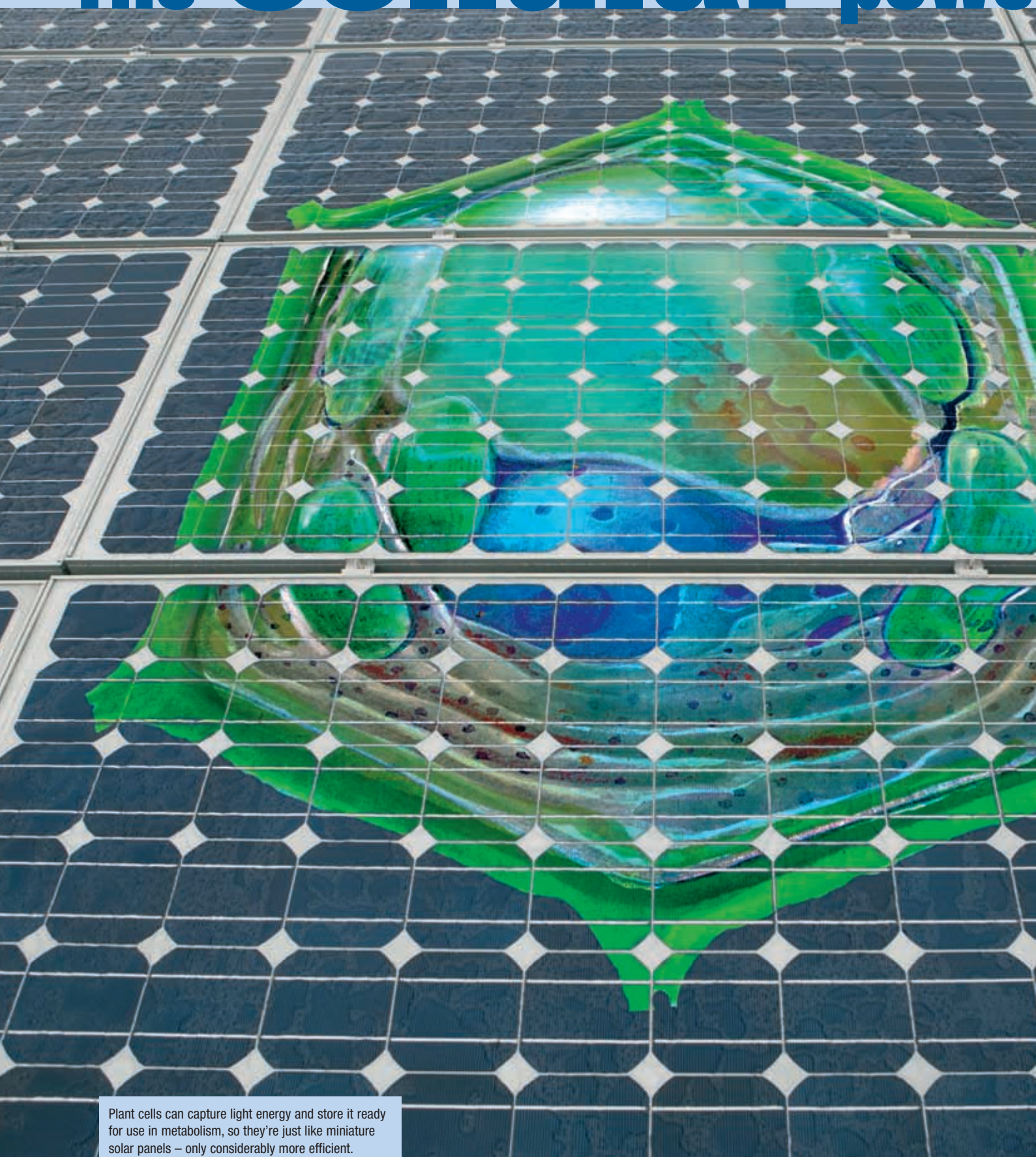


# The **cellular** power



Plant cells can capture light energy and store it ready for use in metabolism, so they're just like miniature solar panels – only considerably more efficient.



