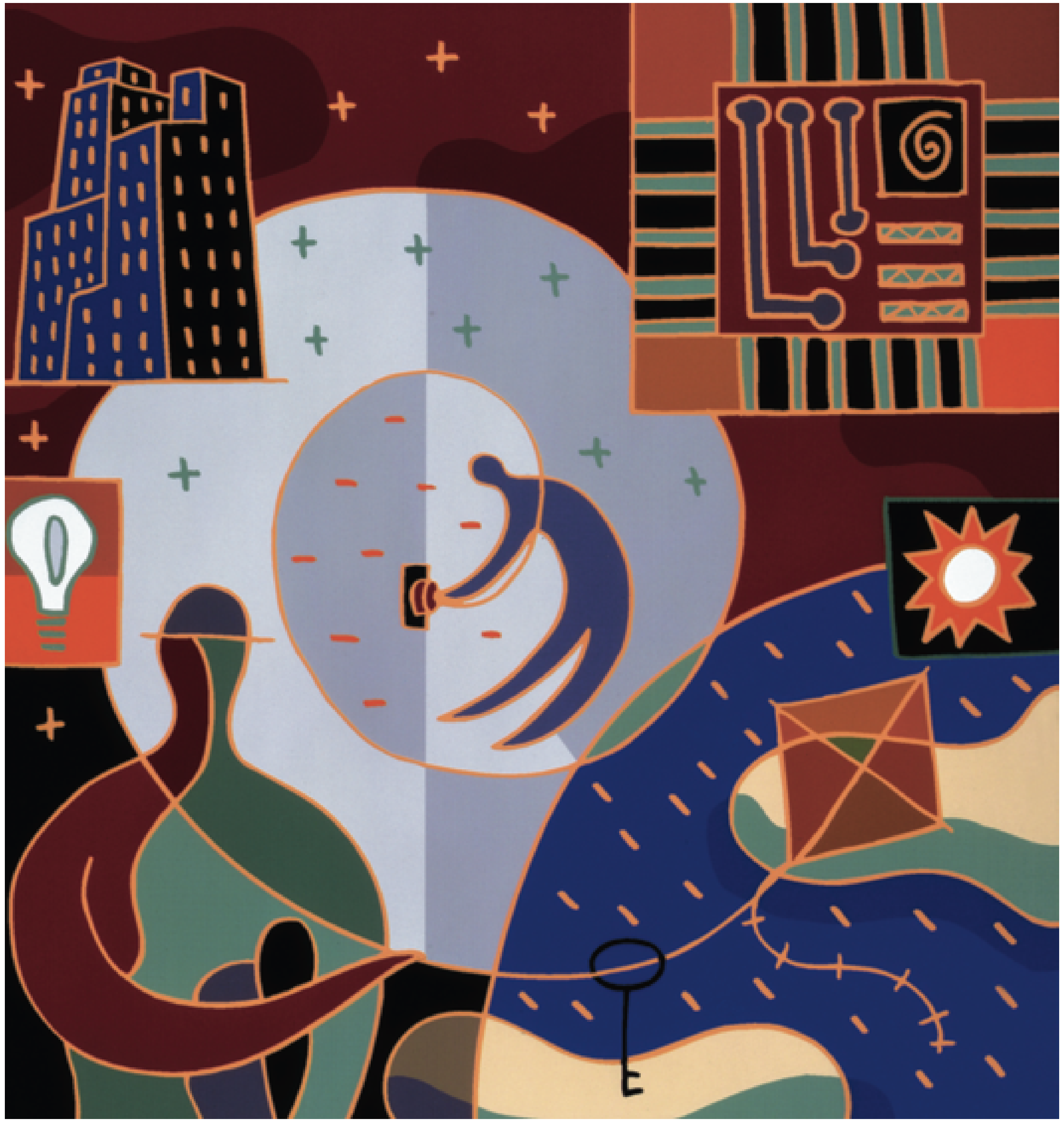

ILLUSTRATION: CORBIS

Synergy Ensures Energy

Pooling basic research and focusing it on reformulated problems: with this approach, the Max Planck Society hopes to shorten the distance between pure and applied research. A first step toward this goal is ENERCHEM, a project-based company that took up its work in January 2005. Within the framework of this research association, researchers from five Max Planck Institutes sound out what chemistry – notably nanochemistry – and materials research can contribute to sustainable power supply. **MARKUS ANTONIETTI** *describes the approaches these sleuths are pursuing toward a post-fossil fuel future.*

