ELEMENTS

Research. Knowledge. The future.

What Comes Out

2/2020

Hydrogen

A common lightweight

Hydrogen (H) is not only the element with the lowest density in the periodic table but also the most common element in the universe. In fact, more than 90 percent of all of the atoms in the universe are hydrogen atoms. However, the element, which was discovered by Henry Cavendish in 1766, does not exist as atomic hydrogen under normal conditions on earth, but only as molecular hydrogen (H_2). This is a colorless and odorless gas that can be kept in compressed-gas storage containers as well as in chemical compounds such as metal hydrides. If it is cooled down to -253 degrees Celsius it can also be liquefied and stored in special tanks. Great care must be taken during experiments, because hydrogen is extremely flammable and the resulting flame is almost invisible.

Henry Cavendish British scientist, 1731–1810
Molecular hydrogen (H_2) A compound of two hydrogen atoms
Metal hydrides These compounds of metals and hydrogen are a subgroup of the hydrides

→ More about hydrogen starting on page 10

DEAR READERS,

Do you know what the energy carrier of the future will be? All of our experts agree that it will be hydrogen. A heating system in the cellar, a public bus, a refinery, and even a steel mill—in the future all of them could be operated without any emissions, because the element hydrogen, which is represented by the symbol H in the periodic table, produces only water when it is burned. It doesn't leave behind any soot or carbon dioxide or nitrogen oxides. That sounds wonderful, doesn't it?

But critics say it's too good to be true. After all, people have been predicting a breakthrough for hydrogen for decades. Why should all of these dreams, whose fulfillment we have so far waited for in vain, be coming true right now? The answer is simple: Innovation is making it possible. What's the present status of research and development in this field? What's the difference between green and gray hydrogen? Who is driving these new technologies, and what can Evonik contribute to this development? These are the questions we explore in depth in this issue—questions in the field of chemistry and far beyond.

Innovations don't succeed overnight, and that also applies to the next generation of surfactants. Without surfactants, shampoos and dishwashing detergents would be pretty ineffective. Europe is the most important location for surfactant development and production—and Evonik is an important pacemaker in this field. Together with the consumer goods group Unilever, our specialists have developed a novel biosurfactant that is not only completely biodegradable but is also produced from renewable raw materials. In this issue we tell you the story behind the story.

And we also make a journey to the land of dreams. That's because even professors of chemistry dream, even while they're working. They're looking for what we call "dream reactions"—solutions to problems in chemistry that researchers have been tinkering with for decades. A research team led by Professor Robert Franke, head of hydroformylation research at Evonik, has now succeeded in making one of these dreams come true. I wish you a thought-provoking reading experience!

Matthias Ruch
Editor in Chief

All of the articles from the printed magazine along with additional current content are also available on the Internet at: elements.evonik.com

As green as it gets: Rhamnolipids in dishwashing detergents are made from natural raw materials, clean thoroughly, and are completely biodegradable

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Shining bright: Companies and governments worldwide are investing billions to promote hydrogen as an energy carrier, storage medium, and industrial raw material. The possible uses range from electrolysis to pipeline systems and filling stations like this one in California

LIMITLESS LIQUIDITY

To make sure that plants growing in huge greenhouse tunnels like these in Valencia, Spain, thrive optimally, they are continually irrigated. The hoses needed for this purpose must be regularly cleaned so that they don't clog up. Hydrogen peroxide (H_2O_2) is an especially environmentally friendly cleaning agent, whose only byproduct is water. Even so, for a long time it was seldom used in greenhouses because of the high costs of transportation and storage. The startup HPNow, in which Evonik has held shares since 2017, has found a way to avoid this dilemma: a modular generator that produces H_2O_2 electrochemically, directly on site and whenever it's needed.

A LOOK AROUND THE WORLD

Innovations from science and research

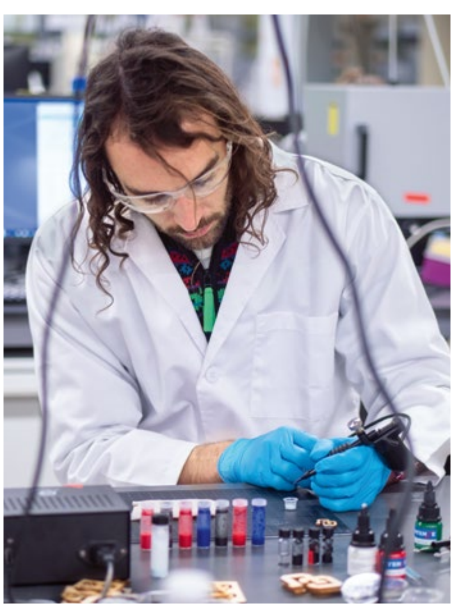
Secure Power for Space

Researchers in the USA want to use chemical reactions to make the energy supply on space missions more reliable

Lots of energy is needed on space missions. This demand is normally covered by solar power, which, however, has a major drawback: Because it depends on the intensity of the sun's radiation, it is not always reliably available. That's why a research team at the University of Central Florida (UCF) is working on a backup system that provides energy using chemical reactions and is thus always available. A compound of silicon and at least one other element is burned slowly as oxygen is added. The energy generated can be easily stored and supplies heat and electricity even in very cold environments.
In the future, this technology might not only benefit space missions but also form the basis for the energy supply of space colonies. The National Aeronautics and Space Administration (NASA) considers this idea to have great potential and has been providing the project with $550,000 of funding since last year.

PEOPLE & VISION

"This tattoo helps protect skin against the sun's rays"



THE MAN

Carson Bruns never really wanted to choose between art and scientific research. When he ate at the dining room table during his childhood in Colorado, he sometimes mixed food such as tomato sauce and juice together and observed how the mixture's color changed—his investigative spirit had been awakened. Later, as a teenager, he took up painting. Art continued to be a part of his life even after he began to conduct research professionally, especially in chemistry. Bruns, 34, is now an assistant professor at the University of Colorado and works in a field, tattooing, that combines both of his big passions.

THE VISION

Carson Bruns has developed a tattoo that serves as a UV sensor for the skin. This tattoo turns blue when human skin is exposed to ultraviolet radiation. This effect is created by microcapsules that contain pigment. The color change notifies the tattoo's wearer that his or her skin should be better protected, and so helps prevent long-term damage such as skin cancer. Although the sun-protection tattoo is still at the testing stage, Bruns is already thinking a step further: He is working on a tattoo that would not only warn of UV radiation but also actively protect the skin against it.

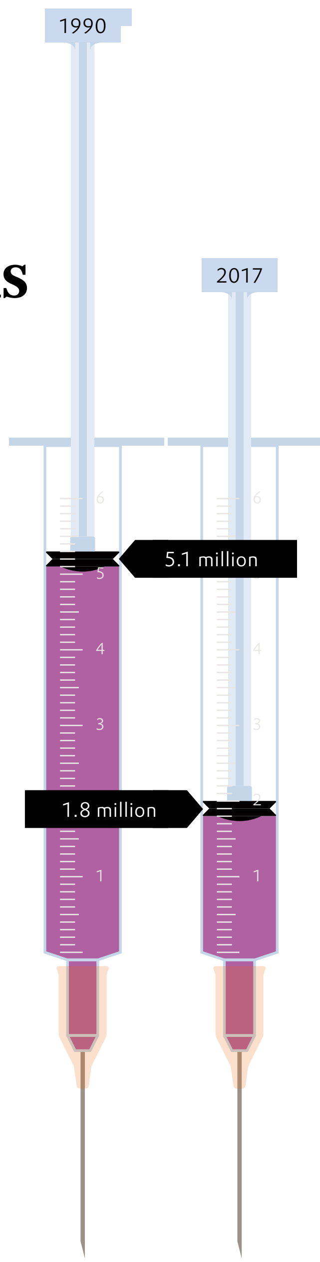
A Botanical Stress Test

Plants have a special protective mechanism that enables them to survive in emergency situations: If they are attacked or are damaged by environmental factors, the plants supply the cells in their leaves with hydrogen peroxide (H_2O_2). It acts as a kind of alarm signal, which causes the cells to quickly produce chemical compounds that repel enemies such as insects and snails as well as repair damage.
In order to better understand how this effective early warning system works in nature, engineers at MIT in Boston have developed special sensors made of carbon nanotubes. The sensors are embedded in leaves, where they can register the H_2O_2 alarm signals and precisely determine how different types of plants react to stress factors such as injury, infection, and damage caused by light.
The results are especially interesting for agriculture. On the basis of this data, agronomists will be able to develop strategies for helping cultivated plants deal with stress and in this way optimize crop yields.