**M**acrococosmos, microcosmos – it’s always fascinating to see that something familiar to us that is very large can also be rediscovered in a corresponding form at the microscopic level. Take, for example, the comparison between a city and a cell: the cell’s equivalent to the city limits is the cell membrane, which delineates the cell from the external environment or from neighbouring cells; situated in the membrane are points of passage that allow for a controlled traffic of “goods”, such as one might find between neighbouring countries. Let’s continue with entities that are above the level of the State, such as the European Union (within which the borders have largely been raised). With a bit of imagination, you can also find their equivalents at the cellular level, for example in the skeletal muscles, where the individual cells are united together into associative units, the muscle fibres, in order to be able to work more effectively. So it’s not surprising that there are also correspondences in terms of energy-production and -transport at the cellular level, where terms such as “power station” and “energy transmitters” can equally be applied.

Plant cells are characterised by the fact that they possess “solar panels”, the so-called chloroplasts. With the help of these cell organs (or “organelles”), they are able to capture light energy and convert it into other forms of energy that are useful to the plant, although not into electrical energy like our solar panels can, but rather into chemical energy, without which biomass could not be created. This ability makes plants the basis for all terrestrial life as we know it: all animals, including man, use the energy that plants fix and turn into biomass, either directly or indirectly, in order to maintain their own vital processes. This certainly applies to herbivores, which consume plants directly, but also to carnivores insofar as they survive by eating herbivores and even, in the end, to decomposers such as fungi, which gain the energy they need for their own metabolism through the degradation of organic matter.

## Natural solar panels

Chloroplasts, the *solar panels* of the plant cell, are extremely complex units. Scientists speculate about their origin: like mitochondria, which we’ll talk about in more detail below, they possess their own ring-formed DNA, similar to that of bacteria and blue-green algae. Chloroplasts are capable of multiplying independently within

the plant cell. Thus the so-called *endosymbiont* theory suggests that chloroplasts were originally independent, blue alga-like organisms that were taken up by other single-celled organisms many aeons ago: but instead of being digested as food, they rather continued to live inside their new hosts in a symbiotic relationship.

Within the chloroplasts can be found the thylakoids, rolled up membrane systems that look rather like a pile of coins. It is here that the light-absorbing agents are stored, particularly the green pigment chlorophyll. And it’s also here that the wonder of energy-capture and conversion occurs – photosynthesis.

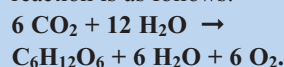
## Sugar made from CO<sub>2</sub>

The process of photosynthesis can be divided into three stages:

- First, light (a form of electromagnetic energy) is absorbed;
- The electromagnetic energy is converted directly into chemical energy;
- Finally, the chemical energy is used in the production of organic matter and is thus made available for subsequent use within the cell.

When light hits the thylakoid membranes in the chloroplast, it sets the electrons present in the absorbing pigments into a more excited, and thus more energy-rich, state. Excited electrons can be given up easily. Operating through several intermediate steps, electron transfer ensures that two molecules important to subsequent metabolic processes are formed – or to be more accurate, are regenerated – the energy-coupling agent ATP (adenosine triphosphate) and the reducing agent NADPH, a molecule with the rather challenging name of nicotinamide adenine dinucleotide phosphate hydrogen.

With the help of ATP, the plant cell is able to synthesize the energy-rich substance glucose within its chloroplasts, using the energy-poor substances carbon dioxide (CO<sub>2</sub>) and water as building blocks. During this reaction, the water molecules are split into oxygen, electrons and hydrogen ions; NADPH is oxidized to NADP<sup>+</sup>, and energy-rich ATP returns to its low-energy form, ADP. The formula for the reaction is as follows:



From six molecules of carbon dioxide and twelve molecules of water, a molecule of glucose arises, as a sort of *energy-store*; the *by-products* of this reaction are six

molecules of water and six molecules of oxygen. This oxygen is released into the surrounding air. The fact that our atmosphere today comprises about 20 percent oxygen is largely the result of millions of years-worth of photosynthetic activity. So people and animals owe not only the basis for their nourishment to plants, but also the air they breathe.

Plants can synthesize glucose from CO<sub>2</sub> in one of two ways. In most crop plants, the intermediate molecules in the reaction have three carbon atoms (the so-called C<sub>3</sub>-plants). In other species such as maize, elephant grass and sugar cane, CO<sub>2</sub>-fixation proceeds via oxalacetate, a compound with four C-atoms (C<sub>4</sub>-plants). This latter reaction is quicker, more efficient, and requires less water. C<sub>4</sub>-plants are therefore often used for producing biomass (*energy plants*). The temperature optimum for C<sub>4</sub>-plants is higher than that of C<sub>3</sub>-plants, so

the former tend to grow in warmer climates.

