**Solar Fuels**

A solar fuel is a synthetic chemical fuel produced directly/indirectly from solar energy sunlight/solar heat through photochemical/photobiological (i.e., artificial photosynthesis, experimental as of 2013), thermochemical(i.e. through the use of solar heat supplied by concentrated solar thermal energy to drive a chemical reaction), and electrochemical reaction. Light is used as an energy source, with solar energy being transduced to chemical energy, typically by reducing protons to hydrogen, or carbon dioxide to organic compounds. A solar fuel can be produced and stored for later usage, when sunlight is not available, making it an alternative to fossil fuels. Diverse photocatalysts are being developed to carry these reactions in a sustainable, environmentally friendly way.

**Overview**

The world's dependence on the declining reserves of fossil fuels poses not only environmental problems but also geopolitical ones. Solar fuels, in particular hydrogen, are viewed as an alternative source of energy for replacing fossil fuels especially where storage is essential. Electricity can be produced directly from sunlight through photovoltaics, but this form of energy is rather inefficient to store compared to hydrogen. A solar fuel can be produced when and where sunlight is available, and stored and transported for later usage.

The most widely researched solar fuels are hydrogen and products of carbon dioxide reduction. Solar fuels can be produced via direct or indirect processes. Direct processes harness the energy in sunlight to produce a fuel without intermediary energy conversions. In contrast, indirect processes have solar energy converted to another form of energy first (such as biomass or electricity) that can then be used to produce a fuel. Indirect processes have been easier to implement but have the disadvantage of being less efficient than, e.g., water splitting for the production of hydrogen, since energy is wasted in the intermediary conversion.

**Photochemical hydrogen production**

A sample of a photoelectric cell in a lab environment. Catalysts are added to the cell, which is submerged in water and illuminated by simulated sunlight. The bubbles seen are oxygen (forming on the front of the cell) and hydrogen (forming on the back of the cell). Hydrogen can be produced by electrolysis. To use sunlight in this process, a photoelectrochemical cell can be used, where one photosensitized electrode converts light into an electric current that is then used for water splitting. One such type of cell is the dye-sensitized solar cell. This is an indirect process, since it produces electricity that then is used to form hydrogen. The other major indirect process using sunlight is conversion of biomass to biofuel using photosynthetic organisms; however, most of the energy harvested by photosynthesis is used in life-sustaining processes and therefore lost for energy use.

A direct process can use a catalyst that reduces protons to molecular hydrogen upon electrons from an excited photosensitizer. Several such catalysts have been developed as proof of concept, but not yet scaled up for commercial use; nevertheless, their relative simplicity gives the advantage of potential lower cost and increased energy conversion efficiency. One such proof of concept is the "artificial leaf" developed by Nocera and coworkers: a combination of metal oxide-based catalysts and a semiconductor solar cell produces hydrogen upon illumination, with oxygen as the only byproduct.

Hydrogen can also be produced from some photosynthetic microorganisms (microalgae and cyanobacteria) using photobioreactors. Some of these organisms produce hydrogen upon switching culture conditions; for example, Chlamydomonas reinhardtii produces hydrogen anaerobically under sulfur deprivation, that is, when cells are moved from one growth medium to another that does not contain sulfur, and are grown without access to atmospheric oxygen.[10] Another approach was to abolish activity of the hydrogen-oxidizing (uptake) hydrogenase enzyme in the diazotrophic cyanobacterium Nostoc punctiforme, so that it would not consume hydrogen that is naturally produced by the nitrogenase enzyme in nitrogen-fixing conditions.[11] This N. punctiforme mutant could then produce hydrogen when illuminated with visible light.

Photochemical carbon dioxide reduction

Carbon dioxide (CO2) can be reduced to carbon monoxide (CO) and other more reduced compounds, such as methane, using the appropriate photocatalysts. One early example was the use of Tris(bipyridine)ruthenium(II) chloride (Ru(bipy)3Cl2) and cobalt chloride (CoCl2) for CO2 reduction to CO.[12] Many compounds that do similar reactions have since been developed, but they generally perform poorly with atmospheric concentrations of CO2, requiring further concentration. The simplest product from CO2 reduction is carbon monoxide (CO), but for fuel development, further reduction is needed, and a key step also needing further development is the transfer of hydride anions to CO.

Also in this case, the use of microorganisms has been explored. Using genetic engineering and synthetic biology techniques, parts of or whole biofuel-producing metabolic pathways can be introduced in photosynthetic organisms. One example is the production of 1-butanol in Synechococcus elongatus using enzymes from Clostridium acetobutylicum, Escherichia coli and Treponema denticola. One example of a large-scale research facility exploring this type of biofuel production is the AlgaePARC in the Wageningen University and Research Centre, Netherlands.