Can artificial photosynthesis solve our energy and climate problems?

In order to achieve the sought-after shift towards sustainable regenerative energy supply, researchers around the world are focusing on the conversion of solar energy into hydrogen and carbon compounds using artificial chemical systems. They aim to achieve much more efficient photosynthesis than plants have. Other scenarios foresee improving the energy balance of photosynthesis by modifying the photosynthesis system.

The photosynthesis of plants is by far the most important energy generation process in nature and essentially provides all food for the animal and human world. Up until humanity started to exploit fossil energy sources, notably in the 18th century with early industrialization in England, photosynthesis was the major primary energy source for humans (especially as fuel), and it has remained so for hundreds of millions of the poorest populations in the world.

Regenerative and sustainable energy sources

The photosynthetic reaction centre in the photosystem II contains four manganese ions and catalyzes the oxidation of water into hydrogen ions and molecular oxygen. © TU Berlin

However, back then in what is frequently referred to as the first “solar era” the use of plants as regenerative (renewable) sources of energy was far from being sustainable: large-scale deforestations and other kinds of devastation were the order of the day. Nowadays, efforts are being made to enter a new solar era and replace fossil energy sources such as coal, oil and gas with renewables – i.e. regenerative energy sources such as bioethanol, biodiesel and biogas.
resulting from the photosynthetic activities of plants. However, it should be borne in mind that “regenerative”, “renewable” and “sustainable” are not the same.

Photosynthesis is a process used by plants to capture the sun’s energy in order to convert atmospheric carbon dioxide (CO₂) and water into organic compounds, i.e. carbohydrates (mainly starch and saccharose). The conversion process has a number of steps: the first step involves the absorption of light quanta whose energy is used to split the hydrogen (i.e. protons and energy-rich electrons) part of water from the oxygen. While plants give off oxygen into the environment where it is taken up by humans and animals, the hydrogen is used in a second light reaction for the synthesis of high-energy organic molecules (ATP) whose energy is then used in a complex enzymatic reaction that reduces CO₂ to carbohydrates.

The discussion about environmentally friendly regenerative sources of energy and sustainable production and consumption revolves around three aspects of photosynthesis: first, sunlight as an infinite and clean source of energy; second, the conversion and storage of energy in the form of hydrogen and hydrogen-rich carbon compounds; third, the production of food for earth’s growing population. Therefore, the two elements in the discussion – environmentally friendly energies on the one hand and food for humans on the other hand – cannot be taken as separate issues.

In principle, the consumption of photosynthetic carbon compounds as energy sources and food only releases as much CO₂ as plants have previously bound. However, this balance does not take into account the energy consumed by machines, chemical fertilizers, herbicides, etc. Other considerations relate to the use of photosynthetic hydrogen because hydrogen (H₂) is a clean source of energy; the combustion of hydrogen only leads to water. Unfortunately, H₂ is highly explosive and difficult to store and transport. Most scenarios relating to future energy supply (e.g., the energy research concept prepared by the German Academy of Science and Engineering – acatech - on behalf of the German Ministry of Education and Research) therefore envisage the conversion of H₂ into methanol and methane, which are easier to handle but have a negative effect on the energy balance.

The “inefficiency” of photosynthesis

Plants only use a small proportion of the sun’s energy for the synthesis of energy-rich carbon compounds; net primary production has – depending on the prevailing environmental conditions – a meagre degree of efficiency of 0.5 to 1.5 per cent. “We can do a lot better”, is the opinion of certain scientists and engineers. Research projects on artificial photosynthesis have been undertaken with the goal of contributing to solving man-made energy and climate problems.

The physicist Professor Dr. Christoph Nebel from the Freiburg-based Fraunhofer Institute for
Applied Solid State Physics uses a modified cytochrome c molecule to capture sunlight. Cytochrome c is a red protein inside the electron transport chain in mitochondria. In his project, Nebel binds the cytochrome c molecules neatly arranged on the surface of a diamond in an aqueous environment. When the cytochrome is irradiated with light, it transfers electrons from the water to the carbon atoms of the diamond, which leads to the generation of hydrogen gas. The degree of efficiency is still less than one per cent, but “in theory we can obtain an efficiency of between 20 and 30 per cent,” explained Nebel, speaking on the TV programme “Forschung aktuell” broadcast by dradio.de on 5th May 2010. Nebel also pointed out that it is not absolutely necessary to use diamond, although it can nowadays be produced quite cheaply. The light-induced transfer of electrons of cytochrome c can also be done using other carbon interfaces. Unfortunately, the intensive irradiation destroys the light-active proteins. As interesting as these experiments are, it is still difficult to imagine that it will be possible to use them for the sustainable production of energy.

