundation, Shell, the Leighty Foundation, the EPSRC and Deutsche Alternative Asset Management) were invited at various points in the meeting to comment.

The idea of making the all the profusion of human structures on the earth's surface do photosynthesis (in most cases without biology) is likely to become a more significant focus of research and policy. The scientific challenge is equally intriguing as, for example, revealing the Higgs Boson or the nature of dark matter, but potentially much more significant morally given the present destructive impact of what may be termed the corporate-military complex on the biosphere. Discussion at Chicheley Hall included the vision of globalised AP technology supporting humanity acting as ecosystem steward in a Sustainocene epoch and thereby supportive of traditional and emerging individual and social virtues such as justice, equity and environmental sustainability than any other vision of technological change (i.e., nuclear or fusion power).⁶ On one approach, the global AP-supported Sustainocene would be a world where enforceable rights of nature are recognised by legal systems, where people work to flourish and create the material conditions whereby themselves, their families and communities can construct lives the lead to happiness and peace of mind.⁷ Delegates were asked to consider whether an equitable globalisation of AP may in fact represent an instance of technology driving an expansion of human sympathy towards recognition of the intrinsic dignity of all life on earth, akin to the moral revolutions that led to the abolition of slavery, the enfranchisement of women, or the eradication of smallpox or may in time result in the elimination of nuclear weapons, poverty, torture or war in general.

2. GAP Focus from the Papers in this Special Edition

Kara Bren in her paper summarises three different approaches for engineering systems for solar driven evolution of hydrogen fuel from water: molecular, nanomaterials and biomolecular. Bren argues that a Global AP project would raise the public profile of this field of research. It would, she argues, fund single-PI grants, multi PI grants and centres of excellence. The single-PI grants would be distributed to fund focused research on the individual components using specific approaches to capitalize on the recognised expertise of individual PIs and their labs. The multi-PI grants would fund efforts at the interface between these areas, for example testing compatibility between the modules of AP research and testing performance. Feedback modifications towards practical device development would be coordinated in centres of excellence that organised sources of specialized equipment, technical expertise, benchmarking, testing product development strategies and scale up of the most successful systems for AP that arise from the multi-PI efforts. The centres of excellence would hold an annual conference for current PIs and other interested researchers and policy makers.

Such a GAP project, Bren argues, would require funds drawn internationally from government sources initially and distributed internationally. One such example, Bren maintains, is the European Research Council . These could be supplemented by funds from large philanthropic organisations provided a mutually agreeable mechanism for distribution of the funds could be developed. A model that sees the fund distributed according to equity criteria amongst the different participating nations would support the principle that photosynthesis in its natural form should be considered common heritage of humanity. Bren proposes that such distribution would be coordinated by an international governing board advised by peer reviewers. Funding criteria would include principles such as diversity, quality of science and geography (socio-political context) so that the taxpayers who were the ultimate source of such funds could expect a direct benefit to their region as well as to humanity and the environment in general. Criteria would also encourage collaboration and rapid development of functional systems rather than decades long study of a single, isolated component. Hence the single PI grants would be for limited time periods (i.e., three years)

with one renewal after which only multi-PI grants could be accessed. This would encourage individual PIs to coalesce their AP research projects in order to maintain funding.

Supporting Bren's vision for the structure of a global AP project, Michalsky, Pfromm and Steinfeld make the case for a single or multi-PI grant that would pursue basic research designed to foster the development of production technologies for renewable ammonia (NH_3) fertilizer, a hydrogen storage and carrier system and combustion source for transportation, domestic and industrial fuel. These authors support a model for corporate as well as government and philanthropic contribution to a global AP fund and for such a project to raise the public profile of the field. They view solar-derived NH_3 as economically more attractive in certain geographically, economically and politically isolated regions than NH_3 from the Haber-Bosch plants. They view solar-driven NH_2 reduction as one of the three central reactions of "synthetic photosynthesis" and of a global AP project (coordinated by an politically and economically neutral agency) alongside solar driven CO_2 reduction and H_2O splitting for the efficient production of solar fuel as well as acquisition of knowledge. They agree that these three core reactions ethically should be regarded as common heritage of humanity and not fully owned by profit-focused industries so that global synthetic photosynthesis is held on trust for humanity and its ecosystems. They support the statement from the Chicheley Hall meeting that "Our goal is to work cooperatively and with respect for basic ethical principles to produce the scientific breakthroughs that allow development and deployment of an affordable, equitably accessed, economically and environmentally sustainable, non-polluting global energy and food system that also contributes positively to our biosphere.

