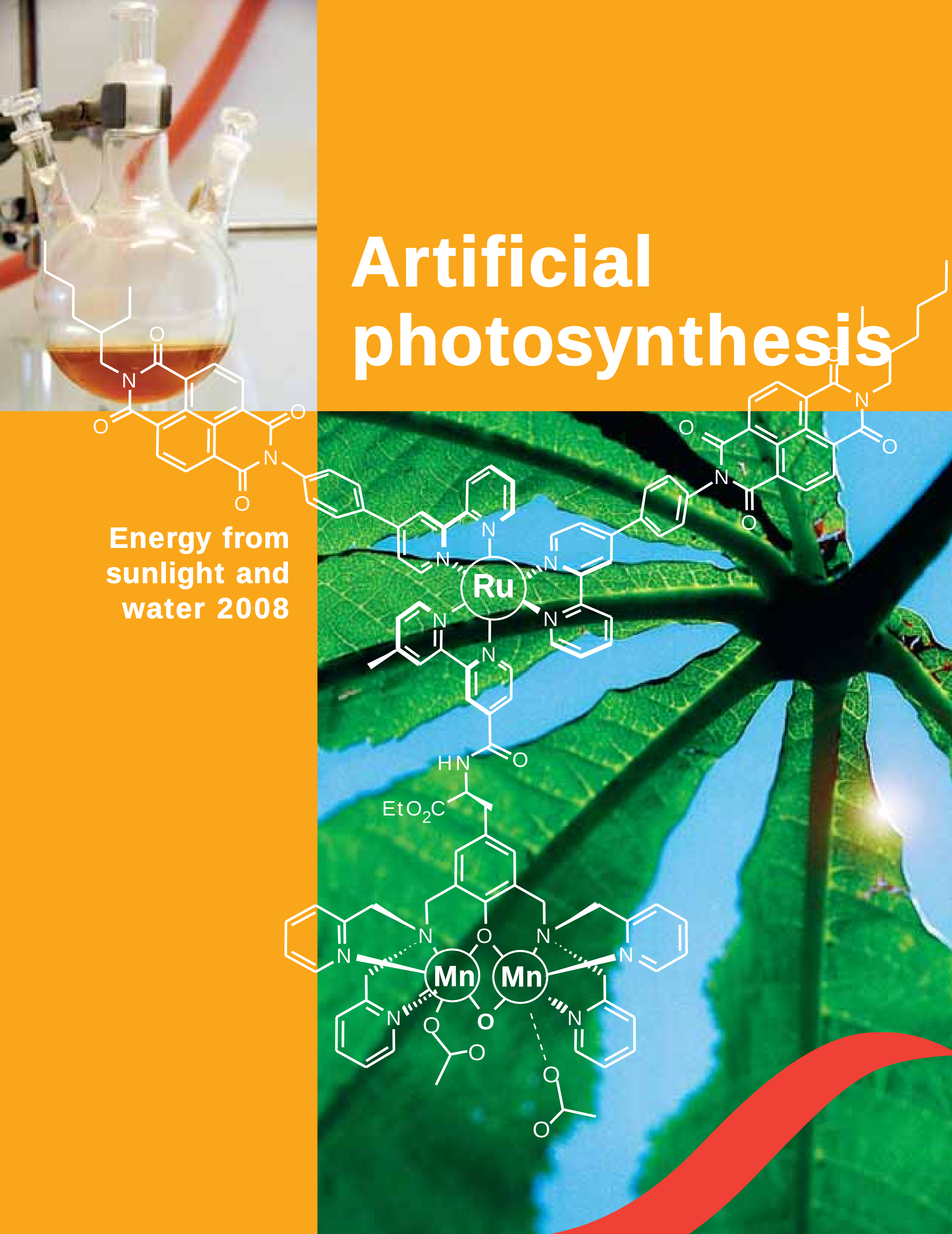
Artificial photosynthesis

Energy from sunlight and water 2008



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A scientist uses laser light to study artificial photosynthesis

Introduction

Climate issues are creating a growing demand for sustainable energy systems based on renewable energy sources with minimal environmental impact. Guaranteed supply is another important demand.

A vast amount of energy reaches the Earth's surface every year, even as far north in Scandinavia. The total energy received in Sweden as sunlight is approximately 400,000 TWh (terawatt-hours) per year. In comparison, annual energy consumption in Sweden is about 400 TWh. The question is, how can this solar energy be transformed simply and cost-effectively into useful forms of energy such as heat, electricity and fuel.

Solar energy is unfortunately at a minimum during the winter, when the dark and cold mean our energy needs are greatest. It is therefore necessary to store the solar energy in a suitable energy carrier.

Hydrogen gas is one of several possible energy carriers. One of its advantages is that the use of hydrogen gas does not lead to the emission of any carbon dioxide. But the current methods for producing hydrogen are based on fossil fuels. An energy-efficient and emission-free way of producing hydrogen would make it one of several interesting energy carriers for a sustainable energy system.

That is why there is research into potential future technologies for hydrogen gas production, using artificial photosynthesis to mimic the way plants make energy from sunlight and water.

Microorganisms that can produce hydrogen from solar energy and water: Synechocystis (top) is a unicellular cyanobacterium; Nostoc (bottom) is a filamentous cyanobacterium, which also can transform atmospheric nitrogen into vital nutrients. The cyanobacteria are grown in a tailor-made bioreactor (middle), where light intensity, temperature and nutrients are carefully monitored. In the future, vast bioreactors filled with cyanobacteria could become a source of hydrogen produced biologically from sunlight and water.

Hydrogen: the energy carrier for the future?

