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Artificial Photosynthesis as a Frontier Technology for Energy Sustainability

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Artificial Photosynthesis as a Frontier Technology for Energy Sustainability

Humanity is on the threshold of a technological revolution that will allow all human structures across the earth to undertake photosynthesis more efficiently than plants; making zero carbon fuels by using solar energy to split water (as a cheap and abundant source of hydrogen) or other products from reduced atmospheric carbon dioxide. The development and global deployment of such artificial photosynthesis (AP) technology addresses three of humanity's most urgent public policy challenges: to reduce anthropogenic carbon dioxide (CO_2) emissions, to increase fuel security and to provide a sustainable global economy and ecosystem. Yet, despite the considerable research being undertaken in this field and the incipient thrust to commercialisation, AP remains largely unknown in energy and climate change public policy debates. Here we explore mechanisms for enhancing the policy and governance profile of this frontier technology for energy sustainability, even in the absence of a global project on artificial photosynthesis.

Globalizing AP- A First Principles Argument

The argument for globalising artificial photosynthesis (AP) appears simple from first principles. Most of the our energy (particularly for transport) at present comes from burning 'archived photosynthesis' fuels (i.e., carbon-intensive oil, coal and natural gas) in a centralised and profitable distribution network with decades long turnaround on high levels of private corporate investment and a well-honed capacity to prolong its existence through innovations such as coal-seam gas 'fracking' and shale oil extraction, despite its significant contribution to critical problems such as atmospheric greenhouse gas emissions and climate change, ocean acidification and geopolitical instability.[1 2]

Molecular hydrogen (H_2) is an obvious alternative, its conversion into electricity or heat yielding only H_2O, with no CO_2 being produced. Currently 500 x 109 standard cubic meters of H_2 per year are used in industrial processes world-wide, of which more than 90 per cent is derived from 'archived photosynthesis,' primarily from natural gas.[3] One of the innovating AP approaches to generating H_2 is simply bubbling it off water using photocatalysis.

The scientific challenges for efficient and globally deployable AP are complex; requiring coupled breakthroughs in light harvesting, charge separation, catalysis, semiconductors, nanotechnology, modelling from synthetic biology and genetic engineering, photochemistry and photophysics, photoelectrochemistry, catalysis, reaction mechanisms and device engineering.[4 5 6 7 8]

In favour of AP is the vast excess of available solar energy compared to present and projected human needs, its capacity to reduce the atmospheric concentration of greenhouse gases and address the problem of intermittent renewable energy (solar pv, wind and hydro) electricity supplies as well as the need for a zero-carbon source for transportation fuels.

One scenario for globalizing AP involves light capture facilities situated in coastal metropolitan areas where sea water would be catalyzed as the source of H_2 and oxygen (O_2). The H_2 gas would be connected by pipelines (or other transport) to adjoining fuel-cell electric power plants or facilities that sequester CO_2 to be combined to make carbon-based fuels. For many developed nations, existing natural gas pipelines could provide a suitable distribution network for transport of H_2 in the gaseous state to centralised hubs, be they power plants for subsequent electricity generation or smaller scale 'gas stations' to supply pressurised H_2 fuel for transportation needs. [9]

Yet another vision for global use of AP as a decentralised energy source is even bolder. Surely energy security and environmental sustainability will be enhanced, as the human population approaches 10 billion by 2050, if all the structures we are covering the surface of the planet with did photosynthesis more efficiently than plants (i.e., making H_2 fuel which when burnt makes fresh water and absorbing atmospheric CO_2 to make fertilizer or basic foods).[10]

Large national AP projects already exist in most developed nations, a prominent example being the Joint Center on Artificial Photosynthesis (JCAP) at Caltech.[11] Some official energy and climate change reports are beginning to briefly mention the possibilities of AP.[12] Yet this is usually with caveats that the AP field is still in the research phase, is far from industrial development and requires substantial improvements in the transition from expensive rare earth metals (platinum/iridium) to cheaper more abundant but relatively unstable iron, nickel and manganese catalysts.[3]

Governance and Policy Obstacles to Globalizing AP

Not only is the potentially 'game changing' technology of AP barely on the energy and climate change policy 'radar' but many governance features exist at national and international levels that will inhibit its rapid deployment The final text of the United Nations (UN) *Rio+2012 Earth Summit (Conference on Sustainable Development)*, 'The Future We Want' reaffirmed, for example, a commitment of nation states to sustainable development, environment protection, a green economy and clean energy in the context of existing undertakings, including those under international law.[13] Yet artificial photosynthesis was not mentioned and, despite activism by major civil society organisations, major governance barriers to rapid widespread deployment of such zero-carbon energy technologies remained untouched; this chiefly being the approx. US$1trillion globally in taxpayer funds subsidising, and so artificially lowering the comparative price of oil, coal, natural gas fuels and undercutting the effectiveness of carbon pricing schemes.[14]