ENERCHEM sees itself as a trans-institutional network. Unlike the traditional institutes of the Max Planck Society, and specifically to complement them, it will not be limited to specific issues relating to a scientific subject, but rather will tackle major problems of special significance to society as a whole. The chemistry and materials science issues that need to be solved with a view to a creating the sustainable power supply we will need for the future presented an ideal subject for this novel research experiment. This includes such topics as the chemical foundations of a hydrogen-cycle economy, the development of nanochemically optimized materials for mobile energy storage, and models for effective decentralized production of energy.

In principle, the general public is also aware what these issues mean for the future of our society. What is much less known, however, is that behind these common buzzwords are scientific problems that can be solved only through concerted and sustained basic research – and that consequently belong to the traditional domains of the Max Planck Society.

Founding project companies that, like ENERCHEM, focus on issues that are commonly recognized by society, rather than on purely expert problems, could have a positive side effect above and beyond the scientific gain. Taken as an example, they point up the importance of and the need for basic research for the future of our society, and drive this point home to a broad audience. ►

Currently, chemistry departments of five institutes are cooperating in ENERCHEM: those of the Fritz Haber Institute (Robert Schlögl, Inorganic Chemistry) and the Max Planck Institutes of Coal Research (Ferdi Schüth, Heterogeneous Catalysis), for Solid State Research (Joachim Maier, Electrochemistry), for Polymer Research (Klaus Müllen, Supramolecular Chemistry) and of Colloids and Interfaces (Markus Antonietti, Colloid Chemistry and Nanostructures).

The project company's research focuses on nanoscience. However, unlike other nanocenters, the spotlight is on problems that have been outlined – and the goal is to tackle these problems using typical nano-based strategies and materials. This involves choosing the topics in such a way that the strengths of all groups involved are brought to bear, converging to create synergy. This puts ENERCHEM in a gap of sorts: between applied research, which aims to develop products to sell, even without having the final basic knowledge; and basic research, whose sole aim is knowledge, without considering utility. This middle course follows the real pre-industrial traditions of science.

A lot of things are still in disorder in chemistry

The focus of this first project company was chosen with a view to the fact that chemistry has recently been experiencing a renaissance that many did not expect. It owes this new strength to refined physi-chemical measuring methods, to back-fertilization from biology, and to systematic investigation in the scale range beyond molecules. Political decision makers and research managers also agree that chemical nanotechnology has now at least caught up with genetics and molecular biology as a promising prospect for the future. This was explained very clearly and substantiated in detail in a recently published strategic report by America's National Research Council.

Thus, a *commodity* from the secure inner core of science became a subject that, in some cases, is the only one capable of responding to the increasingly demanding technological needs of modern society. To date, this trend has not been widely recognized in the German research landscape. For example, research capacities in the life sciences and biophysics continue to be greatly expanded, but chemistry is underrepresented, even compared with branch subjects. Given the scientific and economic importance of chemistry, this is very difficult to understand.

The project company's work packages result from the well-known problem of ensuring power supply for generations to come, which corresponds to the UN definition of sustainability. For reasons of climate protection, as well as in view of Asia's rapid industrialization and the foreseeable depletion of fossil resources, it seems that we can no longer simply update current technology. Therefore, it is not enough for key concepts, such as a hydrogen economy, greatly improved energy storage (batteries), fuel cells, nano-insulating foams for better building insulation, seasonal energy management and more effective generation of solar energy to be the subject of political discussions, they need to be tackled with scientific methods.