Hydrogen is a combustible that liberates a lot of energy when it is used as a fuel, with water as the only waste product that forms when hydrogen is burnt.

But further technological development is needed before hydrogen as an energy carrier can become a part of a sustainable energy system.

Hydrogen is bulky relative to its weight, which makes transportation and storage more difficult. And while fuel-cell technology has made major advancements in recent years, it still needs to be optimised for hydrogen use. These issues indicate that major technological advances are required before society starts using hydrogen widely.

The International Energy Agency predicts that hydrogen might enter the market as an energy carrier around 2020. Yet this timing depends largely on the availability of hydrogen from cheap and environmentally friendly sources. The creation of small, decentralized facilities for hydrogen production is preferable in order to reduce the costs of infrastructure and transportation. Investments in hydrogen-use technology should be made with a long-term perspective.

Successful research into artificial photosynthesis could provide a substantial boost to sustainable hydrogen production. But there are also some other ways to produce hydrogen from solar energy.

From sunlight to hydrogen – several techniques

Solar cells

Quite efficient solar cells are already producing electricity. Silicon-based solar cells, thin film cells and a new type, Grätzel or wet solar cells, are all under development and have already reached an advanced level of refinement. So there is plenty of research and development into solar electricity technologies going on, and solar electricity is advancing on the European energy market.

In some systems, called photoelectrochemical cells, the light-harvesting material and the electrode are one and the same. In this case, the hydrogen production takes place directly in the solar cell, theoretically providing greater efficiency. This technology is still at a basic research level.

Photobiological hydrogen production

Cyanobacteria (commonly known as blue-green algae) and green algae are both capable of converting solar energy to hydrogen gas. The process is catalysed by hydrogenases: proteins that can consume or produce hydrogen, or both. The efficiency of this process is still very low, only a

Hydrogen gas is a versatile energy carrier. It can be used for transportation as well as for heating and power production. In the EU projects CUTE and ECTOS, buses driven by hydrogen gas have been tested with good results in ten different European cities, among them Stockholm.

few percent. But the hydrogen-producing capability can be improved by modifying the genetic makeup (DNA) of these microorganisms.

There is a great deal of research into improving this efficiency being carried out all around the world, and especially in Sweden.

Artificial photosynthesis

As the name suggests, artificial photosynthesis is a way to mimic the photosynthesis of plants artificially, circumventing the expense in time and material (and space) that growing a plant takes. The energy derived from artificial photosynthesis will be used directly to create a fuel (hydrogen gas). The hydrogen gas will be made by sunlight and water, using photochemistry.

Efficient energy conversion

When we estimate the efficiency of natural photosynthesis in plants, we often count only what we can actually harvest as biomass or food. We then find that less than 1 percent of the captured light energy is actually converted into biomass (fuel). This seems very little, prompting the argument that natural photosynthesis – and any artificial counterpart – is inefficient. But such an argument is misleading.

Two processes in natural photosynthesis are interconnected in the path from the capture of solar energy to the formation of energy-rich compounds. The most fundamental of these are the “light” reactions where solar energy is captured and converted into early energy carriers. In secondary (or “dark”) reactions, these energy carriers are used to promote life in the plant, reproduction and build-up of biomass. The secondary reactions have not evolved for energy efficiency; on the contrary, it is in these secondary reactions that energy is consumed ("lost" for human use) in the plants.

The light reactions, on the other hand, are highly efficient, converting as much as 40-50 percent of the captured solar energy into energy carriers. Artificial photosynthesis for hydrogen production mimics the chemical and physical principles governing the light reactions, so it will be highly efficient.

How much energy can artificial photosynthesis generate?

The theoretical maximum efficiency of artificial photosynthesis – the proportion of absorbed energy that can be stored – is estimated to be about 40-50 percent, based on comparisons with natural photosynthesis. In practice, about 15 percent efficiency is considered realistic. How much useful energy is that?

Let us look at an example. Each year, Sweden receives about 1000 kWh of influx of sunlight energy per square metre, in both the south and the north of the country. The energy usage in a standard single-storey house is about 150 kWh per year and square metre. A device that covers the roof of that house, converting solar energy into fuel with 15 percent efficiency, would produce enough fuel to supply the energy requirements of the house throughout the year, including the large amount of heating that the Swedish climate demands.

To provide energy for our transport systems, our hypothetical device would need to cover an area of about 70 square metres per person. In other words, less than one fifth of 1 percent of the total area of Sweden would suffice to supply the country's transport systems with fuel.

These examples show that the development of solar energy does not mean that vast areas have to be covered by solar panels.

Scientific teamwork

Research on artificial photosynthesis is being done on a relatively small scale around the world, including in the USA, Japan, France, Germany and Australia. Each case involves mainly basic research activities; nobody has yet come up with a functioning prototype for a fuel-producing system by mimicking photosynthesis. Most of the international research groups focus on mimicking particular aspects of photosynthesis, and in many cases energy production is not a goal at all. The most common goal is to create molecular systems that look and behave similarly to parts of the natural photosynthetic apparatus.

The Swedish vision is of a complete chemical system that can produce fuel directly from sunlight and water. The inspiration for this – and thoughts about how it can be accomplished – comes from frontline research into natural photosynthesis. These are complicated issues and no scientist can succeed on his or her own

An education in chemistry or molecular biology is the basis for research on artificial photosynthesis.