THAT'S BETTER

Life-saving Injections

Over the past 30 years, the child mortality rate has declined by almost two thirds worldwide. Vaccines play a key role here. Whereas 5.1 million children still died of vaccinable diseases in 1990, this figure had declined to 1.8 million lately. This progress is mainly due to the vaccines DTP against diphtheria, tetanus, and pertussis (whooping cough), and MMR against measles, mumps, and rubella. By contrast, the drop in mortality was much less pronounced for diseases against which there are no vaccines.



Source: Institute for Health Metrics and Evaluation (IHME)

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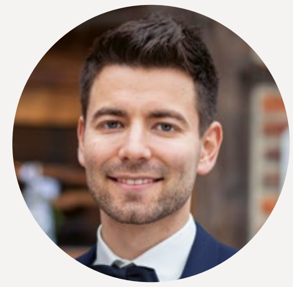
PERCENT

is the annual growth rate of the 3D printing material market until 2024, according to a forecast made by the Research and Markets institute. The medical sector in particular—which uses these materials to make implants, for example—is a key driver of this development.

AUTONOMOUS HEALING

As the corona crisis shows, interrupted supply chains can sometimes cause supply bottlenecks. This carries especially high risks in the case of medications. Researchers at the Max Planck Institute of Colloids and Interfaces in Potsdam have found a possible solution to this problem: It consists of an autonomous, computer-controlled laboratory that can quickly and locally produce organic substances such as raw materials for medicine.

GOOD QUESTION



"Mr. Sandfort, will AI be able to predict the results of chemical reactions in the future?"

Yes, it will be able to do so if the data permits. Chemical reactions depend on a variety of factors. It's hard to predict how effective they will be, which leads to many experiments, including "unnecessary" ones, being carried out. My colleagues and I have therefore developed an AI model that's based on machine learning. From a myriad of experimental arrangements, it filters out those that are most likely to work. Artificial intelligence can, for example, select an optimal catalyst. Until now, researchers have first had to create and test a whole series of catalysts. In addition, AI can predict the selectivities, i.e. the proportions of the desired material in the end product, as well as the yields—the amounts of products. This model is currently limited to a few applications. In order to change that, we need more suitable data and a combination of AI and robotics.

Frederik Sandfort, a doctoral student at the Institute of Organic Chemistry at the University of Münster, is one of the authors of the study titled "A Structure-Based Platform for Predicting Chemical Reactivity."

H Is for Hope

TEXT **TOM RADEMACHER**

A hot topic: Thyssenkrupp produces almost 12 million tons of crude steel in its plants every year. In the future, plans call for hydrogen instead of coal dust to generate the necessary operating temperature in the blast furnaces

When it burns it only produces water, its supply is inexhaustible, and its applications are manifold: Hydrogen has what it takes to fundamentally transform our economic system. Evonik is working in many areas to help make this vision a reality

In Duisburg-Bruckhausen, everything is gigantic. On an area that is 22 times as big as the Vatican, Thyssenkrupp Steel Europe generates around one fourth of Germany's total steel production—about 11.5 million tons a year. The plant's blast furnaces tower more than 100 meters into the sky. For decades, they have been spewing out hundreds of tons of glowing iron per hour.

However, the first tiny and as yet invisible steps in a transition that will completely change this seemingly immovable giant have already begun. With support from the federal state of North Rhine-Westphalia, Thyssenkrupp is taking the first tentative step toward climate-neutral steel production. Instead of coal dust, hydrogen will be blown into a blast furnace—initially as a test "in homeopathic quantities," as the company puts it. If all goes well, the first blast furnace will be converted by the end of 2021. Because hydrogen produces water vapor instead of carbon dioxide when it burns, Thyssenkrupp could reduce its emissions by more than three million tons of CO_2 per year—more than is caused by all domestic flights in Germany. And that's just the start.

The plan is that hydrogen will be the fuel of the future, in the steel sector and beyond. Business communities and policymakers all over the world are intensively driving this development forward. According to the European Union's "Hydrogen Roadmap," almost one fourth of the EU's energy needs could be covered by hydrogen by 2050. Plans call for 5.4 million jobs to be created in a hydrogen economy that uses this odorless gas, which is symbolized by the letter H in the periodic table, in every possible area. All kinds of systems, ranging from furnaces in cellars to regular-service buses, refineries, and steelworks, could be operated climate-neutrally with green hydrogen produced by means of renewable energy drawn from the wind and the sun. Most of the puzzle pieces for completing this vision of the future already →

Gray hydrogen: In steam reformers like this Evonik facility in Marl, hydrocarbons (mostly methane) are split into hydrogen and carbon dioxide

exist. It seems that they only need to be put together. However, many questions still remain unanswered. Evonik is one of those aiming to provide some of the answers.

"Water will be the coal of the future," wrote Jules Verne almost 150 years ago. He believed that the energy source of the future would be water decomposed into hydrogen and oxygen by means of electricity. This idea has never lost its fascination. In the late 1980s a cover story of the news magazine *Der Spiegel* called "The Energy of the Future" claimed that solar energy and hydrogen would provide the power that nuclear energy had promised but never delivered.

The hopes pinned on hydrogen are still running high today. "We have to forge ahead with the production and utilization of hydrogen as fast as possible," says Svenja Schulze, Germany's Minister of the Environment. "With regard to hydrogen, we can't afford to lose any more time," adds Anja Karliczek, the Minister of Education and Research. And her cabinet colleague Peter Altmaier, the Minister for Economic Affairs and Energy, insists that Germany must "become the Number One country for hydrogen."

There are good reasons for their enthusiasm. In light of our concern about the climate, hydrogen's qualities sound almost utopian. Its combustion produces only water. No soot, no carbon dioxide, and no oxides of nitrogen remain—thus, at least theoretically, hydrogen solves crucial problems of the petroleum age in one fell swoop. Besides, the supply of hydrogen is almost inexhaustible. Nine tenths of the atoms in the entire universe are hydrogen atoms. On the earth, hydrogen is mainly found in seawater. The rest of it is chemically bound within almost all fossil and biological raw materials. However, the economic potential of hydrogen is hardly being utilized.

"With regard to hydrogen, we can't afford to lose any more time"

ANJA KARLICZEK, GERMANY'S MINISTER OF EDUCATION AND RESEARCH

A MAJOR COMPONENT FOR THE CHEMICAL INDUSTRY

To date, the main user of hydrogen has been the chemical industry, which needs it to build molecules. More than half of the globally produced hydrogen is processed into ammonia, primarily for fertilizer. Refineries also need huge amounts of hydrogen, for example to crack and desulfurize petroleum products.

Evonik uses hydrogen to make numerous products, especially for the synthesis of hydrogen peroxide (H_2O_2). Hydrogen peroxide is used as an environmentally friendly bleaching agent in paper and cellulose production, as a means of sterilizing beverage containers, and as a fuel for space travel. Evonik is one of the biggest global producers of H_2O_2, with an annual capacity of more than one million tons. Hydrogen also plays an important role in the production of amino acids for animal feed and in the production processes for silanes, fumed silica, and specialty oxides—multifaceted products that are used in glues, plastics, and car batteries. Hydrogen is also frequently generated as a byproduct or a coproduct that is then used later on in other parts of a production network.