The working efficiency of photosynthesis is estimated at around 20-35 percent, depending on the wavelength of the absorbed light. The synthesis of a mole of glucose requires 8,000 to 14,300 kJ of light energy.

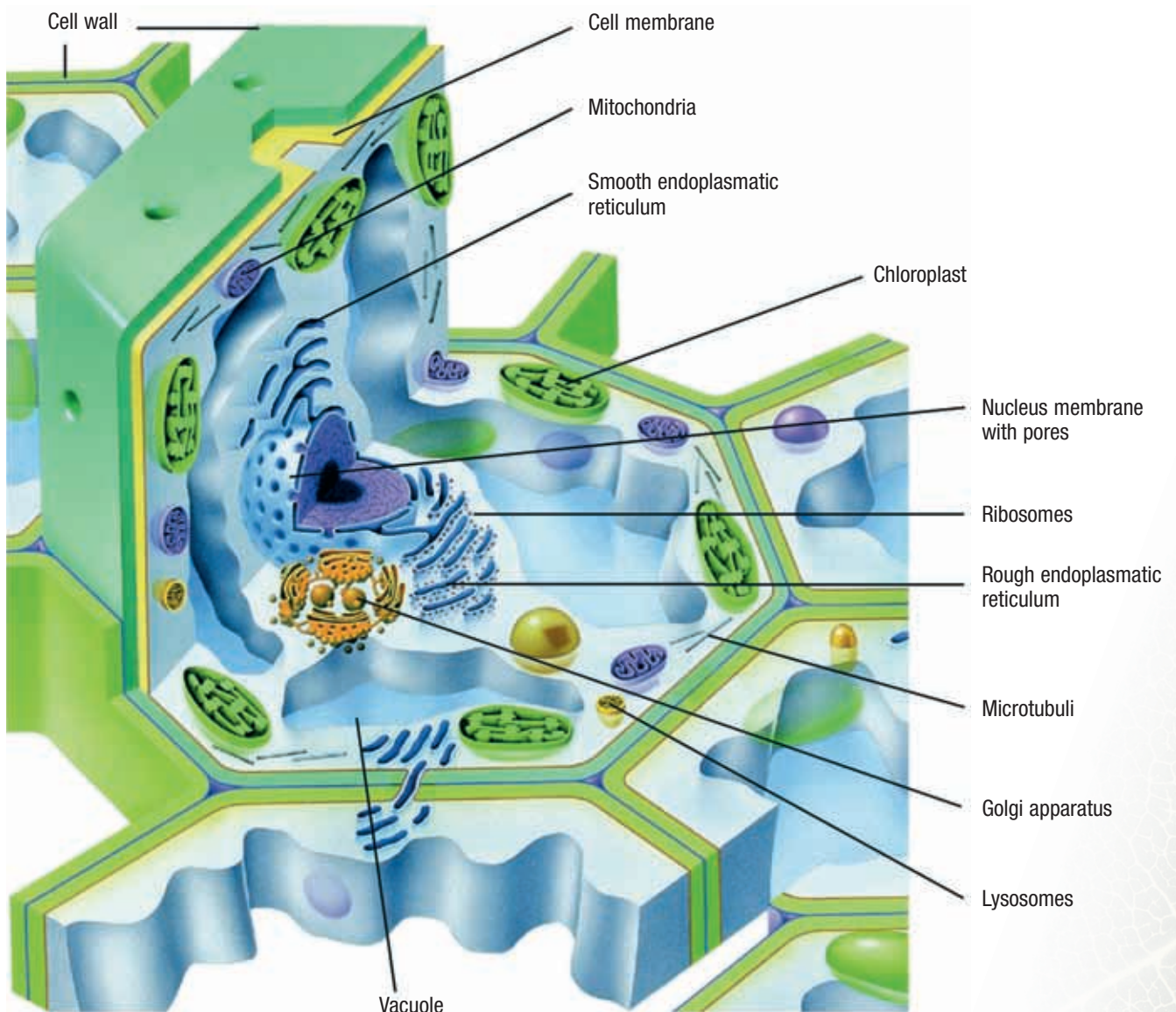
### Energy production in the mitochondria