The Swedish Consortium for Artificial Photosynthesis

The Swedish Consortium for Artificial Photosynthesis was founded in 1994, initially comprising four research groups from three universities, in Lund, Stockholm and Uppsala. As the research activities expanded, the consortium scientists decided to “move in” together. In 2006 most of the consortium moved to Uppsala University, taking possession of new research facilities at the Ångström Laboratory. Today, scientists from a wide spectrum of disciplines – including specialties within chemical physics, synthetic chemistry, biochemistry and molecular biology – are working together. One group of researchers remains at Lund University, keeping in close contact with their colleagues in Uppsala.

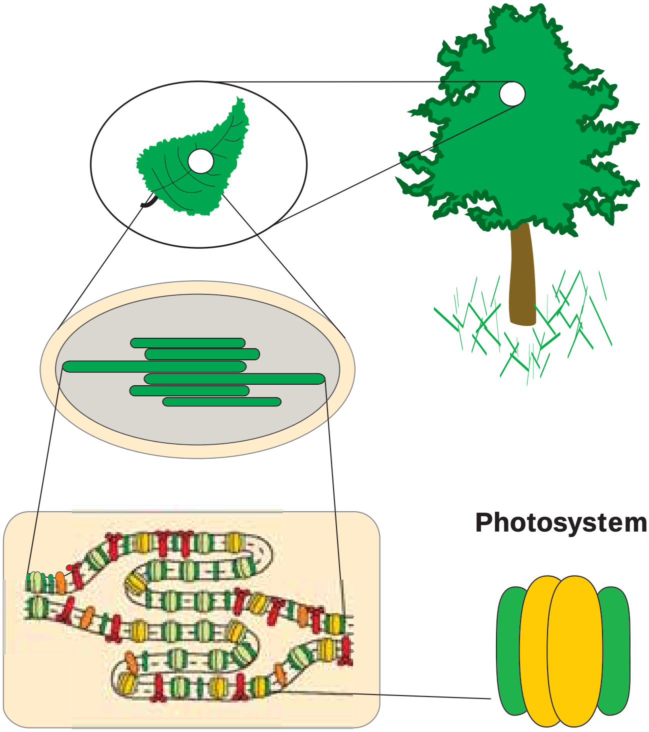
The Consortium for Artificial Photosynthesis consists of about 45 people, all with different areas of expertise and contributing with their particular skills. The researchers in the consortium are working to produce a chemical catalyst that can split water molecules, something the scientific community has considered very hard to achieve. Another area of interest is the possibility of using cyanobacteria that have a natural ability to produce hydrogen from sunlight and water. These different objectives require cooperation between chemists, physicists and biologists.

The Swedish Consortium for Artificial Photosynthesis has realised the necessity of collaboration between scientific disciplines. Thanks to long-standing experience in inter-disciplinary collaboration, the consortium is optimistic about the chances of success. The unorthodox mix of experts from different fields of research that constitutes the consortium has proven productive, giving it a world-leading position in research into artificial photosynthesis for fuel production.

Can I study artificial photosynthesis at the university?

A new master’s programme in chemistry, called Chemistry for Renewable Energy, will start at Uppsala University in the autumn of 2008. It will be open to students with Bachelor of Science degrees, with an emphasis on chemistry. The courses include photochemistry and photobiology, artificial photosynthesis, solar cells, batteries and fuel cells. More information can be found at: www.chemistry.uu.se/master.

Tree and chloroplasts



The action is in the leaves. Light is absorbed by the green pigment chlorophyll in membrane-bound proteins, which are found inside the chloroplasts. The chlorophyll-rich proteins are similar to tiny solar-powered generators. Photosystem II is one of these proteins, and produces energy-rich compounds using sunlight and water as starting materials.

Nature’s solution to the energy crisis

The goal is to produce hydrogen from solar energy using pure water as the raw material. It takes advanced knowledge of the chemical processes in nature, to develop a system for artificial photosynthesis. One important part of this research is therefore to study key reactions in natural photosynthesis.

Photosynthesis starts when plants capture solar energy. The energy is used to split water molecules, in order to bind the energy. Ultimately, the plant uses this energy to grow and reproduce. Oxygen, the very oxygen that we breathe, is produced as a waste product when water is split. Electrons and hydrogen ions, which are important for the creation of energy-rich products, are also released as the water is split. An artificial system will use both electrons and hydrogen ions to make hydrogen gas. The key to it all is to split the water molecules in the first place. That is difficult.

An enzyme binds solar energy

All plants and algae have enzymes bound to biological membranes, which can be thought of as tiny solar-powered generators. Inside these enzymes, electrons are moved from one side of the membrane to the other, with the help of sunlight. When this happens, a voltage is created across the membrane – an energy-rich condition.

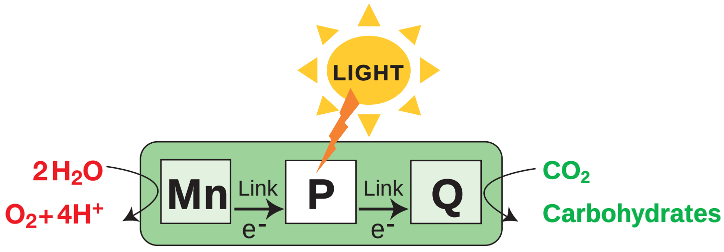
Photosystem II is the enzyme that scientists are particularly interested in mimicking. Photosystem II creates and sustains the voltage across the membrane by capturing light and splitting water molecules. When an electron deficiency arises on one side of the membrane, it has to be balanced by supplying an electron from somewhere else. If this does not happen, the electron will find its way back, to fill the electron "hole" it left behind, and the energy that was captured will be lost again. Photosystem II has the ability to extract electrons from water, and thereby fix the energy so that it can be utilized.

