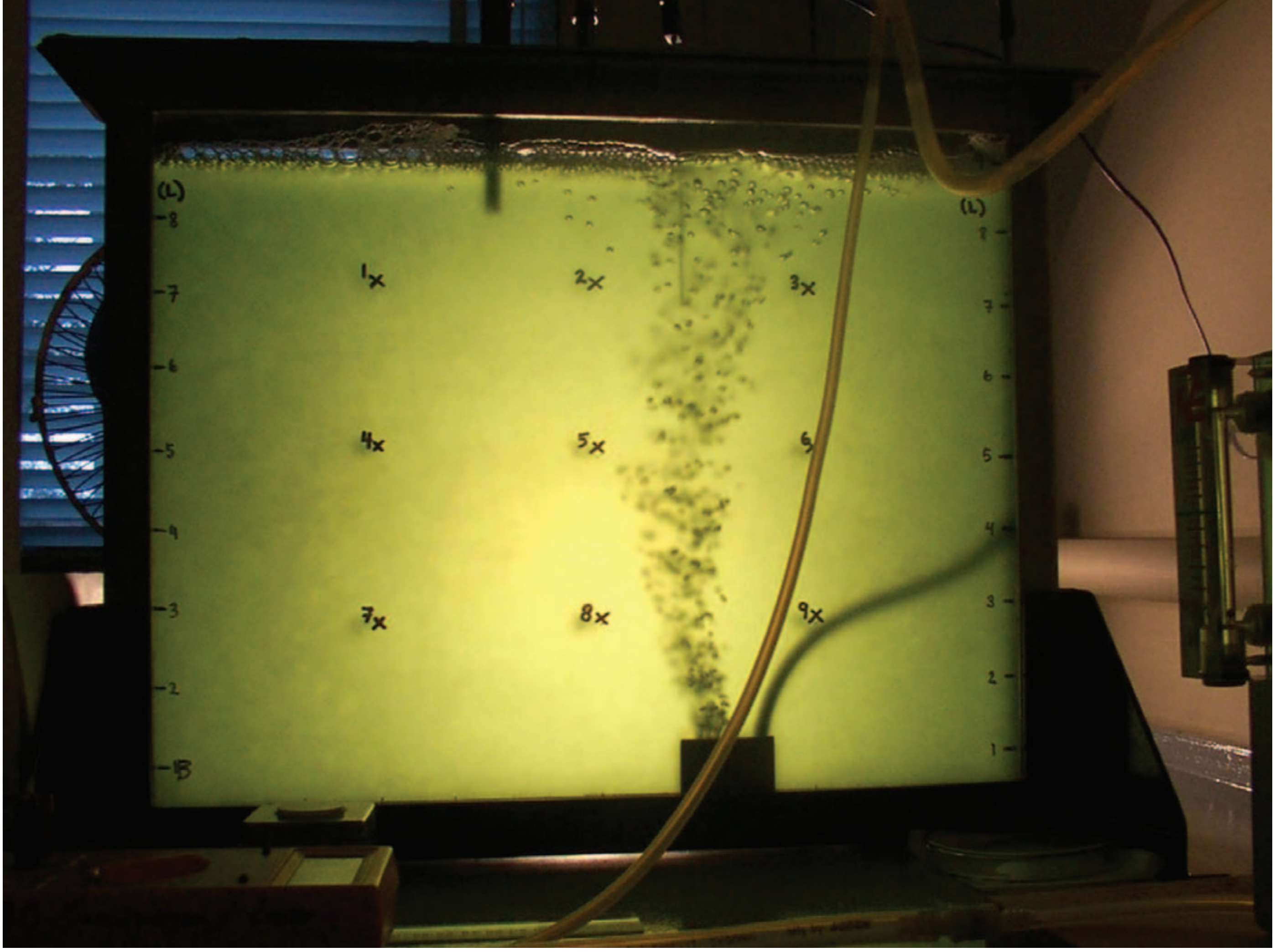

CSIRO Manufacturing and Infrastructure Technology

Scientists are exploring the potential of photobioreactors to exploit the photosynthetic abilities of cyanobacteria and microscopic algae. Cyanobacteria have the right credentials – they've been photosynthesising for billions of years.