Similarly, although the UN, key energy policy institutions such as the International Energy Agency (IEA) acknowledge that we are now in a period of transition in energy/fuel patterns and related social, environmental and industry policy,[15] the revolutionary potential of AP has not been substantially addressed in key energy policy documents such as the US DOE and Council for Automotive Energies *Hydrogen Production Roadmap*, the *EU Strategic Energy Technology (SET) Plan* and the programs of the World Bank.[16]

Much of such public funding of basic AP research remains short term, facilitating entry of new groups, but not their building of infrastructure or retaining key researchers. To ramp up the field these public resources may be leveraged with private capital through initiatives such as the Dutch BioSolar Cells open innovation partnership[17] and the Solar Fuels Institute (SOFI) based at Northwestern University in the USA.[18]

Patents are of crucial importance in drawing necessary investment to AP particularly in the marketing phase for 'start-up' companies. Yet, excessive amounts of overly broad patent claims can slow collaboration and development, locking researchers into areas less likely to be the subject of patent challenges. For AP researchers within academia, patenting will be an expensive business with many institutions often unwilling to cover associated costs without clear financial return downstream in a process that often inhibits collaborations. Enhancement of the research use patent exemption, public good licencing and patent-sharing pools for multiple investors could be important governance initiatives for public funded universities involved in AP research, as could allowing greater control of original AP researchers over patents. Such licensing arrangements could allow other non-exclusive licensees access after an agreed period of time but that commercialisation must proceed within a reasonable timeframe, or ownership will return to the originating organisation. Intra-consortia arrangements about sharing of data might allow results to be more widely and promptly distributed, at internal conferences or to collaborators for example, without having to wait till patents are filed.

Such 'in-house' patent flexibilities additionally might ensure that the investments of large companies in the marketing phase are not over-secured by intellectual property to the point of inhibiting fresh innovation at the proof-of-concept and prototype phases. Flexible venture capital schemes (perhaps coordinated by the World Bank) might provide revolving funds paid back later when AP technology comes to the global market.

Photosynthesis as Common Heritage of Humanity under International Law

Despite their potential challenge to sovereign interests of national states economically reliant on 'archived photosynthesis' fuels, international law governance frameworks such as those on climate change or equity of energy storage, production and conversion systems (i.e., United Nations (UN) *Millennium Development Goals*) may help reduce comparative price lowering mechanisms (such as subsidies) for 'archived photosynthesis fuels,' promote equitable transfer and distribution of AP technology, curb excessive restrictions on AP research by patents.

Photosynthesis is the great invention of life, like biodiversity, the atmosphere, the moon, outer-space, the human genome and the world's cultural and natural heritage, could be treated as subject to common heritage requirements under international law[19] [20] perhaps through a specific UN or UNESCO Declaration. Common heritage of humanity status putatively limits private or public appropriation; requires representatives from all nations to manage such resources on behalf of all, actively share the benefits, restrain from their militarisation and preserve them for the benefit of future generations.[21]

Other international law concepts that could be influential in the governance architecture of improved solar fuels collaboration are those that may declare photosynthesis a global public good, an aspect of technology sharing obligations, or those arising under the international right to health or ethical responsibilities to future generations.[19]

Promoting the Potential of AP for Energy and Environment Policy

The general public, policy makers and investors urgently need to learn more about artificial photosynthesis from enhanced outreach commitments by prominent researchers in the field, including policy briefings and contributions to key energy and climate change policy statements.

The idea of establishing a macroscience global AP project has been recently advanced.[22] Yet such an endeavour, however worthwhile in terms of raising the field's public policy profile, faces substantial logistical and governance hurdles in the immediate future. In this context, many lessons can be drawn from the relative failure of the photovoltaics (pv) industry in the 1970's and 80's about the dangers of 'hyping' a renewable energy field too early. In the case of AP, development of relevant comparative energy-based life cycle analyses in advance of economic life-cycle analyses will facilitate realistic predictions at the research development level, through to scalable production. If such photo-catalyst technology is to be rapidly globally deployed for unregulated use i.e., for localised H_2-based fuel production at residential or farm level, then appropriate recycling methods, environmental risk assessment and monitoring methods must be prepared. Development of governance systems for ethical oversight will also enhance public support. Improved collaboration could assist interaction between scientists and (process/chemical) engineers about such approaches and the establishment of relevant international benchmarks. Such research will assist public concern about potential toxicity to be promptly and properly addressed.

Beyond the prototype phase, continuous technological improvements in AP will require stable and certain incentive laws for domestic and community uptake. Involvement in World Bank energy investment schemes and scalable business models with start-up funds derived from carbon pricing schemes or taxes on global financial transactions could also be important governance and policy initiatives for globalizing AP.

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