Photosynthetic energy conversion – step by step

It works like this: Photosystem II contains chlorophyll molecules that absorb sunlight. When the chlorophyll (P) has been charged with extra energy from the light, it sends an electron to electron carriers in the membrane (quinones, Q). The electron "hole" must be filled, and an electron is therefore moved to the chlorophyll from a complex made of manganese ions. The manganese complex (Mn) in its turn extracts electrons from water molecules (H_2O) that become attached to the manganese complex. The water molecules are thus split, and oxygen is formed.

Water-splitting takes place on one side of the membrane, and the extracted electrons are transported to the other side. The captured solar energy is secured by using the electrons to construct carbohydrates from atmospheric carbon dioxide (CO_2). The electrons are the "glue" that holds the carbohydrate molecules together.

Principles of photosynthetic energy conversion



Photosystem II

Light is captured by chlorophyll molecules (P). Electrons (e-) move from a manganese complex (Mn) to compounds that accept the electrons (Q). The electrons end their journey in the creation of carbohydrates, with carbon dioxide as a building block. Electrons are extracted from water (H_2O), with manganese as a catalyst. When water is split, oxygen (O_2) and hydrogen ions (H^+) are released.

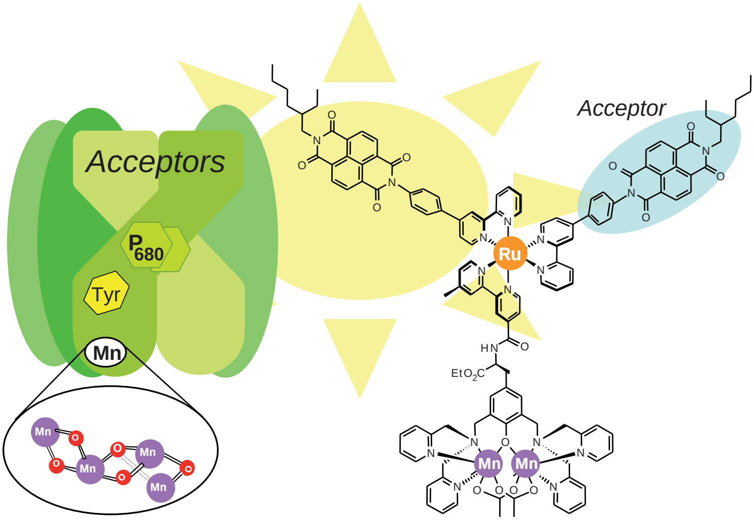
Photosystem II is the ideal

Water-splitting and electron transport – it all seems so complicated. Why make things difficult? The conversion of solar energy into a fixed form – a fuel – requires an electron source, regardless of the type of fuel being produced. Water is abundant on our planet, so if we could extract electrons from water we would have an unlimited energy source. Photosystem II is the only chemical catalyst we know of that is capable of extracting electrons from water.

Photosystem II is the key to almost all life on earth. It is in fact one of nature's most successful inventions. Its secret is to use an abundant electron source, water, and an abundant energy source, the sun. Plants and algae are the dominant life forms thanks to Photosystem II. Where there is water and light, there is life.

Any apparatus based on artificial photosynthesis, which produces fuel using solar energy, needs an ultimate electron source, just like plants do. The Swedish consortium wants to use water for this purpose. Photosystem II is therefore the ideal that the researchers into artificial photosynthesis are trying to model. If one wants to mimic the efficient energy conversion of natural photosynthesis, one must understand how it works in every detail.

Natural photosynthesis – Artificial photosynthesis



An artificial "photosystem" mimics the natural Photosystem II in several ways. Both have a light-absorbing component: "P" in Photosystem II and "Ru" in the artificial system. When light is absorbed, an electron is moved to electron-acceptor compounds. In nature they are quinones; similar acceptors (highlighted in blue) are used in the artificial system. Electrons are taken from a manganese complex (Mn) in both the natural and artificial system. Water is split in Photosystem II, and more electrons are liberated. The artificial system also extracts electrons from water, but not yet as efficiently.

From natural to artificial photosynthesis

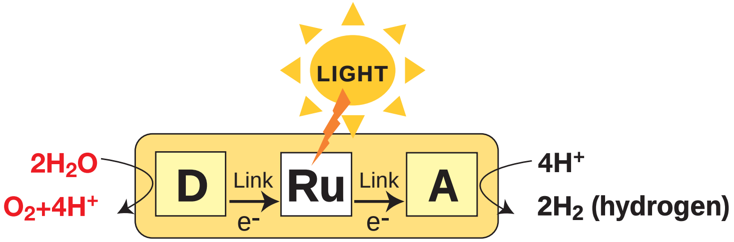
The scientists in the Consortium for Artificial Photosynthesis work with the principles found in nature, but also develop new chemical systems that have no counterpart in nature. Instead of chlorophyll, the materials for capturing light are synthetic compounds containing the noble metal ruthenium. Their properties are similar to those of chlorophyll, in that the ruthenium compounds can capture light and emit electrons in much the same way as chlorophyll does in Photosystem II.

The advantage of ruthenium complexes over chlorophyll is that the ruthenium complexes are robust, while chlorophyll is remarkably sensitive to light. Plants live with their light sensitivity and compensate for it though a complicated system for healing and recovery. Artificial photosynthesis, on the other hand, has to be constructed to be as fail-safe and low-maintenance as possible. In addition to being sturdy, ruthenium complexes are easy to use as chemical building blocks in the construction of more complex structures.