In the future, Evonik intends to be represented in all the phases of the hydrogen value chain, ranging from production to distribution and utilization. "Those who want to see the energy transition can't avoid coupling sectors by means of hydrogen," says Oliver Busch, the Head of Sustainable Businesses at Creavis, Evonik's strategic innovation unit, which is working to develop new and sustainable business areas. "And if we do things right, the transition won't pass us by either." Together with Axel Kobus, the Head of Evonik's Process Technology and Engineering Business Line, Busch wants to promote the hydrogen agenda. "As an industrial group, we have an especially large number of contact points," says Kobus. For example, Evonik produces hydrogen for numerous users and operates hydrogen pipelines that supply a variety of industrial companies. The Group also supplies innovative process technologies and products that could close gaps in the hydrogen economy. Kobus and Busch agree that "in this area we can provide substantial added value as a supplier of solutions."

GREEN IS THE COLOR OF HOPE

At the Marl Chemical Park, it's especially clear to see how multifaceted the uses of hydrogen already are today. "In this industrial park, which is home to almost 20 companies, hydrogen is used in nearly every laboratory and every plant—not always in large amounts, but almost always for crucial processes," says Swen Fritsch, the manager in charge of hydrogen operations at this location. The location's steam reformer delivers several tens of thousands of cubic meters of pure hydrogen per hour. Most of this production volume is used to cover the site's own needs; the rest is drawn off directly by industrial gas suppliers from the region at their own filling stations. Marl has the biggest hydrogen filling station in Europe.

Steam reformers like the one in Marl cover more than 95 percent of the worldwide demand for hydrogen. They use heat, pressure, and catalysts to produce hydrogen from fossil sources such as natural gas. This process generates about ten tons of carbon dioxide (CO_2) per ton of hydrogen. According to the International Energy Agency (IEA), in recent years hydrogen production has generated about 830 million tons of CO_2 emissions worldwide per year. That's more than the emissions of the UK, France, and the Czech Republic taken together. This is not a good balance sheet for hydrogen, the beacon of hope for advocates of an energy transition.

However, a different approach would also be possible. Hydrogen can be produced directly from water by means of electrolysis. The principle is simple and well known: A voltage applied between two electrodes splits water into its chemical components, oxygen and hydrogen. In a fuel cell, this process is reversed: Hydrogen and oxygen from the air react without combustion to form water. The reaction generates an electric current and some waste heat. Within this cycle, hydrogen is the storage medium for electrical energy. This potentially climate-neutral cycle, which is expected to spur the energy transition, is now attracting large amounts of attention and capital. The magic words here are "sector coupling" and →

"Those who want the energy transition will need the sector coupling using hydrogen"

OLIVER BUSCH, HEAD OF SUSTAINABLE BUSINESSES AT CREAVIS

Green hydrogen: In the future, more hydrogen should be produced using electricity from renewable resources

A basic material for industry: Hydrogen is the chemical basis of numerous products, including silanes for tire production, hydrogen peroxide for bleaching pulp, and ammoniac for the production of fertilizer

"power-to-X." In other words, the aim is to store "green" energy, make it transportable, and use it in a variety of applications. Hydrogen makes this possible. It can be produced directly at the sites where renewable energy is inexpensive to produce. It's easy to store it and transport it to distant consumers via pipelines. And depending on the user's needs, it can be burned, used as a material or reconverted into electric current.

A HUNGRY MARKET

Hydrogen has a wide variety of possible applications. For example, cars powered by fuel cells can already drive further on one tank filling than most battery-powered cars and—unlike plug-in vehicles—they can be completely refueled in a few minutes. However, they have not been commercially successful so far. At last count, only 6,558 hydrogen-powered cars were on the road in the USA; in Germany, there were fewer than 400. There still is no network of filling stations, and the technology is still too expensive and too bulky for the mass market. State-of-the-art materials could help to change this situation. For example, thanks to specialized cross-linkers from Evonik, fiber-reinforced plastics can be used to make safe hydrogen storage tanks for vehicles and filling stations that are significantly lighter and cheaper than the gas containers available today.

This technology could become established for commercial vehicles sooner than for cars. Regular-service buses, for example, always use the same filling station, weigh about 20 tons with a full load of passengers, and have a purchase price of more than €200,000. So the present-day disadvantages of fuel cells play a lesser role. The situation of trains is similar: According to a study conducted by the German Aerospace Center, hydrogen-powered trains are the best option for replacing diesel-powered locomotives, especially on long branch lines without overhead wires. Germany's first hydrogen-powered train is already making regular runs in the region around Cuxhaven. Shipyards are also trying out this technology. Norway aims to convert its many ferryboats to fuel-cell operation. And even the aviation industry hopes that hydrogen will one day be driving normal turbines by means of fuel cells or after being processed to form methanol and then kerosene.

Meanwhile, large fuel cells for reconversion are currently attracting interest as buffers for the power grid, and several producers of heating systems are offering small devices that supply households with both electricity and heat.

But the greatest hunger for hydrogen can be found in industrial companies—especially among steel producers. According to its sector association, Germany's steel industry could be operating completely CO_2-neutrally by 2050. What's more, it probably needs to do so if it doesn't want increasing penalties for CO_2 emissions to force it off the global market altogether. Thyssenkrupp plans to use hydrogen to reduce the emissions from its blast furnaces and make the remaining waste gases usable for chemical products. More on page 16 →

Global Pioneers

Some countries make use of hydrogen only sporadically, while others are developing ambitious master plans. Six countries, six strategies:

JAPAN

Japan has long been known as one of the most ambitious advocates of a hydrogen-fueled future, especially in the mobility sector. The country's government aims to lower the price of hydrogen by 90 percent by 2050, thus making it cheaper than natural gas. A crucial part of this plan will be a project in which hydrogen is extracted from lignite in Australia, the resulting CO_2 is sequestered underground, and the hydrogen is then shipped to Japan. Japan, which has few fossil raw materials, already imports more than 90 percent of its energy supply from abroad.

NETHERLANDS

The Netherlands decided to end its extraction of natural gas in 2022. Since then, the country has been preparing its northern region around the city of Groningen to become Europe's future "Hydrogen Valley." The plans call for green power from offshore wind parks in the North Sea to generate enough hydrogen for industry, the region, and the export trade. The Netherlands, formerly the EU's biggest natural gas supplier, could in the future use its freed-up pipelines to also supply its neighbors with hydrogen.

NORWAY

In Norway, plans call for trucks and ferryboats to soon be fueled with hydrogen. Norway may also play a significant international role in the use of blue hydrogen, because the government in Oslo is forging ahead with the large-scale construction of CO_2 storage sites. After decades of extracting and exporting oil and natural gas, Norway has huge underground capacities that are ideally suited to storing large volumes of greenhouse gases from all over Europe.

SAUDI ARABIA

In countries that extract oil and natural gas, such as Saudi Arabia, the production of gray hydrogen from natural gas is particularly economical. According to the IEA, the production of blue hydrogen, in which carbon dioxide arises and is sequestered underground, is also cheaper here than anywhere else. The multinational oil corporation Saudi Aramco opened the country's first hydrogen filling station in mid-2019.

USA

In the United States, California in particular is setting stringent goals regarding climate protection and energy standards. That's why it also has the most ambitious plans for a future hydrogen economy. California's government aims to open at least 1,000 in-state hydrogen filling stations by 2030 and register a million hydrogen-powered vehicles by that date—figures that the Chinese aspire to for their country as a whole. Thanks to the USA's local shale gas production, gray hydrogen is cheaper there than it is in many other countries. That makes the shift to green hydrogen less attractive, unless there is state intervention in pricing.

SOUTH KOREA

Last year Seoul published particularly ambitious goals, especially for the mobility sector. South Korea aims to become a leading producer of fuel cells and hydrogen-powered vehicles by 2030. According to the Ministry of Transportation, all of the country's commercial vehicles will have been converted to hydrogen drive systems by 2035. The hydrogen supply will be secured by the construction of the world's biggest liquid hydrogen plant in the harbor city of Ulsan.

