Tobacco's solar power plant: One of up to 100 chloroplasts from the cell of a tobacco leaf. Its interior is filled with stacks of flat membrane discs (thread-like structures) that contain the molecular machinery responsible for photosynthesis. Like mitochondria, chloroplasts have their own genome (light-colored areas).

Powerhouse in the Foliage

Photosynthesis, a veritable stroke of genius on the part of nature, makes the existence of higher life forms possible. If it can be optimized, it may be able to make an even greater contribution to the resolution of future energy problems. **Manajit Hayer-Hartl** and **Ulrich Hartl** are currently working on this possibility at the **Max Planck Institute of Biochemistry** in Martinsried.

TEXT **HARALD RÖSCH**

Be honest – when you look at a rich green meadow, does a solar power plant come to mind? Of course not. However, plants do something very similar: they convert the energy from sunlight into usable energy. Through photosynthesis, they harness this energy to synthesize sugar in a process that involves numerous intermediate steps. We already tap into this energy source today, for example in the form of biofuel and in biogas plants.

So nature has been building solar power plants for millions of years. The only drawback is that these natural power stations work so inefficiently. Plants are energy wasters – at least when it comes to harnessing energy through photosynthesis. The combined area of Germany and France would not provide sufficient acreage to cover Europe's bioethanol or biodiesel requirements in 2050. If, however, 10 percent of the energy that falls on this area in the form of sunlight could be converted into chemical energy, an area the size of the German federal state of Baden-Württemberg would probably be sufficient. The efficiency of plant photosynthesis is only around 5 percent. In comparison, the solar power cells available today have an efficiency of around 20 percent, but they don't produce fuels that, like bioethanol, can be easily stored and transported. However, there are organisms that achieve far greater levels of efficiency than plants. The green sulfur bacterium *Chlorobaculum tepidum,* for example, has extremely efficient solar power equipment for the absorption of light, and can convert 10 percent of incident light into chemical energy.

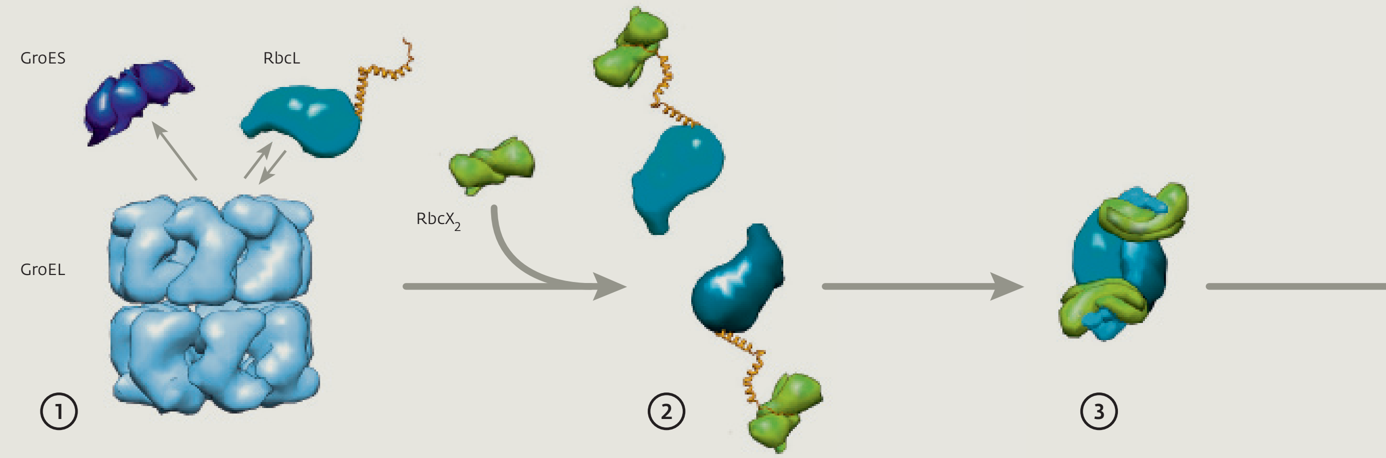
TURBO PLANTS HARNESS MORE ENERGY

For this reason, scientists are working on developing ways to make photosynthesis more effective. Their aim is to optimize various steps in the process of the conversion of light energy into chemical energy, for example by increasing the efficiency of the photosynthesis machinery.