Photocatalytic conversion of carbon dioxide

The media have reported on other “artificial photosynthesis” approaches that have the potential to produce hydrogen. However, a better name for these processes would be “light dependent metal catalyses”. One such project is being carried out at the Institute of Solid State Research at the Jülich Research Centre. The common factor of all “light dependent metal catalyses” projects is that they use rare and expensive metals such as platinum, iridium and ruthenium as catalysts. Another project – Solar2fuel – rather than focusing on the generation of hydrogen, focuses on the fixation and utilization of the climate gas CO\(_2\) in the same way as photosynthesis. Solar2fuel is a cooperative project of the BASF, EnBW, Universität Heidelberg and the Karlsruhe Institute of Technology, and is part of the “Forum Organic Electronics” cluster of excellence. The aim of the project is to develop a process for the photocatalytic conversion of carbon dioxide (CO\(_2\)) arising from combustion processes into methanol. In this project, sunlight will be absorbed by organic dyes and its energy used for converting the carbon in carbon dioxide into climate neutral fuels. The project aims to combine approaches based on nanotechnology and material research with catalytic processes. “A photocatalytic process of this kind has the potential to throw up new ways of generating easy-to-handle energy sources,” said Professor Dr. Michael Grunze of the Institute of Physical Chemistry at Universität Heidelberg. The Solar2fuel project partners believe that this process will enable them to use sunlight directly for the utilization of CO\(_2\) – “similar to how it is used by plants for photosynthesis, but a lot more efficiently.”
The problem is that CO₂ is a relatively stable and inert molecule. According to Professor Dr. Markus Antonietti, the chemical activation of CO₂ is “one of the greatest challenges in the field of chemical synthesis”. The director of the Max Planck Institute of Colloids and Interfaces has been awarded numerous prizes for his research in the field of sustainable chemistry on the basis of environmentally friendly energy cycles and renewable biomass, including a recent Honorary Doctorate from the renowned University of Stockholm.

In contrast to the aforementioned projects, Antonietti and his team use non-metallic catalysts, i.e. graphitic carbon nitride (C₃N₄), a ring system of carbon and nitrogen atoms consisting of graphite-like layers. The carbon dioxide is bound to the nitrogen atoms of the catalyst and activated into a carbamate complex that serves as intermediary for further chemical reactions. The enzyme ribulose-1,5-bisphosphate-carboxylase/-oxygenase (RuBisCO or just rubisco) catalyzes the primary chemical reaction in the fixation of atmospheric CO₂. The enzyme is activated when the CO₂ binds to the nitrogen residue of the amino acid lysine. This research might open up ways that make it possible to reduce the CO₂ pollution of the atmosphere at the same time as synthesizing economically interesting substances. However, as Antonietti said “we need a great deal of patience in order to deal with the complex issues we are working with”, referring to his opinion that the Max Planck Society provides an excellent platform for such challenging projects.

The most abundant protein on earth
Just like the entire natural photosynthesis process, the enzyme RuBisCO is regarded as being notoriously “inefficient”. Rather than just catalyzing the fixation of CO₂ and initiate its conversion into sugar and oxygen (O₂), the enzyme also catalyzes a reaction between ribulose-1,5-bisphosphate and molecular oxygen (O₂). In evolutionary terms, RuBisCO is a very old enzyme; it developed at a time when the conditions on earth were completely different: the atmosphere had a relatively high CO₂ concentration and a relatively low O₂ concentration. At least, this is the reason given by certain researchers to explain the inefficiency of the enzyme. RuBisCO is the most abundant protein on earth, accounting for between 10 and 20 kg RuBisCO per capita (information provided by Prof. Dr. Mark Stitt, formerly of the Institute of Botany at Universität Heidelberg, now at the Max Planck Institute for Molecular Plant Physiology). Numerous research groups, including a team led by Dr. Manajit Hayer-Hartl at the Max Planck Institute of Biochemistry, are now trying to modify RuBisCO in such a way as to enable it to catalyze CO₂ fixation more effectively. However, not all scientists are convinced that the many different approaches used to improve photosynthesis will actually be successful. The process of photosynthesis is quite old in evolutionary terms, dating from around 2.7 billion, or perhaps more than 3 billion years ago. One of the arguments used by those who doubt the claims relates to the notion that evolution has had “all the time in the world” to optimize this fundamental process by way of selection. In addition, photosynthesis is an extremely complex process. Each of the two photosystems in the chloroplasts contains several dozens of different components: light antennas, enzymes, receptors and membrane pumps. It is somewhat hubristic to believe that humans can do better. Ecologists also refer to the need for energy balances to take into account all the steps and components involved in a particular process. When this is taken into account, the efficiency of natural photosynthesis is no longer so bad in relation to man-made regenerative sources of energy. It would appear that plans to achieve a sustainable energy economy of the future will be more successful using more effective crop varieties and the optimized use of food and energy crops than with artificially improved photosynthetic processes.