Schlau-Cohen argues that the fact that photosynthesis generates enough energy from sunlight to power most life on earth provides a natural source of inspiration for improving the design of artificial solar energy devices. Her paper highlights three major principles of the natural photosynthetic process that should be taken up by a global AP initiative- the fact that they are robust to disorder, exhibit multi-functionality through dynamic conformational changes in response to fluctuating changes in the local environment and have environmentally controlled functionality. She acknowledges that this requires expertise in biology, material science and engineering, requiring interdisciplinary communication and

cooperation. She proposes a global AP initiative that involves exchanges between natural and AP researchers sustained through funding projects requiring multidisciplinary teams.

Massin, Kaeffer, Field, Schacher, Popp, Chavarot-Kerlidou, Dietzek, Artero argue that a combined effort at the interface between materials science and molecular chemistry, ideally funded with a global AP project is need to improve the overall performances of the photoelectrodes and progress to economically viable PEC devices. Their study demonstrating that NiO films are suitable materials for the construction of dye-sensitized photocathodes with current densities of up to $300 \mu\text{A}\cdot\text{cm}^{-2}$ resulted from the combined efforts of four distinct groups from France, Germany and illustrates how collaboration can be achieved at the interface of materials science, molecular chemistry, theoretical chemistry and physical chemistry.

Cox, Pantazis, Neese and Lubitz use their work demonstrating how nature's water-splitting catalyst a $\text{Mn}_4\text{O}_5\text{Ca}$ co can be developed from biomimetic and bio-inspired approaches. factor incorporates inherent structural flexibility to convert to an 'activated' form immediately prior to O-O bond formation, to illustrate how new design criteria for water splitting catalysts using first row transition metals. They see a global AP project as bringing together researchers across a range of disciplines to work on such approaches to the construction of a globally deployable AP technology that is affordable and accessible throughout the world with maximum benefit for all. They agree that photosynthesis in its natural form should be considered common heritage status under international law.

Sovacool and Gross draw upon research into market and community barriers to and acceptance of solar photovoltaic and wind energy systems to propose nine factors likely to be critical to global uptake of AP technology. These factors are 1) strong institutional capacity 2) political commitment 3) favourable legal and regulatory frameworks, 4) competitive installation financing 5) mechanisms for information and feedback 6) access to financing 7) prolific community and /or individual ownership and use 8) participatory project siting and 9) recognition of externalities or positive public image. They propose that once AP systems are ready to be piloted, quantitative case studies could be done to determine market segments and social barriers unique to AP.

Ueno, Misawa and Oshikiri present one of the first studies of plasmon-induced water splitting as a source of hydrogen evolution linked with synthesis of ammonia after nitrogen fixation (as a more energy dense fuel source than hydrogen) using gold nano-structured SrTiO_3 photoelectrodes, where redox reactions proceed front and back with the evolved gases being controlled by the reduction co-catalyst. They demonstrate that these gold nanoparticles exhibit good long term stability and their plasmon band can be tuned to cover a large part of the solar spectrum by simply changing their shape and size. Their work is a priority of the Japanese Ministry for Education, Culture, Sports, Science and Technology) under the KAKENHI project involving 43 research groups which provides insights about develop a global AP initiative- the aim being to achieve hydrogen evolution of 5-10% conversion efficiency.

Cedeno and Moore in their review illustrate how developing improved methods to immobilize catalysts on semiconductor surfaces will be a major area of work in a global AP project. They look to such a project for the governance structure, guidance and organizational retooling required, though with the caution that the project not undermine the important contributions of small groups and independent researchers working on unconventional yet potentially transformative science.

Purchase and de Groot drawing on their experience with the Dutch Biosolar Cells consortium review the scientific challenges that need to be overcome to develop AP devices and materials. They argue that AP is largely unknown in energy and climate change policy documents and such a project may not only bring AP scientists together but raise the policy 'visibility' of the field. They claim that the most compelling reason for a global AP project derives from the sheer size of the required energy system. They estimate a capital investment of 1 trillion dollars will be required to 1% of the world's energy mix and this can only be achieved through a global effort

Bruce and Faunce in their paper, argue that a global AP initiative needs to focus on fully functioning AP technology providing food, fertilizer and ecosystem sustainability as well as renewable hydrogen fuel for human uses from solar-driven water splitting. They maintain

that establishing a global AP project could become a focus for a new way of thinking about how as a species we plan to survive on earth. It could take the lead, for example, in developing complex policy options about long term energy and resource production and allocation, food security and eco-systems preservation. Without such an initiative, they argue, massively increased urbanisation with attendant pollution, environmental degradation and mass exploitation of animals for food is likely to replicate the destruction of civilisations and has so often happened previously when humans failed to respect environmental sustainability.⁸