Plants that have been upgraded in this way would be capable of forming more biomass for the purpose of fuel production. In contrast to this, some scientists want to dispense with plants altogether and equip bacteria with an optimized photosynthesis device instead. Another possible approach will be independent of the services of any kind of organism: hydrogen, for example, could be generated in bioreactors in which photosynthesis takes place using just a few necessary proteins. Nature has, in fact, created enzymes that can split water with the help of solar energy and that could thus replace costly platinum in fuel cells. And nature also has enzymes that subsequently produce hydrogen from the water fragments (see MaxPlanckResearch 3/2006, page 32 ff.).

At the Max Planck Institute of Biochemistry in Martinsried, near Munich, researchers are looking for a way to make plant photosynthesis more effective – and have already made significant progress toward achieving this objective. The scientists working with Manajit Hayer-Hartl have discovered the folding process of a key protein in photosynthesis, known as Rubisco. Armed with this knowledge, the re-

Photograph: SPL – Agentur Focus



Protein origami: The chaperonins GroEL (light blue) and GroES (dark blue) manage the folding of the large Rubisco subunit RbcL (turquoise, 1). Following release from the cylindrical chaperone complex, the helper protein RbcX binds to end pieces of the Rubisco subunits that are not yet folded (2) and causes two subunits to assemble next to each other (3). Four of these dimers then form a cylinder (4). Four small RbcS subunits (pink) occupy both the top and bottom areas of the cylinder (5) and in this way break the bond between RbcX and the finished Rubisco complex (6).

searchers can now work on finding a way to produce Rubisco artificially and modifying it so that it works more efficiently.

Rubisco is not only the most common protein on Earth, it is also one of the most important. Without Rubisco, life would simply not exist in its current form. It binds carbon dioxide from the atmosphere and brings about its conversion to sugar and oxygen. However, Rubisco works very slowly and ineffectively. It reacts not only with carbon dioxide, but also with oxygen: on average, it binds one oxygen molecule after three to five carbon dioxide molecules. "When Rubisco emerged around four billion years ago, this was irrelevant, as there was not yet any oxygen in the atmosphere. Today, however, the amount of oxygen in the air is around 20 percent," says Manajit Hayer-Hartl, who is carrying out research on Rubisco with her husband Ulrich. Rubisco could, therefore, work far more effectively if it no longer reacted with oxygen.

CHAPERONES ENSURE GOOD ORDER AND FORM

That is why the Martinsried-based researchers want to modify Rubisco in such a way that it can bind only carbon dioxide. To do this, they must first establish how the protein is actually formed. Rubisco is one of the largest of all proteins and consists of eight large and eight small subunits. "With so many subunits, there is a significant risk that the wrong parts of the protein will aggregate and clump together," explains Manajit Hayer-Hartl. In order for the protein to function correctly, the amino acid chains must be correctly folded and the subunits assembled so that they form a cylinder. This complex folding process is managed by special proteins known as chaperones.

According to the researchers, three proteins are required to recreate a functional Rubisco complex: in addition to the previously identified chaperonins GroEL and GroES, a recently discovered helper protein (RbcX). RbcX ensures that two large subunits of Rubisco can assemble next to each other. Four of these dimers then form the cylinder, and four small subunits position themselves at the top and bottom areas of the cylinder. "We now understand why, for example, bacteria are not able to produce functional Rubisco. If we insert only the DNA for the protein into the bacterial genome – without the corresponding helper protein – functional Rubisco cannot be formed," says Ulrich Hartl.