Light Factories

Nature does it best. Or does it? An ambitious trans-Tasman cooperation is aiming to perfect artificial photosynthesis. Researchers want to exploit its potential to produce just about everything under the sun.

WE TEND TO TAKE for granted the deceptively low-key ability of plants to make carbohydrates using the energy in sunlight, so enabling life on Earth. But the researchers now attempting to emulate this feat appreciate the complexity and ingenuity of the plants and bacteria that carry out the fundamental process we call photosynthesis.

While a lowly cabbage can photosynthesise with uncanny ease, humans attempting to imitate the biochemistry and biophysics of plants through artificial photosynthesis face some daunting challenges. It requires such a broad range of expertise that, in this part of the world, some 40 researchers from 11 institutes in Australia and New Zealand are cooperating to develop the technology and have formed a collaboration known as the Australian Artificial Photosynthesis Network (AAPN).

It raises the question: if plants and certain bacteria are so good at photosynthesis, why bother to mimic them? Plants provide us with food, fibre, timber, oxygen and pharmaceuticals; they feed our livestock, underpin nearly all ecosystems, and absorb the excess carbon dioxide (CO_2) that is upsetting climates. So what's the point of designing artificial methods? Can we really improve on nature?

Doing it better than plants

Dr Tony Collings, of CSIRO Telecommunications and Industrial Physics, and an AAPN member, appreciates the value of natural photosynthesis – it is the inspiration for his work as leader of the division's Artificial Photosynthesis Project – but he also points out that plants have some weaknesses.

'Plants tend to be incredibly wasteful of water because moisture escapes from the leaves as CO_2 is absorbed through leaf pores,' says Collings. 'This is especially true for some crops. It takes thousands of litres of water to produce a kilogram of cotton, which doesn't worry the cotton plants, but given the value of water in Australia, it would be very useful to develop more water-efficient artificial systems for trapping solar energy.' These could eventually complement other improvements in agricultural water use.

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What's more, environmental factors like temperature and CO_2 concentration tend to limit the rate of photosynthesis in plants whereas, in artificial plant-free systems, the environment can be carefully controlled in order to optimise outputs. The maximum efficiency of solar conversion in plants is only about 5% and scientists are confident that they can better this in man-made systems.

Collings also emphasises the versatility that artificial photosynthesis systems will offer. While some research groups are particularly interested in using the technology to mop up CO_2 and so counter global warming, he says the potential benefits are much broader than that.

Outputs could include: proteins for feeding humans and livestock; sugars for direct consumption; cellulose fibres for use as textiles; isoprene, rubbers and sealants; or sustainable fuels including hydrogen (from water) and ethanol.

CSIRO Plant Industry

Photosynthesis in plants is only 5% efficient in solar energy conversion, and wastes large amounts of water as CO_2 is taken in through the leaves. Researchers can build in much more efficiency.

Mimicking the Light and Dark

Australia is a world leader in artificial photosynthesis technology, but how do scientists go about the design and construction of artificial plant-like systems? The concept is sometimes likened to 'leafless trees', but this is rather misleading. It is the process of photosynthesis that is being imitated or re-invented, not the plant as such.

Photosynthesis in plants occurs in two phases known as the Light Phase and Dark Phase. Each of these is a series of reactions that occur in chloroplasts (cell structures) within the leaf cells. In the Light Phase, energy from sunlight energises an electron in the green pigment chlorophyll, enabling it to pass along an oxidation chain. This electron transfer results in the pumping of protons (H^+) across membranes within the chloroplasts.

The Light Phase produces energy-rich ATP and NADPH compounds which power the incorporation of carbon dioxide into carbohydrate, via a series of intermediate compounds, in the Dark Phase of photosynthesis. Oxygen is released as a by-product during the Light Phase.

Using the plant as a model, researchers are endeavouring to mimic these processes and one advantage of this is that the Light and Dark Phases can be uncoupled. In plants they occur within and between membranes, respectively, inside the chloroplasts within plant cells. But engineered systems can be located kilometres apart, and connected by conventional power lines or by transfer of fuel intermediates such as hydrogen.