"Our customers want concrete answers regarding the CO_2 backpack that our products are dragging around with them"

AXEL KOBUS, HEAD OF THE PROCESS TECHNOLOGY AND ENGINEERING BUSINESS LINE AT EVONIK

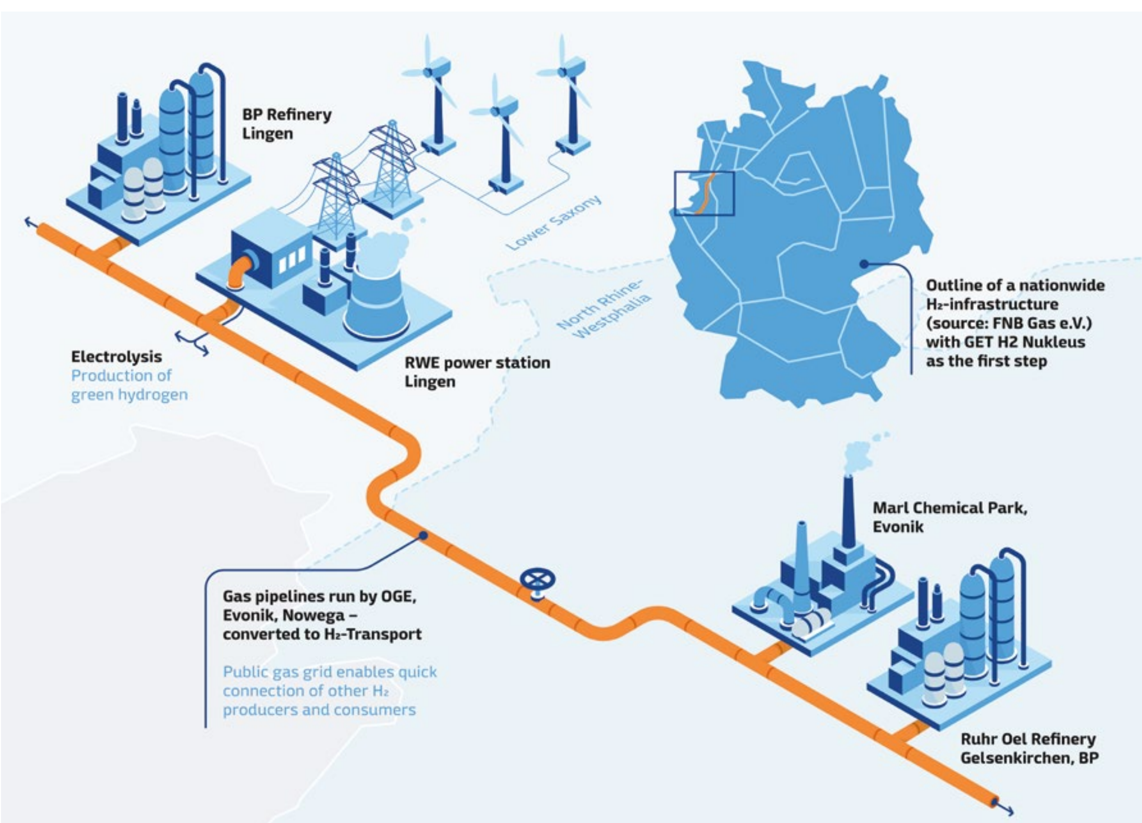
Carbon2Chem, a development project in which Evonik is participating, is searching for ways to manufacture chemical precursor products from burned carbon. For the long term, however, almost all steel producers are focusing on the direct reduction process, which thanks to hydrogen operates completely without carbon and coke.

This technological transition will cost Thyssenkrupp about €10 billion in the coming decades, according to the experts at the group's headquarters in Duisburg. And the volumes of hydrogen that will be needed for this transition are gigantic. "Around 2050, we will need about eight billion cubic meters of hydrogen per year," says Jens Reichel, who heads the Sustainable Production unit at Thyssenkrupp. According to Reichel, in order to produce this volume of hydrogen via electrolysis, 40 terawatthours of energy are needed. That's the approximate output of eight of the biggest Irsching 5 natural-gas power plants or about 3,800 offshore wind turbines in the three-megawatt class.

A BOOST FOR ELECTROLYSIS

This has been a tremendous spur for the developers of efficient electrolytic processes. The oldest, and so far the most frequently used, technology for hydrogen production by means of electricity is alkaline electrolysis. A newer technology called Proton Exchange Membrane (PEM) electrolysis has been gaining ground for about two decades. Other processes, such as solid oxide electrolysis, promise to be even more efficient but are still objects of research. Evonik too is working on key materials for new processes (see the article starting on page 28).

According to the IEA, currently less than 0.1 percent of the hydrogen produced around the world comes from electrolysis. The expansion of these capacities has begun. Since 2000, the IEA's database has registered more than 300 hydrogen projects that are either under construction or in the planning stage. Most of them are in Germany. Recently, however, new electrolysis facilities have on



A CORE BUSINESS
The GET H2 initiative, in which Evonik is participating, is forging ahead with the Nukleus project, which aims to transport hydrogen produced using wind energy to various industrial users through a 130-kilometer-long existing pipeline.

A desert dream: In the future, large volumes of hydrogen could be produced in sunny regions such as North Africa and then transported to consumers via pipelines or tank containers

average had a capacity of just one megawatt. In the town of Wesseling near Cologne, Shell is building the world's biggest electrolysis facility, which will have a capacity of ten megawatts. The IEA estimates that the next generation of such facilities will deliver 100 megawatts or more. However, ten of these facilities would be needed in order to supply a single steel mill with hydrogen. A number of experts are therefore skeptical as to whether Germany can cover its predicted hydrogen requirements soon enough by means of electrolysis.

Added to these technical hurdles are economic ones: "Green" hydrogen is currently about three times as expensive in central Europe as "gray" hydrogen derived from natural gas. Because modern steam reformers like the one in Marl supply hydrogen efficiently and reliably, and because hydrogen is essential to the creation of the network, many experts in the sector believe that these steam reformers will have to play a crucial role in the medium term. The carbon dioxide generated in the process could be captured and stored. Hydrogen produced in this way is referred to as "blue" hydrogen. On a large industrial scale, this storage might take place in the underground reservoirs that remain after the extraction of natural gas. However, such caverns exist in only a few regions, and the technology itself is controversial (see the debate on page 22).

Another possibility is to capture and process the CO_2 that is emitted. For example, instead of hydrogen and carbon dioxide the steam reformer in Marl could also produce synthesis gas, which is a mixture of hydrogen and carbon monoxide—a common precursor product for the chemical industry. Evonik itself is working on a whole series of research projects that aim to use industrial waste gases to produce valuable intermediate and special products for the chemical industry in small modular plants. For example, Evonik is cooperating with the power plant operator STEAG and the University of Duisburg-Essen on the Vulcanus project, which is developing a new process chain that uses carbon dioxide and methane to produce higher alcohols for the production of high performance polymers.

COLD-PRESSED

In the future, industrialized countries may also be able to import more and cheaper hydrogen from renewable sources, for example from North Africa. The Desertec project was launched there more than a decade ago. The original aim was to transport solar and wind energy from the Sahara via direct-current lines through the Mediterranean to Europe. This aim was not achieved. The new hope is that the energy from the Sahara, in the form of green hydrogen, could be delivered to consumers by ship or by pipeline.

On principle, it's easy to transport hydrogen, but not every means of transportation is efficient. Because of the extremely low density of this gas, even 40-ton trucks with their impressive white high-pressure tanks can →

carry only about 300 kilograms of hydrogen. That's only a little more than the permissible load of a smart. Even the largest available tank trucks can transport a maximum of 1.1 tons of hydrogen at a pressure of 500 bar.