Let's return once more to the endo-symbiont theory: plant cells benefit from the presence of chloroplasts because of their ability to capture the energy of light through photosynthesis and channel it into energy-rich organic substances such as glucose and starch (macromolecules comprised of many glucose units). When the cell needs energy – as it always does, to run metabolic processes, growth and cell

division – then the glucose energy safe must be *cracked*. Just as for photosynthesis, the cell does this with the help of certain organelles that possess their own DNA, reproduce themselves independently and also appear to have an ancestry going back to bacterium-like predecessors – the mitochondria. These organelles are found in the cells of all complex organisms, in plants as well as in animals and fungi. Mitochondria are particularly numerous in cells that use a lot of energy, such as muscle cells, nerve cells and egg cells.

In the mitochondria, the chemical energy stored in glucose or other organic substances is made available through oxidative degradation. With the release of energy, the cell's *battery* – the ADP/ATP-System – is *recharged*. The complete oxidation of one mole of glucose delivers 38 moles of ATP, meaning that the efficiency of oxidative glycolysis lies at almost 40 percent – mak-

## Specimen of a plant cell



ing it a pretty effective system, on a par with the energy yield of modern steam turbines. Thus the mitochondria really do earn their reputation as the cell's powerhouse. During the oxidation of organic compounds, hydrogen is split off and brought together with molecular oxygen to produce water ( $4\text{ H} + \text{O}_2 \rightarrow 2\text{ H}_2\text{O}$ ). The formation of water is the main energy-yielding reaction. You could consider this process (cell respiration, as it is called) as being the opposite of photosynthesis: in the chloroplasts, glucose and oxygen are produced from  $\text{CO}_2$  and water (with sunlight providing the energy); whereas in the mitochondria, glucose and oxygen are degraded again to  $\text{CO}_2$  and water in order to release energy.

### Consequences for the farmer

The growth and yield of crop plants will increase as the factors that are important for photosynthesis approach their optimum levels. Factors such as sunlight and temperature are of course beyond the farmer's control (the temperature optimum for photosynthesis in full sunlight lies at  $35^\circ\text{C}$ ). Drought has a negative effect on photosynthetic productivity because the plant protects itself from drying out by closing its stomata, thereby limiting the exchange of the gases necessary for this process.

Given the facts of climate change, it is interesting to note that photosynthesis functions most efficiently at an ambient  $\text{CO}_2$ -concentration range of 0.1 to 1 percent. However, the  $\text{CO}_2$ -concentration in the atmosphere currently lies at around 0.037 percent (370 ppm), meaning that plants are working at below capacity. The anticipated increase in the concentration of the greenhouse gas  $\text{CO}_2$ , which is expected to reach about 500 ppm in the course of the coming decades, is likely to boost the growth of plants to some extent.

Laboratory studies have indeed shown that considerable yield increases (of 20-30 percent) might be anticipated as the result of this so-called  $\text{CO}_2$ -fertilising effect. But are these results really so easily translated from the laboratory to the field? On the other hand, would it really be possible to simulate an enhanced  $\text{CO}_2$ -concentration in the field (for example over a cereal crop) in order to obtain a realistic picture in situ?

The effort involved is considerable – but studies like this are indeed running at several sites around the world. One of these locations is the Johann Heinrich von Thünen-Institut (vTI), the former German Federal Agricultural Research Centre, in

Brunswick, Germany. In the *Brunswick carbon project*, which is running over several cropping seasons, the  $\text{CO}_2$ -concentration in the air above selected portions of a field is being maintained at a constant 450-550 ppm using controlled release of the gas. The scientists are measuring growth, but they are also monitoring other parameters such as the plants' water balance. The results obtained so far are actually rather sobering: biomass production in wheat and sugar beet increased by a rather modest 6-14 percent; at the same time, water use decreased. Moreover, protein content decreased by about 10 percent in the grain of winter barley, for example. Thus, the yield may increase, but the quality of the harvest also changes.

This demonstrates once again how highly complex the metabolism of plant cells is; the capture, storage and use of energy are only three aspects among many. A glimpse into these biochemical processes is fascinating, but it quickly becomes obvious that it is not easy to intervene or indeed to steer them. And that's another way in which a microscopically small cell is similar to a large municipality. ■