Building a chemical model

The consortium's work principle is to develop artificial photosynthesis in steps, by adding one piece at a time and gradually building up larger molecules. The goal is to construct a supermolecule where a ruthenium complex is linked to a manganese complex, in a construction similar to

Energy conversion in an artificial system



Artificial photosynthesis

In a future solar-energy system, the light will be captured by ruthenium (Ru). Electrons will move from the donor (D) to the acceptor (A). The electrons will be taken from water (H_2O), just as in nature. On the acceptor side, the electrons and hydrogen ions (H^+) will be used to make hydrogen (H_2).

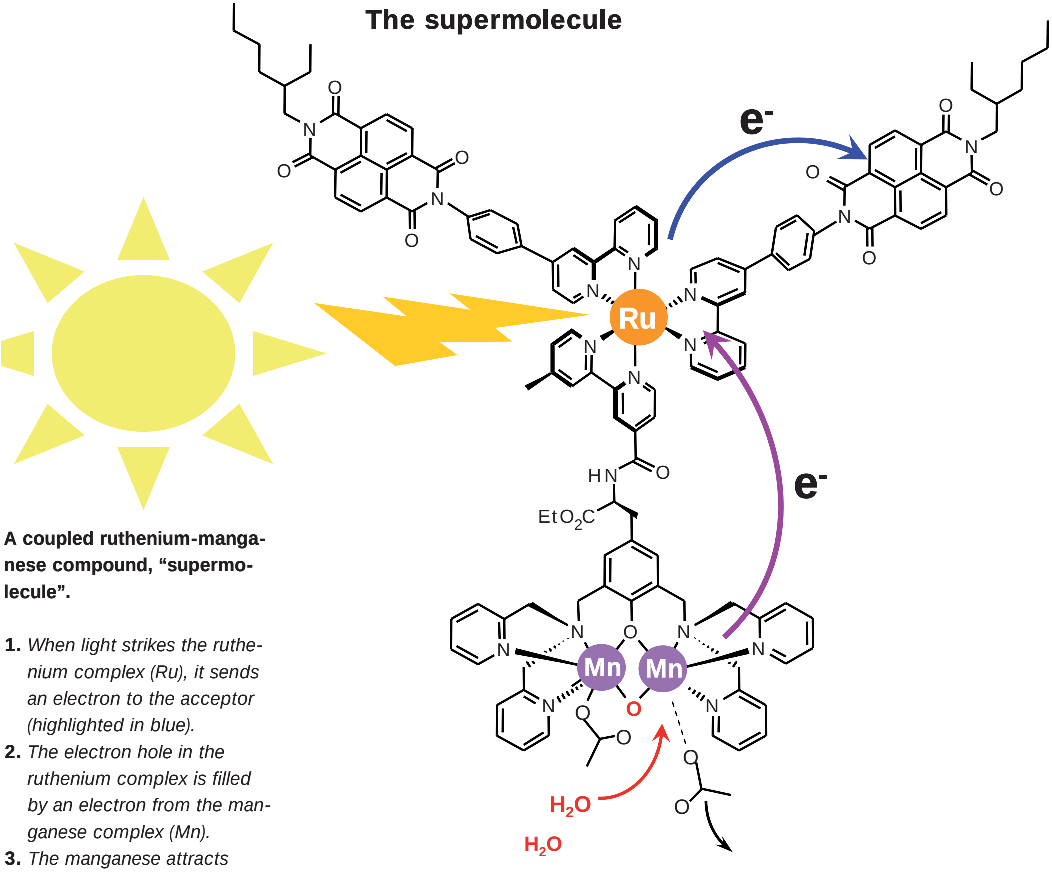
the arrangement in Photosystem II. The aim is to mimic the series of events that takes place when plants convert the energy in sunlight to a chemical form. This is how the artificial system is supposed to work: When the ruthenium (Ru) is struck by light, an electron is sent to the acceptor part (A) of the supermolecule. The electron hole in the ruthenium complex is filled by an electron, which is transported from the manganese complex (Mn) to the ruthenium. The manganese complex then takes electrons from water molecules (H_2O). The result of these events is the release of electrons, which can be utilized for producing a fuel. In addition, hydrogen ions (H^+) and oxygen (O_2) are also liberated. Thus far, the artificial system mimics the natural.

The important part is what the electrons are used for – how the energy is secured and stored. In this case, the consortium has a different solution to the one plants have. We humans would like fuel production that is as efficient as possible, so the electrons and hydrogen ions will be used to make hydrogen using a chemical catalyst.

From idea to reality

In 1994, when this research project started, the scientists realized the difficulty of connecting the ruthenium and manganese parts in a single molecule, and it took a while before the first compound was created. It was a simple molecule with one ruthenium complex loosely connected to one manganese ion. The basic idea proved correct: the two metals could be connected and light-induced chemistry could be accomplished. Most importantly, an electron could be moved from the manganese to the ruthenium, using light.

The next step was to include more manganese ions. In Photosystem II there are four manganese ions that together perform water oxidation. It



A coupled ruthenium-manganese compound, “supermolecule”.

1. *When light strikes the ruthenium complex (Ru), it sends an electron to the acceptor (highlighted in blue).*
2. *The electron hole in the ruthenium complex is filled by an electron from the manganese complex (Mn).*
3. *The manganese attracts water molecules and extracts electrons from them. This course of events can then be repeated two or three times.*

is a long-held view in the scientific community that four manganese ions are necessary for water oxidation: one manganese ion for each electron that is extracted. Chemically, it is difficult to combine four manganese ions, so in early attempts the scientists settled for two. This ended up working beyond expectations.