The low density of hydrogen also creates problems related to storage. In chemical parks such as the one in Marl you can find lots of gasometers and big pressurized containers full of oxygen, nitrogen, methane or ethylene, but you would look in vain for big tanks of hydrogen. Hydrogen can be compressed into cost-effective tank volumes only under tremendous pressure. It's true that hydrogen can be stored in the underground cavities that are left behind after the extraction of salt or natural gas. However, just like natural CO_2 storage facilities, they can be found in only a few regions. Hydrogen can be stored in a liquid, and thus especially compact, form only at a temperature of -253°C. That requires a great deal of cooling energy and elaborate insulation.

On the move: In northern Germany, hydrogen trains are already running regularly. The HY4 test aircraft with a fuel-cell motor made its maiden flight in 2016

"The only really efficient way to distribute hydrogen is via pipeline," says Thomas Basten, who heads Evonik's logistics business involving pipelines for all kinds of industrial gases and liquids. The Group operates more than 2,000 kilometers of pipelines all over Germany, three quarters of them under contract for other companies. In this function, Evonik is a participant of an initiative called GET H2, which is planning a public hydrogen network for Germany. The plans call for the network's "core" to initially be a 100-megawatt electrolysis facility that is being planned by the RWE power company in the town of Lingen—that's why the project is called Nukleus. Here in the Emsland region, not far from numerous wind farms in the countryside and in the North Sea, plans call for generating hydrogen by means of wind power.

RWE aims to transport this wind energy in the form of green hydrogen to industrial consumers by means of pipelines. One of these consumers is the BP oil refinery on the site; others are located in the Marl Chemical Park in North Rhine-Westphalia (see the graphic on page 16). A 130-kilometer-long steel pipeline could easily deliver up to 100,000 cubic meters of hydrogen per hour and help to supply consumers in the region. Best of all, a connection of this kind already exists, and it's partly operated by Evonik. These are pipelines that in some cases have become available because the Netherlands has discontinued its natural-gas business; these pipelines can be converted for carrying hydrogen.

HYDROGEN ON PIGGYBACK

"The pipeline business is not for poor people," says Basten. Laying pipelines has always been an expensive enterprise. In particular, fulfilling the bureaucratic requirements consumes a great deal of resources. That makes the use of existing pipelines an attractive option. Germany currently has approximately 50,000 kilometers of high-pressure pipelines for natural gas. If green electricity in the form of hydrogen is flowing through parts of this infrastructure, it might be unnecessary to build additional power lines.

At Evonik, this idea is being developed even further: Thanks to a Group-owned membrane technology, some parts of Germany's many-branched natural-gas distribution network, which is 500,000 kilometers long, could be repurposed. Commercially available natural gas already contains a low percentage of hydrogen today. However, more hydrogen could also flow through these pipelines in piggyback fashion without any problems. At various points in the network, SEPURAN® membranes from Evonik could be used to divert hydrogen for supplying filling stations or other consumers, for example.

In order to finally make the vision of a hydrogen economy a reality after 150 years, many factors have to come together: The network, the supply system, the de-

For home use: The Daimler automotive group is further developing fuel-cell technology for stationary power plants

mand, and the technology—all of these factors must develop in parallel while the price of green hydrogen decreases. This is where national governments must step in. "Everyone's waiting to see the German government's national hydrogen strategy," says Basten. "It would have to exempt hydrogen electrolysis facilities from the EEG-surcharge, change the energy industry law to permit the transportation of hydrogen in public networks, and create incentives for consumers to use green hydrogen." It's important to coordinate national planning and international partnerships. Evonik too wants to combine its numerous activities related to hydrogen within a comprehensive strategy. The Group's experts are feeling the growing pressure of the market. "Our customers want concrete answers regarding the CO_2 backpack that our products are dragging around with them," says Axel Kobus, the process technology engineer who is responsible for Life Cycle Management, among other things.

That's why the Group's hydrogen peroxide department in particular is considering when and how it can procure green hydrogen at market-appropriate prices—and how it can capture and process its own steam reformers' carbon dioxide emissions until then.

Unlike the steel industry and the energy business, the chemical industry is not aiming to exclude carbon from these processes. Carbon is a basic component of chemical products, and for that reason alone it's much too valuable to be burned and blown into the sky, says the Creavis manager Oliver Busch. "The ideal we are working on in the chemical industry is closed material cycles. Hydrogen offers us the unique opportunity to close material and energy cycles simultaneously." Now it's only a matter of putting together all the pieces of the puzzle.

"The pipeline business is not for poor people"

THOMAS BASTEN, HEAD OF EVONIK'S LOGISTICS BUSINESS INVOLVING PIPELINES

THE COLORS OF HYDROGEN

GREEN HYDROGEN
If hydrogen is produced via electrolysis using renewable energy, no CO_2 is generated.

GRAY HYDROGEN
About ten tons of carbon dioxide are generated for each ton of hydrogen produced in steam reformers using fossil energy carriers such as natural gas.

BLUE HYDROGEN
The carbon dioxide from steam reformers can be captured and compressed in underground cavities, usually former storage facilities for natural gas. This process is controversial.

TURQUOISE HYDROGEN
In methane pyrolysis, biogas or natural gas is cracked in a reactor with liquid metal. This generates only hydrogen and solid carbon, which can be stored or used. This method is the object of research.