CSIRO Plant Industry

Thousands of litres of water are needed for just one kilogram of Australian cotton. Scientists hope artificial photosynthesis will complement improvements in agricultural water use.

Future projects

An exciting prospect is that of artificial photosynthesis directly generating electricity. This is a logical approach, given that natural photosynthesis involves excitation of electrons by light and so-called 'redox' reactions in which electrons are passed through a series of electron carriers. In plants, a continuous flow of electrons from water to the compound NADPH is used to fix carbon, that is to lock the energy of sunlight into carbon bonds in glucose.

The trick will be to tap into a similar source of electrons to produce low-cost 'green' electricity at an industrial scale and supply it directly to the national grid.

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The researchers in CSIRO Telecommunications and Industrial Physics are improving on a simple photochemical cell constructed by the renowned photosynthesis scientist Melvin Calvin. They are developing experimental photovoltaic or solar cells in which electron-donating molecules associated with an organic pigment, similar to chlorophyll, are coupled with a proton-pumping photocycle in a synthetic membrane not unlike the membranes in plant chloroplasts. Specially designed multi-layered structures form a series of light-active interfaces in which many tiny voltage differences add up to boost the electricity produced.

The team is also developing a so-called gas-electrolysis system. This consists of an electrolyte sandwiched between two thin porous electrodes that mimics some of the processes occurring in leaves, but at a much larger scale. Close contact between CO_2 and water molecules occurs in the artificial system. When gold is added to boost the process, the CO_2 is transformed into carbon monoxide and the water into hydrogen. With scaling-up of the system, this mixture of gases could be processed into various fuels, including hydrogen, or useful organic materials such as alcohol.

Another tact is to design synthetic membrane systems that copy plants' ability to convert light into the biochemical energy of ATP. In one version, developed by the CSIRO group, a purple membrane protein called bacteriorhodopsin, from a type of bacterium, is tethered onto a solid surface to which a lipid bilayer is anchored. The idea here is to eventually use the ATP to sequester $CO_{2,}$ to counter global warming.

Recently, Dr Tim Schmidt joined CSIRO to pursue the computational modelling of rubisco, a key photosynthetic enzyme for carbon fixation, along with Collings and Dr Peter Vohralik. The researchers are attempting to redesign this 6000-atom protein on the computer. This may seem ambitious, but the scientists have in mind the huge benefits, not least in agricultural productivity, if they can achieve just a 0.1% improvement in rubisco's efficiency of 1.5%. This work will complement studies at the Australian National University and the University of Sydney.

Meanwhile, in a collaborative effort, Dr Dilip Desai of CSIRO Manufacturing and Infrastructure Technology, Dr Michael Zachariou of CSIRO Molecular Science and Dr Dean Price, Dr Murray Badger and Professor John Andrews, of the ANU, are working on a photosynthetic bioreactor route. This will use cyanobacteria to harvest light and produce isoprene, a liquid hydrocarbon which can form rubber and other compounds.

Cyanobacteria, famously responsible for first generating the oxygen-rich atmosphere on Earth, are both aquatic and photosynthetic and hence ideal for artificial photosynthesis. In fact, the chloroplast of plants is essentially a cyanobacterium within the plant cell. The cyanobacteria required for the bioreactor are being specially developed by incorporating plant-derived isoprene synthase genes provided by the University of Wisconsin, USA.

The idea here is to eventually use the ATP to sequester $CO_{2,}$ to counter global warming

Working with Adelaide University, the researchers are also exploring the use of photobioreactors containing wild-type cyanobacteria or microalgae. These have the potential to generate a number of products including polyunsaturated fatty acids, hydrogen gas, and a compound produced within some microbes, called PHB (polyhydroxybutyrate), that is useful for making biodegradable plastic.