The “supermolecule” in the picture has two manganese ions connected to one side of the ruthenium complex, and two acceptor molecules on the other. When the ruthenium absorbs light energy, an electron is sent to the acceptor, and one electron is transported from the manganese to the ruthenium. Thus far, the molecule worked as expected. What the scientists in the consortium did not expect was that three or four electrons can be transported from the manganese, although there are only two manganese ions in the molecule.

The next surprise was that the manganese ions actually extract electrons from water. Although the water-splitting is nowhere near as efficient as in Photosystem II, it has taken the scientists closer to a solution to the water-oxidation puzzle.

The final dilemma that the consortium has to resolve is to make the mechanism come full circle: to make the system reset itself so that more water molecules can be split in a sustainable process.

A sensational discovery

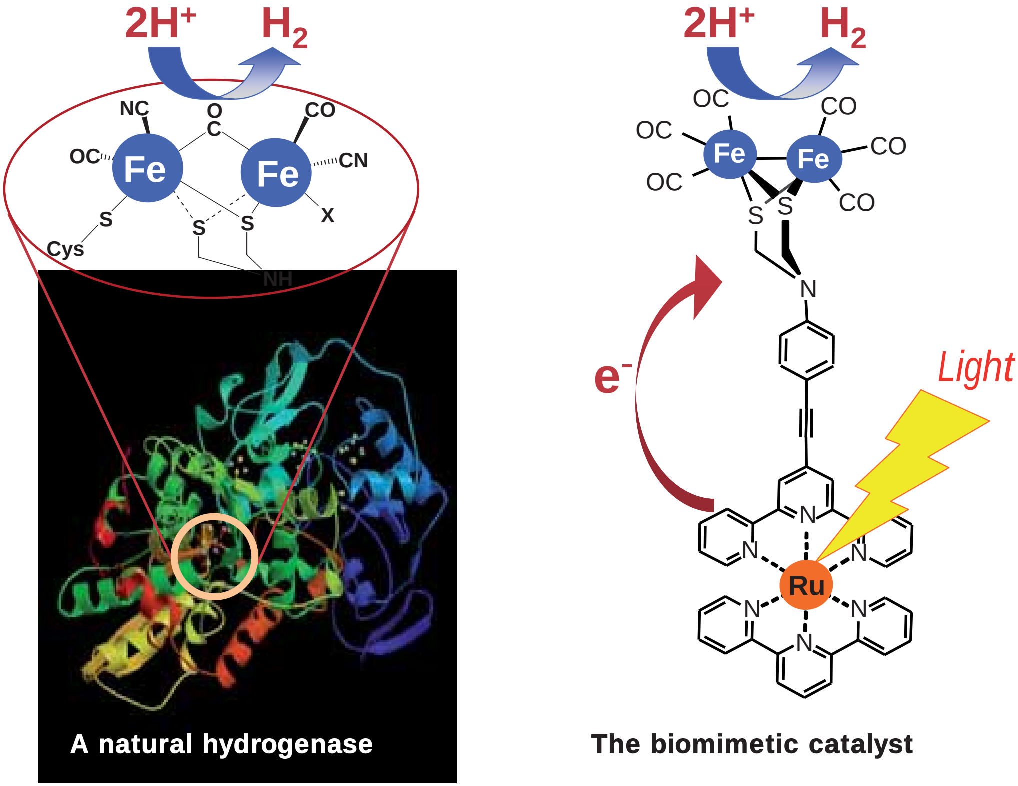
So far, the consortium has produced close to 50 different manganese and ruthenium compounds. The molecule in the figure is the most advanced, and has produced a sensational result, at least on the research level: it is the only artificial molecule in the world that combines several essential building blocks for an artificial "photosystem" with unique photochemical properties. First, it can move more than one electron from the donor side to the acceptor side. When positive and negative charges exist on separate locations in a molecule, one speaks of a charge-separated state. The second unique property is that the charge separation in this molecule is unusually long-lived.

Long-lived charge separation is well known in nature. Water-splitting in Photosystem II is a very "slow" process (a thousandth of a second is a long time on a chemical time scale). The electron that gets transported must be tied up long enough for water-splitting to take place, so that the energy can be used to make fuel. For research on artificial photosynthesis, solving the problem of short-lived charge separation has always been an important priority.

Lasting results

This is where the research stands today. A supermolecule has been designed that absorbs light and moves electrons to an electron acceptor. Several electrons can be moved from a manganese complex on the donor side of the molecule, and the manganese takes electrons from water. To this end the scientists have managed to mimic key events taking place in Photosystem II. These are lasting results that make the consortium optimistic about the future.

The remaining challenge is to make a manganese complex that can split water catalytically, so that the system can take electrons from water over and over again in a useful and sustainable way. The Swedish consor-



A natural hydrogenase

The biomimetic catalyst

A natural hydrogenase (left) that produces hydrogen. The biomimetic catalyst (right) has an iron-iron complex resembling the natural enzyme, and which can produce large amounts of hydrogen under controlled conditions. In the near future, this is how it will work: when the ruthenium complex absorbs light, it sends an electron to the iron complex. When the iron has received two electrons, the complex reacts with two hydrogen ions (H^+), and hydrogen (H_2) is formed