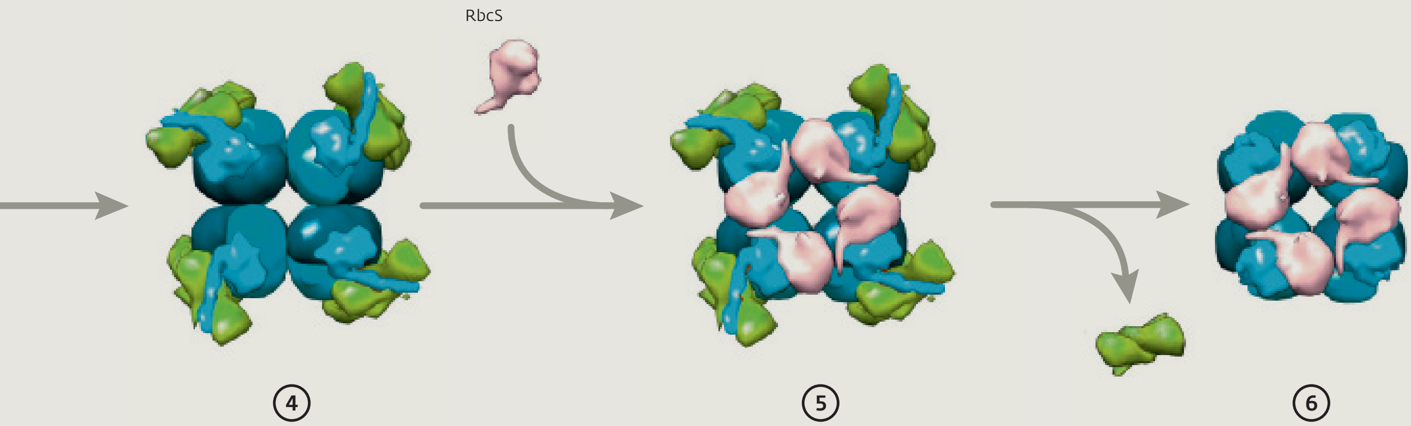
Having achieved this breakthrough, the scientists can now get to work on producing Rubisco artificially in the laboratory. To this end, they want to introduce the DNA for Rubisco, the two chaperonins and the helper protein into bacteria. The rapidly reproducing microorganisms will then produce the Rubisco protein in sufficient quantities. The researchers are seeking to find a more efficient variant of Rubisco with the help of such bacteria. "If we introduce the Rubisco DNA into a bacterial strain that can survive only with functional Rubisco, we can test all possible mutations in the Rubisco gene and immediately establish how well the individual variants work," explains Manajit Hayer-Hartl.

CAN HUMANS SUCCEED WHERE NATURE FAILED?

With the help of this process, multiple mutations can also be generated and studied in different positions in the Rubisco gene. This is an important advantage, as it may not be possible to further optimize the protein by replacing a single amino acid. This would explain why nature itself did not adapt Rubisco to the increasing oxygen content in the air over the course of evolution. Some scientists believe that nature has already found the optimum structure for Rubisco, and that Rubisco cannot be improved. The scientists in Martinsried disagree. They are convinced "that the Rubisco molecule of plants is definitely not the best possible variant. Some red algae have a more efficient form. This suggests that the plant enzyme can be improved, too."

However, finding mutations that would render Rubisco more specific to carbon dioxide is not the only challenge the scientists have to face. The new results show that nothing will work without the matching molecular chaperones. Unlike Rubisco itself, RbcX works extremely selectively and also assists in the folding of the natural plant Rubisco. For this reason, it has not been possible, for example, to transfer the

Graphic: designergold, based on original material from the MPI of Biochemistry



BLUEPRINT FOR A BACTERIAL SOLAR POWER PLANT

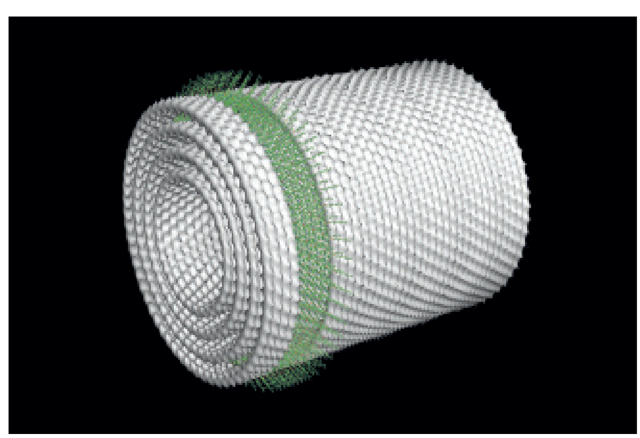
An organism that needs light to survive but lives in places where little light is available requires a special antenna. The green sulfur bacteria *Chlorobaculum tepidum*, whose habitats include the deep, dark layers of oceans and lakes, have just such antennae. With their chlorosomes, they operate the most efficient solar power plants found in nature: they convert 10 percent of the light energy into chemical energy, namely sugar.