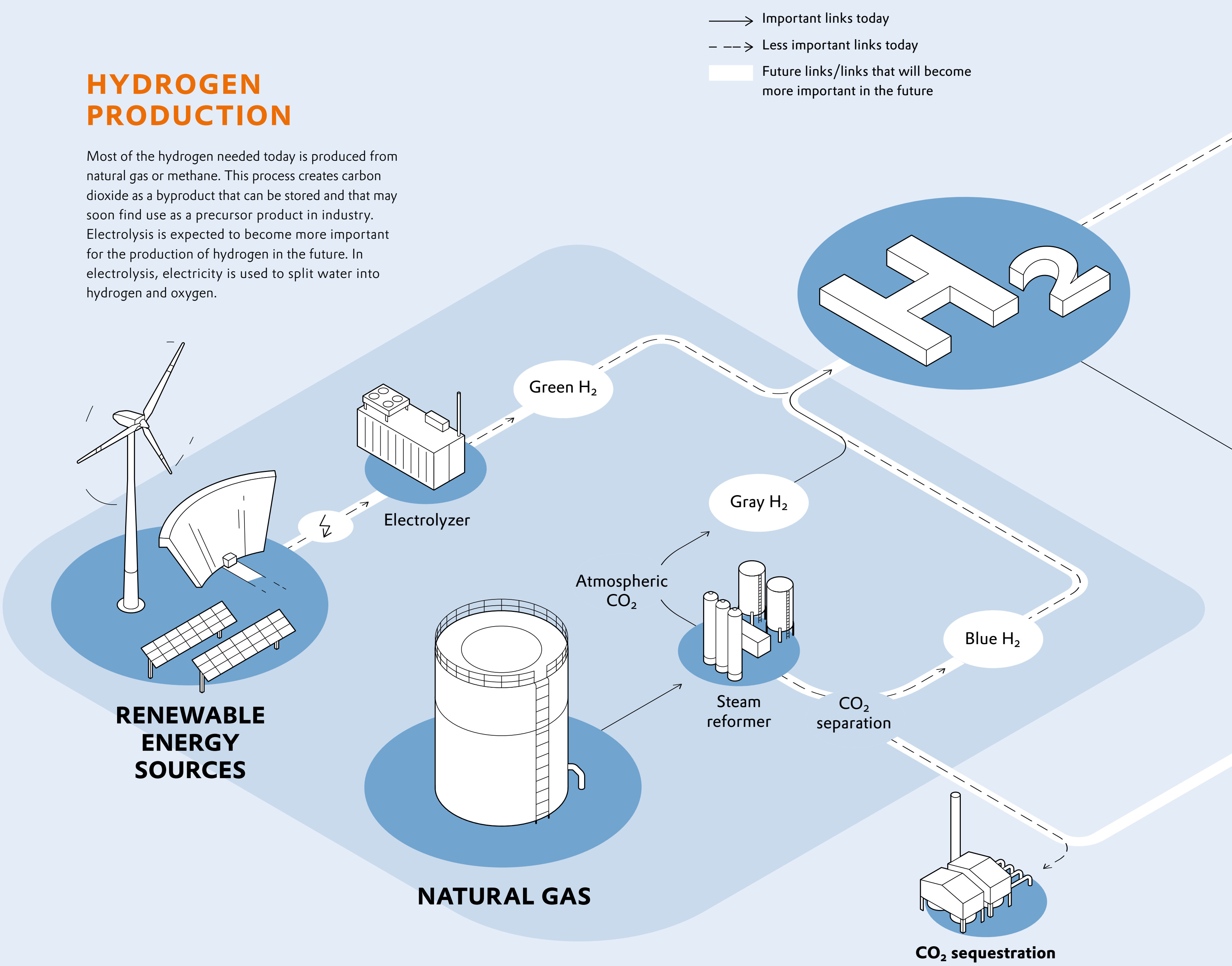
A System for Tomorrow

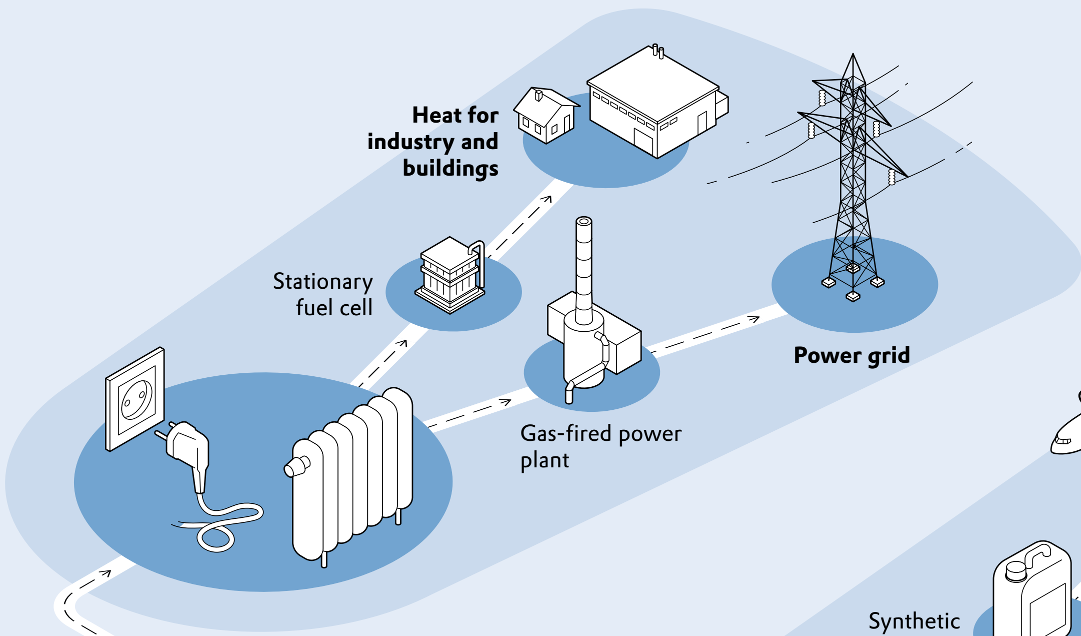
Hydrogen is already being used today in the energy sector, industrial applications, and drive systems. Although this sometimes occurs on a large scale, its use is often still restricted to tests and small numbers of units. This overview shows the economic potential of this gas—from its production and processing to its use

INFOGRAPHIC **MAXIMILIAN NERTINGER**

HYDROGEN PRODUCTION

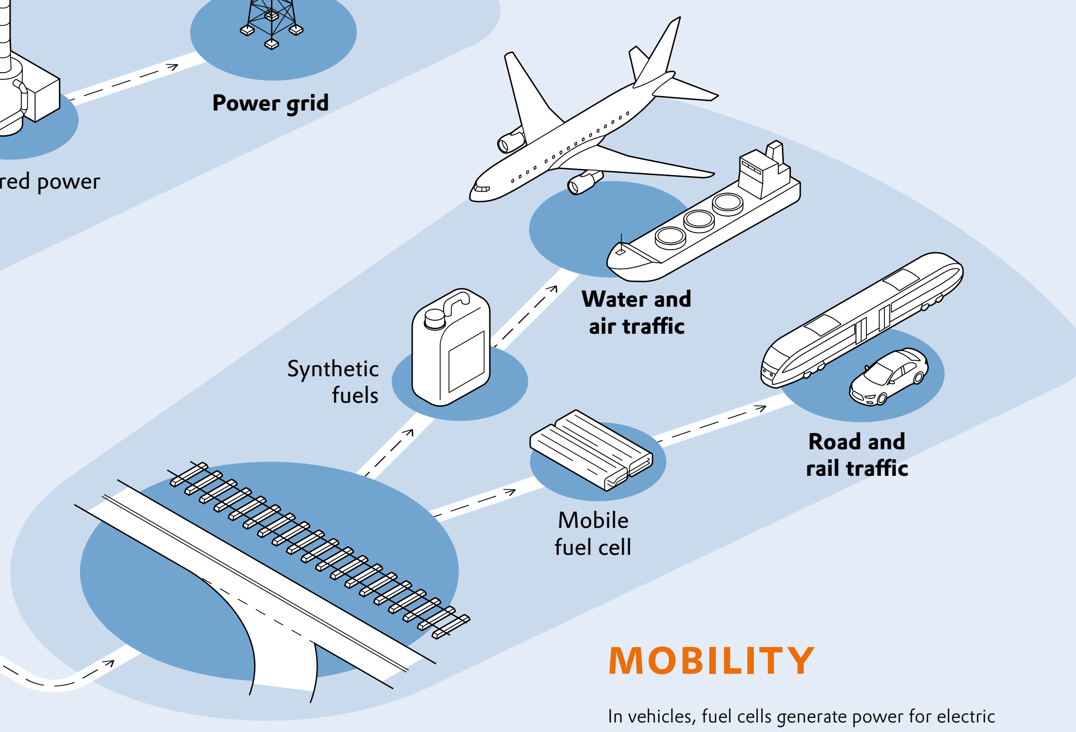
Most of the hydrogen needed today is produced from natural gas or methane. This process creates carbon dioxide as a byproduct that can be stored and that may soon find use as a precursor product in industry. Electrolysis is expected to become more important for the production of hydrogen in the future. In electrolysis, electricity is used to split water into hydrogen and oxygen.