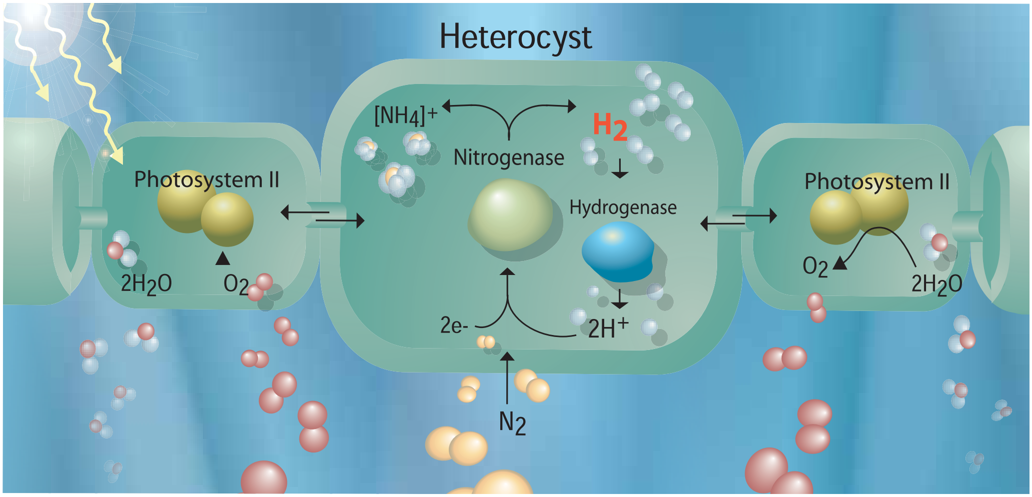
tium is also working hard to develop the part of the supermolecules that will produce hydrogen.

Biomimetic catalysts drive hydrogen production

Many microorganisms have particular enzymes (biological catalysts) called hydrogenases. Hydrogenases put together hydrogen ions and electrons to make hydrogen. Iron-iron hydrogenases have two iron atoms in their catalytic centres. Similar biomimetic catalysts can be made synthetically, and the consortium is therefore developing ways to connect their supermolecules with such synthetic catalysts.

In recent years, much research has been focused on how to construct the iron complexes, and the results were immediate: the consortium has designed catalysts that produce hydrogen with high yield under controlled conditions. The goal is to drive hydrogen production by light, but reaching that goal demands more research.

Heterocysts in cyanobacteria produce hydrogen gas



Cyanobacteria are photosynthetic microorganisms that can produce hydrogen from sunlight and water. This picture shows a particular kind of bacterial cell, called a heterocyst, which can take atmospheric nitrogen and convert it into valuable nutrients. When that happens, energy-rich hydrogen is formed as a waste product, and then consumed by the mechanism of the cell. Scientists are developing ways to "domesticate" the cyanobacteria, so that it liberates the hydrogen rather than consuming it.

Hydrogen-producing microorganisms a source of inspiration

Cyanobacteria and green algae are microorganisms that have the ability to produce hydrogen from sunlight and water. They already possess the chemical apparatus that the consortium scientists are trying to create artificially. Nature's hydrogen-producing systems are a definite source of inspiration for artificial photosynthesis research.

These organisms' natural hydrogen production is very low, and it is not yet feasible to grow cyanobacteria for the purpose of hydrogen production. Two of the research groups in the consortium are therefore trying to alter cyanobacteria genetically, to produce much more hydrogen with sunlight as the energy source.

Like all living organisms, the cyanobacteria have evolved to conserve energy. Hydrogen is formed in small amounts as a part of the microorganisms' natural metabolism. The cyanobacteria consume all the hydrogen produced, because it is an energy-rich compound. One strategy for getting the cyanobacteria to release the hydrogen instead is to knock out the genes that regulate how the organisms re-absorb the hydrogen. Here too the consortium is among the leading groups in the world.

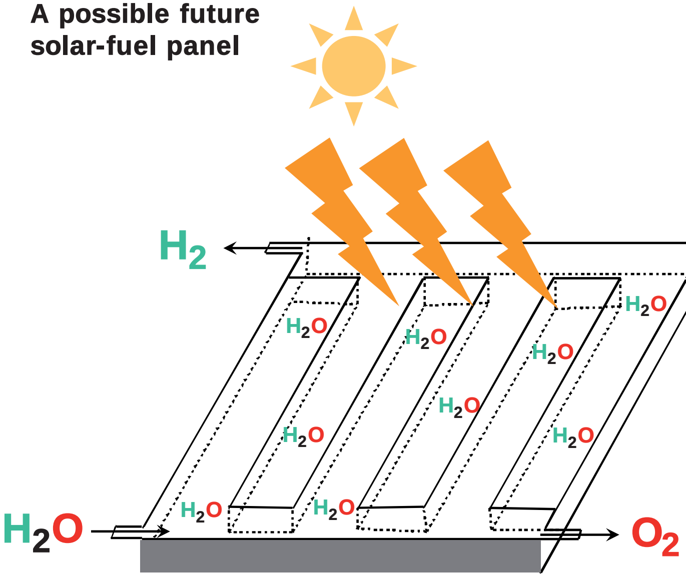
Research into cyanobacteria is creating other demands on the scientists that go beyond artificial photosynthesis, so communication and the exchange of ideas between colleagues are important parts of the day-to-day work. New and fruitful ideas are being born in the interplay between biology and chemistry, so it is important that research into biological hydrogen production is done in parallel with artificial photosynthesis.

Major progress

Summing up, research into artificial photosynthesis has made major progress over the past four or five years.