These fields are already being explored extensively by a large number of groups and centers, of course, but the main approaches are still strongly focused on current technologies, markets and interest groups. The founders of ENERCHEM were surprised to learn that such activities are so often characterized by a lack of medium-term, non-interest-specific basic research, primarily as a result of the structure of such centers. In addition, the approaches currently being pursued are frequently not progressive enough and do not meet even the basic requirement of contributing to a system solution. In some cases, it is even a matter as simple as not asking the right questions. Moreover, concepts that do not view our current power supply as the default are scarce.

This presented the Max Planck Society with a field of research that, without regard for economic constraints and influences, can pursue and track solutions long enough to allow for comparison with conventional energy concepts. Since this final system comparison is not subject to the statutes of the Max Planck Society, it should be carried out in cooperation, either with industry partners or with other research organizations – for example by getting Fraunhofer Institutes on board when the project has made sufficient progress.

A systemic analysis of the research requirements delivers a wealth of obvious approaches and projects. For example, energy should be generated more efficiently, but it should also be possible to transport and store it, and losses during transportation and use should be minimized. Each of these problems takes on a dimension for which even small improvements bring big results.

To further develop the argument, a classification is needed – that of centralized versus decentralized energy production. The current dogma is centralized energy production and distribution, whether through ever-larger power plants or even, in the distant future, through nuclear fusion. But this energy must then be transported and stored in the optimum manner, since the majority of the consumers, such as cars or aircraft, operate in a decentralized way. Furthermore, the centralized concept entails the disadvantage that energy occurring at decentralized locations cannot be used effectively. This means that solar energy remains in the desert, extensive wind energy is lost on its way to the consumer, and millions of tons of natural gas are still being burned each year because it does not pay to transport it. Those are the main weaknesses of a centralized approach.

The highlights of decentralized energy production are improved production and storage, for example through new solar cells and new electrode materials, which may even transform sunlight directly into chemical energy without taking a detour via electricity. The energy produced at many different locations must then be stored, transported, distributed and then consumed – so cand dates for the new material flows must be identified and evaluated without any ideological influences. Furthermore, the storage medium must be capable of releasing the energy simply and effectively, for example as in a fuel cell.

Although the carbon/hydrocarbon cycle offers the advantage of leak-proof transportation and storable energy, the disadvantage is that the carbon dioxide it produces isn't really cyclable, and acts as a greenhouse gas. By comparison, the end product of the potential hydrogen cycle – water – makes it very attractive. However, it is very difficult to store and transport hydrogen effectively: 2 grams of hydrogen have a volume of 22.4 liters, and even at an uncomfortable pressure of 500 bar, the density is just 50 grams per liter.

Herein lies the strength of chemical storage systems: a liter of methanol, for example, can be stored and transported easily and binds no fewer than 100 grams of hydrogen, which would take up a volume of 1,000 liters. The above argumentation now requires merely a chemical reaction that will also ensure the decentralized cyclability of the hydrogen/methanol system. The *forming/reforming* equilibrium is suitable for this, described by the following reaction equation:

$$\underset{\text{methanol}}{CH_3OH} + \underset{\text{water}}{H_2O} \xrightleftharpoons{\text{ENERGY}} \underset{\text{hydrogen}}{2\,H_2} + \underset{\text{carbon dioxide}}{CO_2}$$

Finding catalysts that reliably promote this reaction, also decentralized – and on a very small scale, such as in a laptop – is incredibly difficult and is being addressed at ENERCHEM, under Robert Schlögl at the Fritz Haber Institute. With their help, the energy of windmills or solar cells could be stored and tapped as needed.

In order to store gases like hydrogen and methane as energy carriers, pressure techniques can be used to liquefy them. However, another option is to store gases in porous systems with practically no external pressure. Here, the storage takes place through the gain in interfacial energy. This effect is also described in the form of a capillary pressure that is dependent on the material and the pore size – and that can take on values up to 1,000 bar with very small pores. For a number of reasons (accessibility, chemical variability, chemical and mechanical stability), porous carbon appears to be the most promising target structure. The ability to take up substances highly effectively, as well as reversibly, is known from activated carbon in air conditioners and gas masks. However, the chemical structure and the architecture of modern porous carbon are very different from that of its ancestors.

