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# Energy and environment policy case for a global project on artificial photosynthesis

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A policy case is made for a global project on artificial photosynthesis including its scientific justification, potential governance structure and funding mechanisms.

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## Improving photosynthesis – the great scientific and moral challenge for our time

The United Nations General Assembly declared 2012 the *International Year of Sustainable Energy for All*, recognizing that access to modern, affordable energy services in developing countries is essential for the achievement of the *Millennium Development Goals*.[1] Here we explore how achievement of such laudable goals can be accelerated by a global macroscience project designed to improve upon or draw inspiration from a full characterisation of the photosynthetic process that in its present and historical forms provides the bulk of our food and energy, as well as sustaining the ecocosystems upon which we depend.

Many technologies are being proposed as potential solutions for the energy and climate change problems associated with the growth of human population to $\sim$10 billion its energy consumption to $\approx$500 EJ per year ($\approx$20 TW) and the increased burning of carbon-based 'archived' photosynthesis fuels (such as oil, coal and natural gas).[2,3] The latter has been prolonged, despite adverse environmental consequences, through cost-decreasing new resource discoveries and developments such as those involved in shale oil and gas extraction as well as 'fracking'.[4] Yet, we argue, no new technology has the long-term potential to so radically transform the planet towards sustainability as artificial photosynthesis engineered (alone or together with other technologies) in more efficient form as an 'off-grid' zero-carbon energy solution into all our structures (*i.e.*, buildings, roads, vehicles). The policy position we advocate is that developing and globally deploying artificial photosynthesis, for example either by engineering it into building materials or in discreet practical devices, is one of the great scientific and moral challenges of our time and would be a major step towards national and global economic security as well as preservation of our biosphere.[5]

There is presently a considerable energy and climate change policy focus on the capacity of photovoltaic electricity fed into centralised grid structures to provide (in combination with sources such as nuclear, wind and solar-thermal) an increasing portion of the world's zero-carbon renewable energy sources.[6] Yet it is unlikely that unravelling the scientific challenge of photosynthesis will or should simply halt at its light capture component. Rather, it must proceed into fully understanding at a molecular level how the structure and function of the 'natural' photosynthetic process[7,8] can be a source of insight and inspiration[9–11] for discovering how solar energy can be stored in a chemical bond as a low mass, high energy carrier fuel. This may involve water splitting-derived $H_2$ alone, or $H_2$ in combination with products derived from industrial or atmospheric-sourced $CO_2$ reduction, that can be readily stored and transported to allow release of energy as required, for instance either by reaction with oxygen[12] or conversion into electricity *via* a fuel cell.[13,14]

## Reasons for a global artificial photosynthesis project

The complexity and overlap of scientific disciplines involved in fully characterising and improving the photosynthetic process provide a rather obvious reason for coordinating and thence accelerating them within a global project. A shared feature among most solar fuels strategies is a focus on a particular scientific challenge. Thus, researchers in this field are striving to design molecular mimics of photosynthesis that utilize a wider region of the solar spectrum, employ catalytic systems made from abundant, inexpensive materials that are robust, readily repaired, non-toxic, stable in a variety of environmental conditions and perform more efficiently allowing a greater proportion of photon energy to end up in the storage compounds, *i.e.*, carbohydrates (rather than building and sustaining living cells).[15–18] Relevant approaches utilize coordination chemistry, material science and nanosciences,[19–23] as well as modified bio-engineered, synthetic biomimetic and bio-inspired techniques, to construct photo-semiconductors and solid state catalysts for water oxidation,[24] plus hydrogen evolution catalysts based on enzymes.[25–27] It has been suggested that only the most efficient components of natural photosynthetic energy transduction should be a target of such chemical mimicry that needs to become more systematised and outcome focused.[28]

The second reason justifying a global project is that a variety of other evaluation processes have already determined the value of investing considerable funds in this area at the national level. A dozen European research partners, for example, form the *Solar-$H_2$ Network*, supported by the European Union.[29] The Max-Planck Society has just founded an *Institute for Chemical Energy Conversion*, a 100 million Euro foundation in Germany. The US Department of Energy (DOE) *Joint Center for Artificial Photosynthesis (JCAP)*, led by the California Institute of Technology (Caltech) and Lawrence Berkeley National Laboratory, has been awarded US$ 122 million over 5 years to demonstrate a manufacturable, scalable solar fuels generator using earth-abundant elements that, with no wires, robustly produces fuel from the Sun ten times more efficiently than current crops. Some Energy Frontier Research Centers (EFRCs) funded by the US DOE are focused on solar fuels related endeavours; for example, the *Argonne-Northwestern Solar Energy Research (ANSER) Center* led by Northwestern University, the *Center for Bio-inspired Solar Fuel Production (BISFuel)* led by Arizona State University, and the *Center for Solar Fuels* led by the University of North Carolina. Prominent international examples include the *Energy Futures Lab* at Imperial College London,[30] the *Australian Centre of Excellence on Electromaterials Science* (ACES) Energy Research Program[31] and the *Solar Fuels Lab* at Nanyang Technological University in Singapore.[32] In Japan, the *Advanced Low Carbon Technology Research and Development (ALCA)* project aims to produce a carbon-free fuel based on hydrogen peroxide.[33] In South Korea, the Pohang Steel Company, is contributing to the *Korea Center for Artificial Photosynthesis (KCAP)*.[34] In China, the first national lab for clean energy research has been set up with the broader mission of also reducing carbon emissions.[35] A global initiative could leverage further support and encourage efficiency through combined approaches such as specialization.