That's why Alfred R. Holzwarth and his research group at the Max Planck Institute for Bioinorganic Chemistry in Mülheim an der Ruhr are studying chlorosomes with the aim of using the bacterial solar power plant as a model for efficient energy generation. The scientist has already taken an important step toward fulfilling this aim: an international research team, which, in addition to Alfred Holzwarth and Michael Reus from the Max Planck Institute in Mülheim, also included scientists from the universities of Leiden and Groningen, as well as Penn State University in Philadelphia, discovered how the chlorosomes are structured.

The researchers ingeniously combine various experiments and calculations. In this way, they established that the chlorophyll in the chlorosomes piles up to form helices. "A key question up to now concerned the various possible ways in which the individual chlorophyll complexes might be arranged next to each other," says Alfred Holzwarth. "We have now found the answer." And not just to this question. Little was previously known about the arrangement of the chlorophyll stacks. Most researchers who are looking to the bacterial solar power plants for inspiration for the biofuel production of tomorrow favored layers – a misconception, as Holzwarth's research team has now established. "The simple chlorophyll helices are, in turn, twisted into a helix and thus form a tube," he explains. The individual tubes must also subject themselves to another order: several tubes with different diameters are inserted into each other like a telescopic pole. "Unlike in higher plants, this complex hierarchical structure arises on an entirely self-organized basis," says Holzwarth. In higher plants, proteins step in as mediators. "As the chlorosomes contain only chlorophyll, they provide suitable models for self-organizing technical light antennae," he explains. It is extremely difficult to imitate the proteins in the chloroplasts of higher plants.

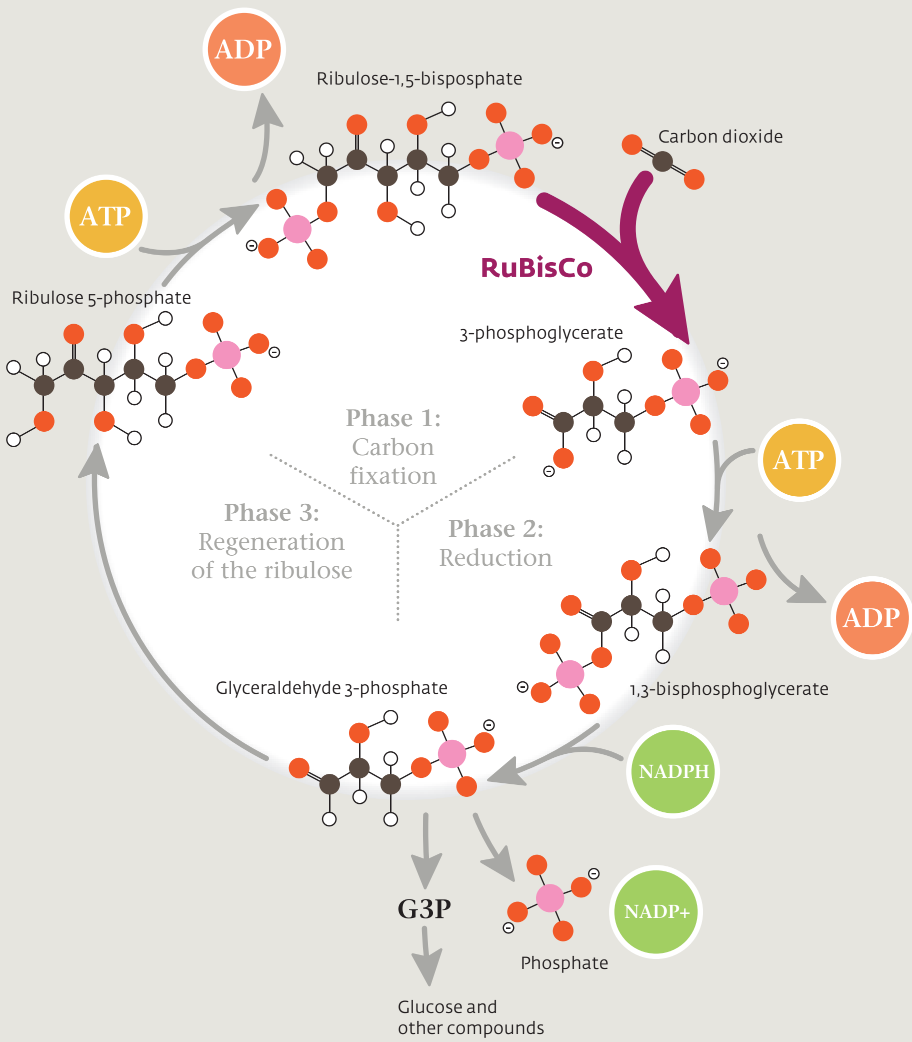
Before Alfred Holzwarth and his colleagues can copy the antennae for technical purposes, they must first resolve some fundamental issues. "We want to find out more about how light absorption in the chlorosomes works," says Holzwarth. This is the only way the search for artificial antennae with a similar level of efficiency has any prospect of success. And this would be only the half-way mark in the quest for a way to efficiently bind solar energy in biofuel, as Alfred Holzwarth explains. "We have to couple the antennae to a simple system that converts the captured light energy into chemical energy – that is, a system that, like photosynthesis, develops sugar from carbon dioxide or splits hydrogen from water."