Carbon holds great potential

Ferdi Schüth's group at the Max Planck Institute for Coal Research, for example, using a method known as nanocasting, has produced carbons that exhibit a surface area of 2,000 square meters per gram of carbon. For one thing, these carbons have a very light structure and a pore volume of up to 3.3 cubic centimeters per gram of carbon, and for another, they are chemically variable and monolithic – that is, they consist of a single piece, in contrast to carbon nanotube powders, for example. Investigating such structures for gas storage, as well as hydride and electron storage, for example in high-power capacitors for future electric cars, is one of the issues ENERCHEM addresses.

The principle of catalysis plays a key role in all energy conversion and cleaning steps. The electronic burning of hydrogen in fuel cells, for example, lives on a thin layer of noble metal catalysts, usually made of platinum or palladium. But rare elements such as noble metals are not a sustainable technological solution: the Earth does not have sufficient reserves of these elements to convert even just all cars to fuel cells. ►

Thus, the key – and unusual – question is whether the electronic and chemical particularities of such catalysts couldn't also be copied by simpler and less rare elements. Following a careful study of the elementary processes, carbon seems to be a possible alternative here, too.

Robert Schlögl and his group were able to show that special carbon-nanostructures catalyze a dehydration reaction. This gives them the hope that, conversely, hydrogen can also be activated for electrocatalytic combustion. The aim of their research is the relevant chemical doping of carbon with geometric defects – nitrogen and oxygen groups for adjusting special chemical reaction profiles.

Tiny structures form large surfaces

Another aim of the ENERCHEM researchers is to manufacture battery material with greater power. A group led by Joachim Maier at the Max Planck Institute for Solid State Research is working on this issue. A significantly larger storage capacity compared to current systems has already been achieved through targeted nanostructuring of the positive pole of a modified version of conventional lithium batteries.

ENERCHEM partner Klaus Müllen and his team are pursuing the same the goal at the Max Planck Institute for Polymer Research in Mainz. They succeeded in manufacturing the graphite electrode at the negative pole of lithium batteries from a new kind of carbon. In contrast to conventional graphite, which is composed of parallel platelets in the micrometer range, carbon nanodisks are loosely linked to form a three-dimensional network into which the lithium atoms can diffuse. This novel material is difficult to manufacture, but very attractive, since previously, about six carbon atoms were needed to store one lithium atom; now, however, only three or four are needed. Even if battery materials don't achieve the energy density of chemical storage, they are still very important for centralized energy scenarios. In addition, treating the components of both centralized and decentralized energy cycles is in line with the project company's philosophy.

The search for new nanostructured electrode materials – whether for solar energy production or for fuel cells – is taking a similar direction. These materials, too, should offer the largest surface possible for exchanging electrons. In other words, they should ideally be nanoporous; at the same time, however, the pore structure should not reduce the electronic conductivity and the electrochemical potential, but far rather improve it. In recent years, my working group at the Max Planck Institute for Colloids and Interface Research has developed chemical template techniques for building crystalline layers from mesoporous oxides. In the process, we just recently succeeded in manufacturing structurally perfect layers from complicated functional oxides from the class of perovskites and spinels.

With such techniques, it was hoped, it would be possible to bring the electronic structure of electrodes ever closer to their energetic task – for all kinds of potential uses. The ultimate goal here is likely the photochemical cleavage of water by light – that is, the direct production and storage of light energy through artificial photosynthesis. In any case, here, too, it is expected that even small improvements will accomplish great things since, to date, systems have eluded such fine structural control.

Although ENERCHEM will, at first, take advantage of the Max Planck Society's short communication and decision-making paths to quickly achieve a certain visibility, the project company is nevertheless to be integrated into the German research landscape right from day one through scientific contacts. Concrete cooperation ventures may result from content-dependent requirements and the respective optimum allocation of rights and duties. In this context, a policy of free access can be expected, as befits interest-free basic research – with the appropriate consideration for the necessary protection of intellectual property. In this way, the foundation of the project company could grow into a new and promising model for cooperation between research and industry.

It remains to be seen which of the intended goals will actually be met in the medium term. However, based on the tenor of the foundation activities and the initial results already achieved, we have every reason to be optimistic.

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