The third reason is that a global artificial photosynthesis (GAP) project would significantly raise the public profile of artificial photosynthesis and drive policy and governance changes to facilitate rapid deployment of the technology. The policy reality is that artificial photosynthesis technology is one of a number of alternative energy technologies vying for research and development support from government and industry investors in a time of tightening budgets. The funds previously mentioned as dedicated to artificial photosynthesis research are miniscule compared to those allocated to other forms of renewable energy research, for example, carbon capture and storage technologies, at a time when fossil fuels (particularly liquid natural gas) remain relatively cheap and accessible, at least in the short term because of government subsidies, taxation and investment incentives. Artificial photosynthesis has unique, safe long-term capacity to provide an 'off-grid' zero-carbon, safe, affordable energy and climate change solution to particularly meet the needs of developing nations or those living in hostile environments, but to do so significant ethical and legal challenges will need to be addressed.[36] Some of these challenges are discussed in the next section dealing with the form and structure of a GAP project.

## Form and structure of a global artificial photosynthesis project

One approach to structuring such a global initiative could involve incrementally building towards it by encouraging each existing national project to add relevant collaborations into grant proposals for renewed funding. An additional component here could involve encouraging intellectual property lawyers protecting the interests of the respective universities, industry partners and public funders to agree to meet and discuss suitably secure forms of ideas sharing (such as date and time-stamped communications designed to protect priority). Such changes could be facilitated by periodic higher-level meetings of the leaders of the different national projects in conjunction with senior representatives of their respective funding agencies to develop guidelines or memoranda of understanding for collaboration.

Given the extent to which issues of state sovereignty and lobbying by the 'archived' photosynthesis fuel industries may frustrate related national efforts, prioritizing private resources may have the dual advantages of leveraging existing governmental support and providing significant flexibility with regard to initiating international partnerships that can rapidly respond to new solar fuels research and development opportunities. Such an approach, might involve a structure with an Advisory Board of high profile philanthropists or those with connections to large possible investors, as well as an a Science Advisory Board able to vet the merit of different proposals for funding. Linking strategies to achieve a strong positive impact on global energy needs with an emphasis on private sector funding forms the primary driver of the *Solar Fuels Institute* (SOFI) consortium of universities, government labs, industry, scientists, economists and public policy specialists united around the goal of developing and commercializing a carbon-neutral liquid fuel using the sun's energy within 10 years.[37]

The great lure of a global project for researchers will be increased funding, so a further or complementary model could be that as national projects end their first funding cycle, an international initiative under the auspices of the United Nations or one of its affiliated organisations could commence under which nations contribute a set percentage of their respective gross domestic product (GDPs), or obtain funds from other sources (such as uniform carbon pricing mechanisms or a multilateral treaty-based tax on international financial transactions). Researchers with expertise peer-reviewed by the project's Scientific Board could be seconded to such a project for a set period and permitted during that time to contract teams of researchers from the various national projects to advance work on important but comparatively lagging selected projects (such as $CO_2$ reduction). A set proportion of the project's funds could be set aside (as it was under the HGP to foster policy and ethics experts capable of effectively engaging in policy debates concerning the project.[38]

Work under a GAP project is likely to be distributed across a variety of laboratories in different nations, rather than being focused in one place, like the International Project on Fusion Energy (ITER). Yet, unlike ITER GAP research involves a wide spectrum of innovative activities (electrochemistry, inorganic and organic chemistry, material sciences, biochemistry, *etc.*) all of which could produce new catalysts for a range of processes outside the AP arena (*e.g.*, cheap alternatives to Pt in electrolysis) with considerable intellectual property value to the involved research groups, universities, institutes and countries as a financial return on their respective investments. Nonetheless, the successes of ITER may highlight the benefits of having signatories in a GAP collaboration that agree to share scientific data, procurements, finance and staffing.[39] The governance structure of a GAP project will also need to include a robust mechanism to increase the breadth of options efficiently tested, and facilitate the sharing of research progress and information on a real-time basis, so as to avoid unnecessary and duplicating investments, specifically pinpoint and orchestrate required research efforts, share requisite large scale facilities (such as nanofab centers, highest resolution TEMs, time-resolved spectroscopic facilities, technical supports), and provide the various types of prototypical pilot plants, as well as the basic elements—curricula and subjects—required to educate students and the general public.

Badging a GAP project as a specific scientific challenge tightly linked to important policy controversies associated with energy security (particularly for poor people in developing nations without an established electricity grid) and environmental sustainability could make it acceptable to a broad political base, as well as the general public. Declarations of basic principle by UNESCO and the United Nations on how such technology should be used initiatives such as the *Millennium Development Goals*, could play valuable roles here.[40]

## Conclusion

History is replete with examples of how technological progress has spurred and assisted the transformation of ideals into governance norms and structures. Yet public policy change as we advocate here should not follow many such examples and erupt from a crisis, but grow systematically. The author Kurt Vonnegut shortly before his death described the earth as a living organism; when tasked with how we should find solutions for its ailments, he suggested we should "get a gang" and do something about it.[41] The governance structures of the best types of science 'gangs,' of course, should not preclude or lessen the importance of small groups/individuals generating important but initially apparently unconventional ideas. However, on a large scale, a GAP initiative with a transparent, ethical and innovation-promoting governance framework drawing from the models discussed here may be exactly the 'gang' that humanity and the environment urgently needs.

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