Peter Hergersberg



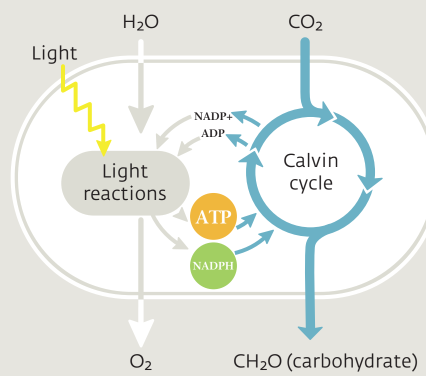
The chlorophyll in C. *tepidum's* chlorosome arranges itself in spirals that form concentric tubes (green ring: detailed view).

Image: G. Oostergetel/University of Groningen



left: Carbon dioxide conversion in the Calvin cycle: In this cycle, carbon occurs in the form of carbon dioxide and leaves it as sugar. The cycle uses ATP as an energy source; NADPH provides energy-rich electrons for the formation of the sugar molecules. In order for a sugar molecule to be produced, the cycle must be run through three times, and three carbon dioxide molecules must be fixed. The enzyme Rubisco enables the addition of carbon dioxide to the sugar ribulose-1,5-bisphosphate (carbon fixation). In phase 2, glyceraldehyde 3-phosphate – a sugar with three carbon atoms from which the plant can build other organic compounds – forms. The ribulose is regenerated again in phase 3.

below: During the light reactions, low-energy electrons from water molecules are elevated to a higher energy level and stored in the NADPH. ATP is also produced in the process. Using the chemical energy stored in the NADPH and ATP, sugar can then be produced during the Calvin cycle.



red-algal Rubisco to plants – it simply does not fold correctly in this case. It is thus possible that an optimized Rubisco variant will also require its own specific assembly chaperone.

MORE ENERGY WITH LESS WATER

Despite all the difficulties it presents, the objective behind this research is worthwhile: on the one hand, algae or plants with an optimized Rubisco variant could be used as a weapon in the fight against the rising carbon dioxide concentration in the atmosphere; on the other hand, the availability of such turbo plants with a significantly higher growth rate would also be a huge advantage for agriculture. "We could benefit from a form of Rubisco that is 10 or 15 percent more efficient," says Manajit Hayer-Hartl. It is not just a question of accelerating growth, but of even making it possible in the first place in some locations, as more efficient conversion of carbon dioxide into sugar reduces the plant's water consumption. As a result, in the future, agricultural activity would be possible in areas that are currently too arid for today's crop plants – and such areas are set to expand further due to the increasing scarcity of water on Earth. ◂

GLOSSARY

Chaperone
Proteins can function only if their amino acid chains are correctly folded. Like the chaperones of the 19th century whose job it was to shield young ladies from improper influences, special enzymes in cells ensure that proteins do not end up on the wrong path and assume the wrong form. Some chaperones take the form of a cylinder in which only a single molecule can fold. Such chaperones found in bacteria, chloroplasts and mitochondria are known as chaperonins. A lack of functional chaperones can result in the clumping of proteins and cause various diseases, such as Alzheimer's and Huntington's chorea.

Photosynthesis
Photosynthesis involves the production of carbohydrates from carbon dioxide and water with the help of solar energy. The process can be subdivided into two connected stages: The light reactions (photo part) make energy available for the water to be split into electrons, protons and oxygen. The energy-rich electrons and protons are used in the Calvin cycle (synthesis part) to convert carbon dioxide into sugar.

Graphic: designergold, based on original material from the Max Planck Society