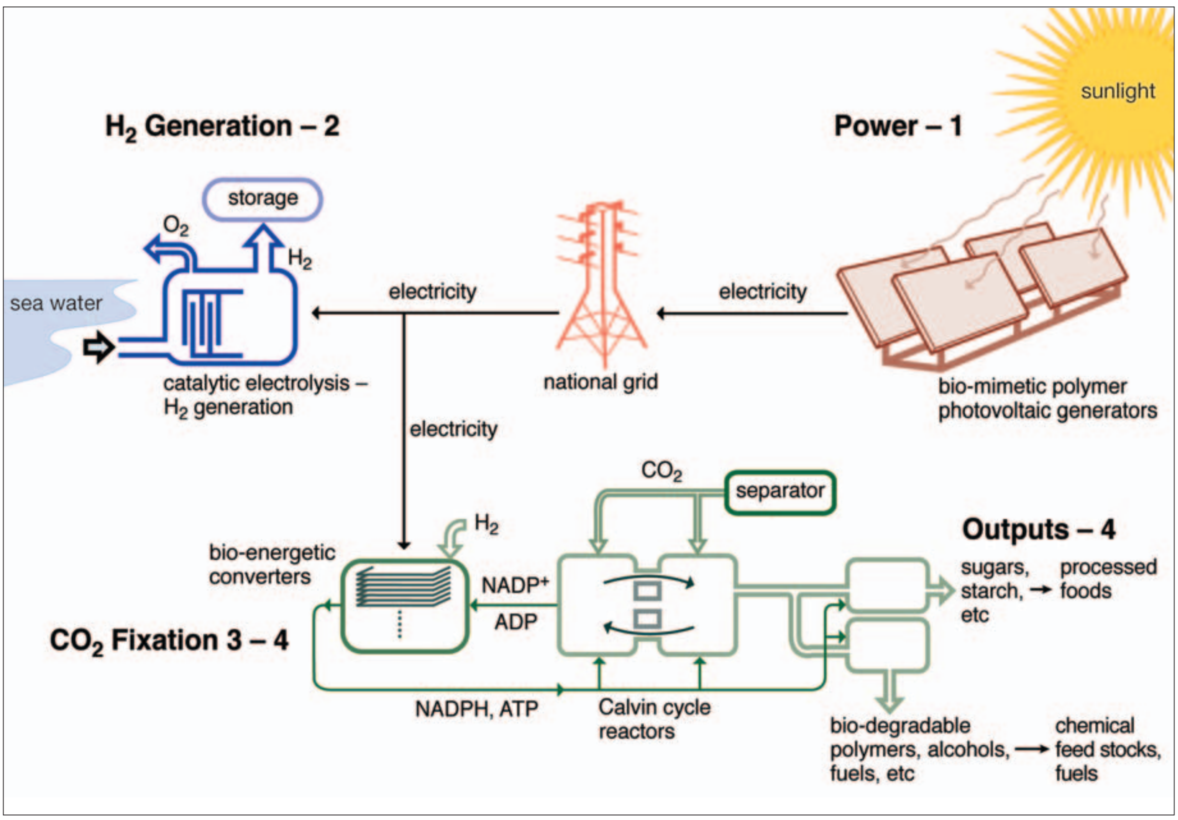
Plants are still ahead

The projects are at an embryonic stage and it will be decades before we are likely to see the plant-mimicking methods commercialised, perhaps removing CO_2 from emissions from factories, or producing dry food, or perhaps even generating electricity from light without reliance on fossil fuels.

Collings says artificial photosynthesis technologies under development by different research groups can also be interlinked, either all together or in various combinations (see the diagram). Compared, say, to a wheat crop, the systems have a small footprint (environmental impact), but, unlike the complex processes that have evolved over many millennia in plants, the artificial technologies need considerable improvement. For the moment, we will have to continue to rely on the work of real plants, but the artificial equivalents are an exciting prospect.

● **Steve Davidson**

More about artificial photosynthesis: www.aapnetwork.org
Contact: Dr Tony Collings, (02) 9413 7148



Professor Ron Pace, ANU.

Various artificial photosynthesis technologies – biological generation of electricity, splitting of water to produce hydrogen, and conversion of carbon dioxide into carbohydrates – could be linked together for sustainable production of sugars, food, polymers, alcohols, hydrogen fuel and chemical feedstocks, while absorbing excess carbon dioxide.