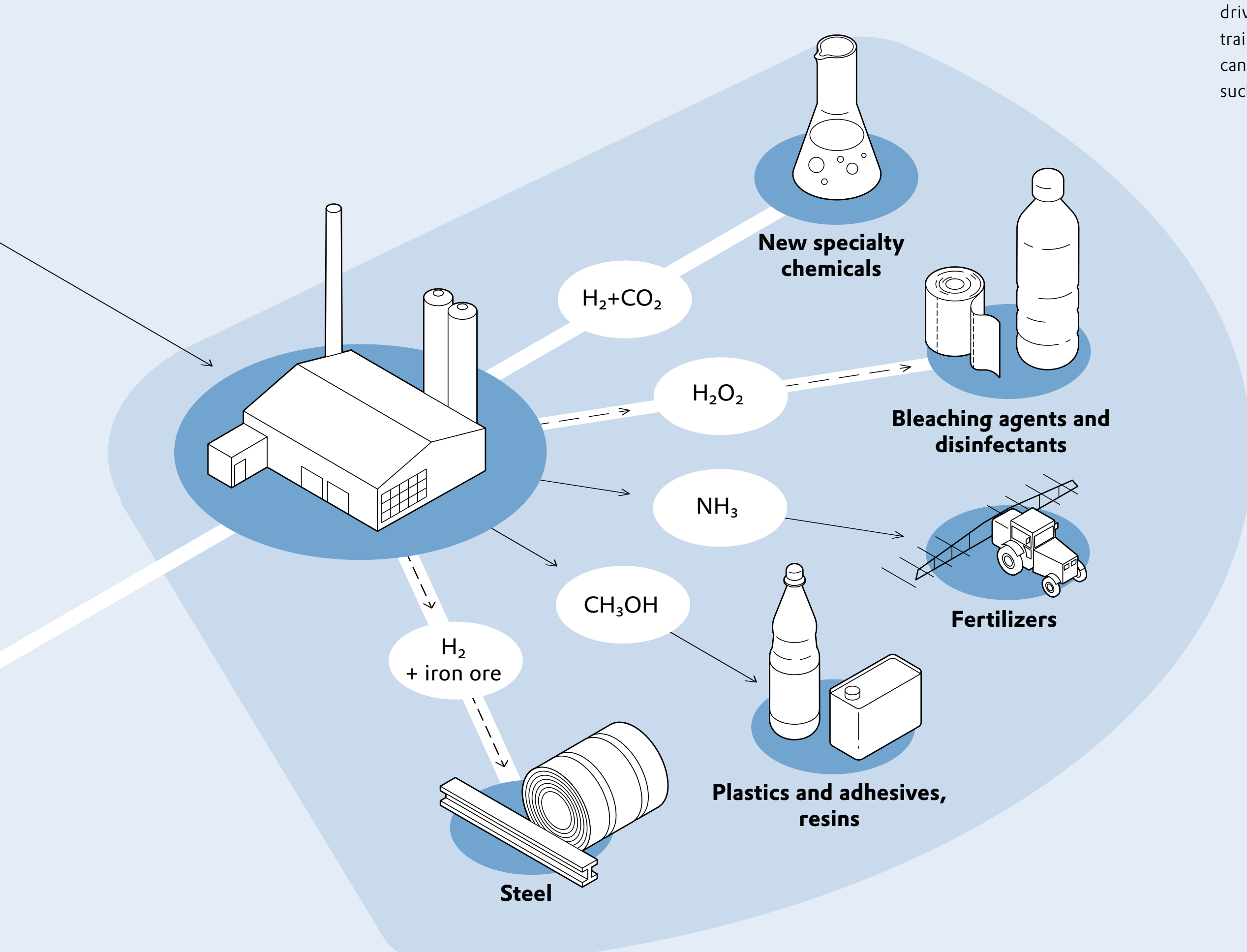
POWER AND HEAT

Fuel cells can supply buildings with energy. The reaction of oxygen and hydrogen produces heat and electricity. Some gas-fired power plants are already replacing natural gas with hydrogen fuel. In this way, hydrogen is indirectly serving as a power storage system.



MOBILITY

In vehicles, fuel cells generate power for electric drive systems. This works especially well in trains, trucks, and buses. Hydrogen-based fuels can be used wherever low weight is important, such as in aviation.



INDUSTRY

Hydrogen is already being used to produce ammonia (NH_3) and methanol (CH_3OH), which can be found in many products. Hydrogen peroxide (H_2O_2) is becoming increasingly important, as is the use of hydrogen for the reduction of iron ore in the steel industry and, in combination with carbon dioxide (CO_2), for specialty chemicals.

"We need to reduce emissions to zero as soon as possible"

HANS-JOSEF FELL,
PRESIDENT OF THE ENERGY WATCH GROUP

"Ideological prescriptions won't help us make progress"

JORGO CHATZIMARKAKIS,
SECRETARY GENERAL OF HYDROGEN EUROPE

The President of the Energy Watch Group, Hans-Josef Fell, is calling for the almost exclusive utilization of green hydrogen from renewable sources. Jorgo Chatzimarkakis, Secretary General of the industrial association Hydrogen Europe, believes this is not enough. A debate

INTERVIEW
TOM RADEMACHER, JÖRG WAGNER
ILLUSTRATION
ORIANA FENWICK

Mr. Chatzimarkakis, Mr. Fell, not too long ago the International Energy Agency predicted a breakthrough in the utilization of hydrogen. Today practically the only things we're talking about are the effects of the coronavirus pandemic on the economy and our society. Are you worried about the fact that the vision of a hydrogen economy is slipping off the political agenda?

HANS-JOSEF FELL I've been hearing bulletins about the imminent breakthrough of hydrogen for the past 25 years. The last big hype occurred in 2000 or thereabouts. Unfortunately, not much has been happening. And I feel skeptical, especially right now, about whether a breakthrough will happen as fast as we would need it to happen. Since the oil prices are relatively low at the moment, there's even less motivation to switch to other forms of energy—especially now that the coronavirus has pushed the prices of emissions certificates into the cellar.

JORGO CHATZIMARKAKIS I believe that this crisis is offering us the opportunity to speed up the system change to hydrogen. We've just had an online conference with the Executive Vice President of the European Commission, Frans Timmermans. What came out of that conference is a very concrete plan for 80 gigawatts of capacity for the production of green hydrogen from renewable power sources: 40 gigawatts in Europe and 40 gigawatts in Africa. This plan would probably not have materialized so quickly without the big post-corona Marshall Plan that is being put together in Brussels right now. It's true that we've tumbled down very drastically from some of our previous hyped-up high points. But the technology has now reached maturity. I drive a hydrogen-powered car in my everyday life.

What role will hydrogen play in future energy consumption?

FELL Green hydrogen will play an important role in the transition to a 100 percent supply from renewable energy sources, especially for the cross-sector linkage—in other words, the connection between environmentally friendly energy generation and heating systems, transportation, and industry. We need green hydrogen as a long-term storage option for green electricity and the decarbonization of industries. The core strategy for climate protection and for a zero-emissions economy is a quick and complete transition to renewable energy sources. That ultimately means a 90 percent share of green energy. Unfortunately, this expansion is being massively obstructed in Germany, especially by the national administrations led by Angela Merkel.

CHATZIMARKAKIS Mr. Fell, I agree with you that we have to hurry up and reduce emissions to zero. However, I have a problem with the ideological demand for a 90 percent share of green power. Renewables are not being neglected, and certainly not in Brussels. However, today 20 percent of our energy needs in Europe are covered by electrons and 80 →

"If we prohibit blue hydrogen, we're closing off the path to decarbonization for industry"

JORGO CHATZIMARKAKIS

percent by molecules—in other words, by fossil fuels. Simply switching these percentages around means that we would have to make massive investments in cables and batteries. These are things we simply don't have yet, and I'm not even talking about the political authorization structure. So let's open up new channels for renewable energies by transforming them into molecules—that is, hydrogen—and transporting them via existing gas pipelines.

FELL Energy that is completely generated from renewable sources has nothing to do with ideology, Mr. Chatzimarkakis—this is natural science. The USA's National Aeronautics and Space Administration (NASA) announced in January that the Earth's climate had already heated up by 1.2°C. In other words, we will already have passed the 1.5°C mark in 2032. At that point we can no longer afford to release any more emissions into the atmosphere. I'm a big supporter of using existing infrastructures for renewable energies, including the natural gas infrastructure. However, we cannot afford to continue running the fossil-fuel economy—via blue hydrogen, for example—because then we will not be protecting the climate. On the contrary.

Blue hydrogen is derived from natural gas. The CO_2 that is released in the process is captured and sequestered underground, for example in old natural-gas storage reservoirs. Mr. Fell, why do you feel that the hydrogen decarbonized in this manner is not a climate-friendly solution?

FELL Because the hydrogen generated from natural gas brings immense methane emissions in the upstream chain—for example, as a result of leaks during its extraction and transportation. And methane's effect on the atmosphere is 80 times more intense than that of carbon dioxide. At the Energy Watch Group we recently compared the emissions of a new natural-gas power station with those of a coal-powered one. If we calculate in the methane emissions, the natural-gas power station is not one bit cleaner than the coal-powered one. And if the natural gas comes from fracking, the greenhouse gas emissions increase by as much as 40 percent. If we use natural gas as the source of blue hydrogen, we don't need to talk about climate protection any more.