Yet, Bruce and Faunce argue that because the sunk and switching costs to alternatives such as AP technology are enormous, states have become practically unable to escape their commitment to fossil fuel systems.⁹ Fossil fuel technologies, exploited in the personal transport and energy generation sectors have enjoyed the benefits of a long history of state investment and regulatory preferences.¹⁰¹¹ This makes them likely to potentially resist the globalisation of AP technology.¹² This position that can be alleviated, however they maintain, through strategies in competition law. Some relevant legal and policy strategies they evaluate in this context include greater citizen-consumer involvement in shaping market values, legal requirements to factor services from the natural environment (i.e, provision of clean air, water, soil pollution degradation) into corporate costs, reform of corporate taxation and requirements to balance maximisation of shareholder profit with contribution to a nominated public good, a global financial transactions tax, prohibiting horizontal cartels, vertical agreements and unilateral misuse of market power.

3. Ethical Foundations of a Global Project on Artificial Photosynthesis

The Chicheley Hall meeting discussed the ethical importance of a global AP project having a defined challenges at the levels of both fundamental science and benchmarking as well as a realistic time line for its achievement. It was proposed that benchmarking in this context should include not just technological efficiency and competitive advantage, but precautionary life cycle risk analysis and cost-effectiveness assessment. The importance of making the activities of such a global AP project express a narrative relevant to the concerns of the general populace in both developed and developing nations was also stressed. In terms of building such a global AP project it was suggested that initial involvement of

smaller organisations with greater flexibility in terms of financially supporting visionary ideas could leverage subsequent involvement of larger stakeholders. The importance of a global funding mechanism supporting diverse projects, including those of younger investigators was also emphasised. Whilst a long-term goal of AP research could be to develop a wholly non-biological system, bio-inspired, bio-mimicing and bio-enhanced approaches to AP all would probably have their place in at least the initial phases of a global AP project.

It was accepted that a global AP project would need to engage ethicists, policy makers and analysts. It should incorporate programs of education for young scientists, the public and policy makers. It would need to connect with and be supported by high profile philanthropic and international organisations as well as governments. Some considered that the role of private corporations in a global AP project would be problematic initially if there was a rigid insistence on intellectual property rights (which may slow collaboration and innovation) as a condition for investment. There was widespread support for the view that photosynthesis in its natural form should be considered to fall within the concept of 'common heritage of humanity' under international law to the extent that knowledge of its fundamental processes could not be owned entirely by profit-making interests, militarised or manipulated to promote social inequality or environmental degradation. Governance of a global AP project would need to comprise a highly qualified scientific committee capable of evaluating single and multi-investigator grants as well as a policy-oriented board capable of lobbying for, securing and coordinating recurrent funding and other resources.

The case was made that the developing world which comparatively lacks electricity and energy production and storage capacity may be more likely to understand the advantages of a global AP initiative. It was also argued that a global AP project could have different goals-with mature AP technology deployed at community level or 'fully distributed' and servicing individual homes. Correspondingly, the energy storage issue could be a major point of policy leverage for a global AP project in the developed world.

4. Conclusion

One motive for a global project on AP is the view point that, at this perilous point in human history, the moral culmination of nanotechnology is global artificial photosynthesis.¹³ It is coherent with the spirit of such a realisation that the natural process of photosynthesis should be declared 'common heritage' not just of humanity but of life on Earth so as to ensure that unravelling its details primarily should be a gift to all life on this planet rather than a source of profit to a minority.¹⁴

The process of imagining a world free of war, poverty, cruelty, oppression of each other and other life forms has been continuing for many centuries. Only now, with approaches such as nanotechnology and with the capacity of global AP technology to make human structures support their own population and contribute positively to the ecosystem sustainability, are such dreams within practical reach. Rather than heading down a destructive path involved with the making of weapons of war, the selling carbon-based fuels, the degradation of the environment or creation of greater social inequality, governments and large corporate interests by backing a global AP project can transform themselves into morally valued agents for the Sustainocene.

Perhaps the most idealistic component of developing a global AP project to assist the material preconditions for peaceful coexistence and environmental sustainability spread across the earth, is that by embracing such a vision humanity will have begun a great moral revolution in its collective consciousness. One analogy would be to compare this to the Copernican revolution- humanity across the globe no longer viewing itself and its interests at the core of ethical thinking, but wishing to consistently apply principles that respect the capacity for all life on earth to flourish. In such a vision is coherent on a global scale with the altruistic consciousness sustained for individuals by contemplative traditions. To highlight to the public and policy makers how a global project on AP could drive such a coherence between human imagination, intellect and conscience, it may even be appropriate to refer to a global synthetic photosynthesis project.

Acknowledgements

The author wishes to acknowledge the assistance provided by the Hooke Committee of the Royal Society in coordinating the Chicheley Hall meeting, as well as an Australian Research Council Discovery Grant.

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