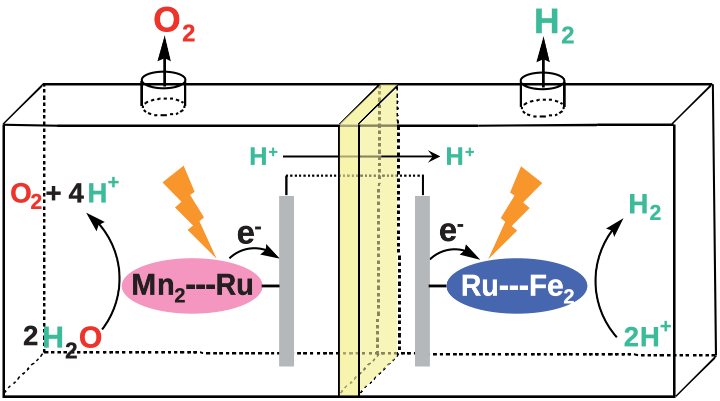
- The consortium has designed a “supermolecule” consisting of a light-absorbing component, a donor component and an acceptor component. It mimics key aspects of Photosystem II in plants, and has the most stable charge separation of all artificial molecules of its kind.
- Other newly created molecules, designed to mimic natural hydrogenases, are producing hydrogen catalytically. The new catalysts are the most efficient hydrogen-generating molecules to have been made synthetically.
- A big issue in chemical science – how catalytic water oxidation can be accomplished – is close to being resolved, thanks to investigations of synthetic manganese complexes. The compounds that the Consortium for Artificial Photosynthesis has been working with for years have been shown to react with water in a fruitful way.

A possible future solar-fuel panel



Artificial supermolecules fill two compartments separated by a membrane. In one compartment, water is split and oxygen is produced. Hydrogen is produced in the other compartment.

A solar fuel apparatus



In theory, a solar-fuel apparatus might work like this: a ruthenium-manganese complex absorbs light and ejects electrons. The complex splits water to extract electrons and oxygen, and hydrogen ions are formed. The hydrogen ions pass through the membrane to the other side, where a ruthenium-iron complex absorbs light and uses the hydrogen ions and electrons to make hydrogen gas.

There is still work left to be done before the dream of artificial photosynthesis can become a reality. Water-splitting has to be catalytic – it must be continuous over time – and hydrogen production using synthetic catalysts has to be driven by light. Given more time, the consortium is optimistic about solving these issues as well. And when these goals are achieved, the development of an apparatus for solar-fuel production can begin.

The future

What will a future solar-fuel system look like? There are several alternatives. One big supermolecule might do all the work, and many such molecules together inside a solar panel would split water and emit hydrogen. Another possibility is to divide the two processes, so that water-splitting molecules are in one place, while hydrogen-producing molecules are in another. The apparatus would then consist of two compartments, or tanks, separated from each other. The compartments should be filled with water, and separated by a membrane. On one side of the membrane, water is split, releasing electrons, hydrogen ions and oxygen. On the other side of the membrane, the hydrogen ions and electrons are used to make hydrogen. Both processes are driven by sunlight.

All these ideas are plausible solutions to the practical problem of designing a solar-fuel apparatus, but it is still too early to say what the winning concept will be. So far, the consortium is working on a basic research level, meaning that the primary goal is to resolve issues around the fundamental principles of artificial photosynthesis. There is no working prototype yet, but one can speculate about what it might ultimately look like.

One possibility is a kind of solar panel that could be placed on unexploited surfaces such as rooftops. When the solar-fuel apparatus is working, it will produce life-giving oxygen at one end and powerful hydrogen fuel at the other. The hydrogen can be used immediately, or stored in hydrogen-absorbing materials such as metal hydrides. It is anticipated that the system will be nearly self-sufficient: all that will be required is to fill the tank with more water now and then. The apparatus could be built in modules, so it could easily be taken apart for maintenance.

Great expectations

How close to reality is the dream of a truly sustainable energy source? It is not clear today how the complete conversion all the way from sunlight to fuel will be achieved. But we know how to convert sunlight into chemical reactions, and we know how to make fuels chemically. Connecting these two is one of the great challenges in research, and it is hard to tell how long it will take. New discoveries and innovations often happen in steps, both large and small. A realistic scenario is that a working prototype of a supermolecular system is ready within 5-10 years, and that the first solar-fuel apparatus will see the light of day in 10-15 years.

Our ambition is to replace environmentally damaging forms of energy with clean, renewable and readily available energy sources. Artificial photosynthesis for fuel production from sunlight and water has the potential to meet this ambition. There is still a long way to go and major efforts from creative scientists are needed before the goal can be reached. Otherwise it will remain a dream.

Do you want to know more?

Got questions? Contact
Stenbjörn Styring – Professor and chair of the consortium.
Ann Magnuson – Associate professor, main author of this booklet.

You can find more information about the research and the people involved at the homepage: www.fotomol.uu.se

The Swedish Consortium for Artificial Photosynthesis works at the Department of Photochemistry and Molecular Science, Uppsala University, and at the Department of Chemical Physics, Lund University

An efficient and environmentally friendly energy supply system

The Swedish Energy Agency aims at achieving a reliable, environmentally friendly and efficient energy system in Sweden and internationally. The Agency works to improve energy efficiency and to increase the amount of renewable energy, it is also responsible for the country's strategic energy preparedness for crisis situations. An important part of the Agency's work is the financing of research, development and demonstration activities in the energy sector.

This research overview describes the research field of Artificial Photosynthesis. It aims at producing hydrogen gas using sunlight and water in a photochemical process. The method mimics parts of the natural photosynthesis. The key reaction being studied is natural photosynthesis's ability to split water.

Hydrogen gas is a combustible which does not emit any carbon dioxide when used. If an energy-efficient and emission-free way of producing hydrogen gas can be developed, it would become one of several interesting energy carriers for a sustainable energy system. Successful research into artificial photosynthesis could provide a substantial boost to sustainable hydrogen production.

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