CHATZIMARKAKIS We can get to grips with the methane leaks. Unfortunately, they mainly occur in regions where EU law does not apply: in Russia and the USA. But we can use an import duty on products with a high CO_2 load to put the necessary pressure on the sourcing countries. Mr. Fell, you've just warned that we have to act quickly in view of the looming climate crisis. Blue hydrogen will help us to do exactly that. Steel companies could decarbonize their production processes by up to 95 percent, or even completely, by using hydrogen instead of coking coal. However, this hydrogen is not yet available in a form that is produced from renewable energy sources. If we prohibit blue hydrogen, we're closing off the path to decarbonization for industry—including the chemical industry, by the way.

Mr. Fell, doesn't blue hydrogen at least have a justification as a stopgap technology?

FELL No investment in greenhouse gas-emitting technologies helps to protect the climate. Blue hydrogen does not decarbonize, due to the methane emissions in the upstream chain. Besides, you also have to invest in the CO_2 sequestration. All of this means throwing away insane amounts of money and thus ultimately prolonging the survival of greenhouse gas-emitting sectors such as the natural gas industry. It's far better to focus all our efforts on investing in zero-emissions technologies! That will trigger a tremendous surge of innovation. And then we won't need this outrageously expensive stopgap solution at all.

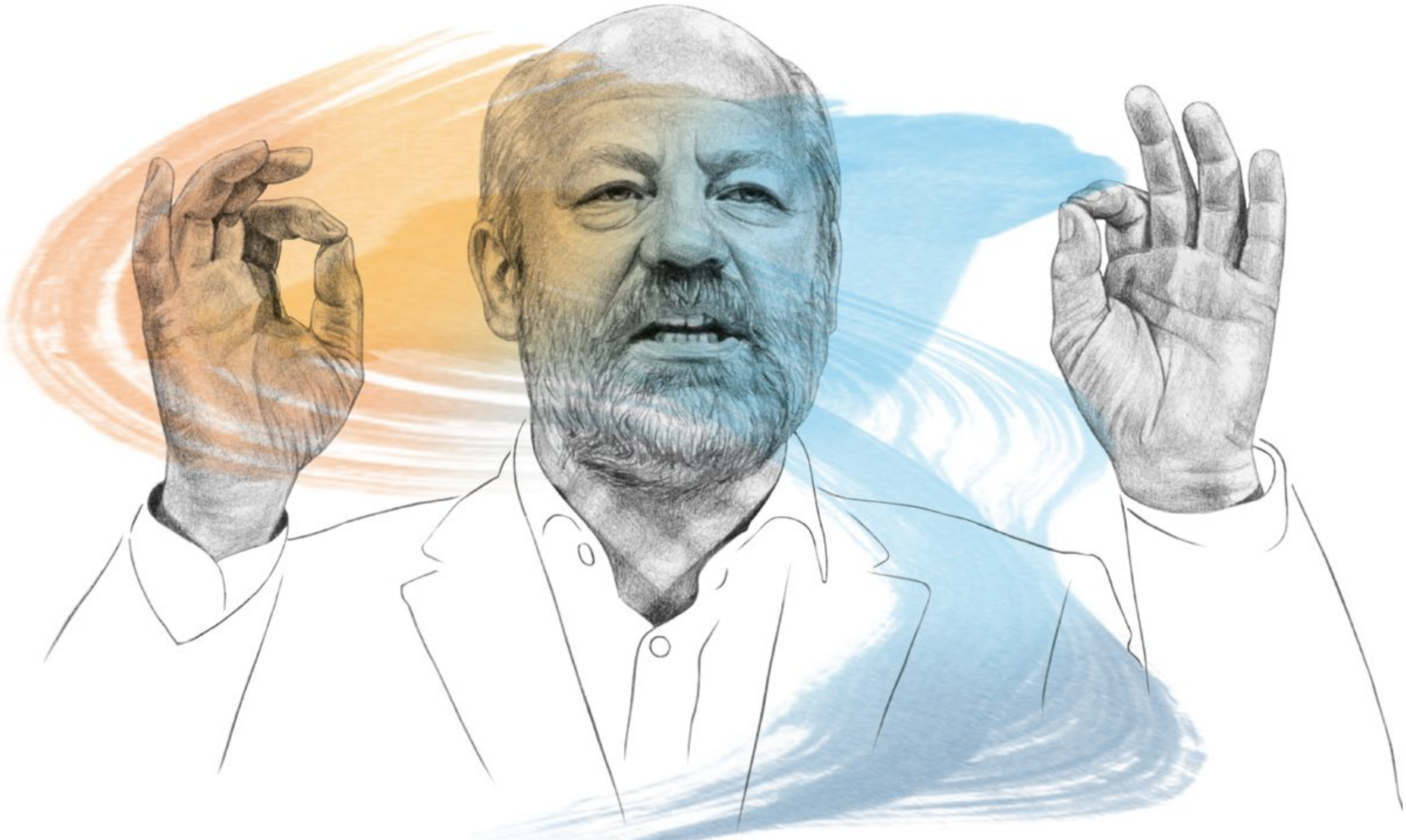
Georgios "Jorgo" Chatzimarkakis was born in Duisburg in 1966. He has degrees in agronomy and political science and a German as well as a Greek passport. Among his other accomplishments, Chatzimarkakis was an FDP-aligned member of the European Parliament for ten years. During the Greek financial crisis of 2014, he served briefly as the Special Ambassador of the Athens government. By his own admission, the Chernobyl catastrophe spurred his entry into politics in 1986. Since 2016, Chatzimarkakis has been the Secretary General of Hydrogen Europe, an association of approximately 160 members from numerous sectors, including automakers, technology companies, and energy providers. Chatzimarkakis is married with four daughters and drives a hydrogen-powered car.

CHATZIMARKAKIS Even the Intergovernmental Panel on Climate Change (IPCC) says in its latest report that we don't have the time to wait for renewable energies. We have to use all of our available technologies right now—and the IPCC expressly mentions CO_2 sequestration. If we use this technology now, and if major companies enter the hydrogen economy, significant volumes of hydrogen will quickly enter the system.

Norway is planning to sequester carbon dioxide on a large scale in old natural-gas storage reservoirs, and Japan plans to import blue hydrogen made from Australian coal. Are other countries overtaking Germany because they have fewer reservations regarding blue hydrogen?

FELL Japan is moving in the wrong direction, and not only because of climate change. You're heading into a system that requires gigantic streams of capital and huge volumes of energy for extraction, transportation, and processing operations. Today only a few countries are pursuing a zero-emissions agenda that includes green hydrogen. So I don't see anyone overtaking us.

CHATZIMARKAKIS I have a different opinion. I, for one, see the threat of other countries passing us by. For example, the Chinese are making grander announcements every day, about their switch to automobiles powered by fuel cells, for example. Asian countries are now implementing their system change—with blue or gray hydrogen, if necessary. We Europeans are standing by like a bunch of losers. The same thing could happen with power-to-gas... →



Hans-Josef Fell was born in Hammelburg in Lower Franconia in 1952 and was a physics and sports teacher at a college preparatory high school for 20 years. From 1998 until 2013, he was a member of the German Bundestag representing Alliance 90/The Greens. He acted as the parliamentary group's speaker for research and energy policy for many years. He is regarded as one of the fathers of the Renewable Energy Sources Act (EEG). In 2006 Fell founded the Energy Watch Group (EWG), an independent worldwide network of scientists and parliamentarians that commissions studies on energy-related topics. He has been the President of the EWG since 2014. Fell is married and has two sons and a daughter. He lives in a wooden house that is completely powered by renewable energy. The family's cars run on solar power and sunflower oil.

...in other words, energy storage by means of hydrogen.

CHATZIMARKAKIS Exactly. Today we're still leading the global market. But we have to make sure we don't delay and obstruct with well-meaning policy due to the fact that we're demonizing a technology that can help us get the market up and running.

Mr. Chatzimarkakis, if blue hydrogen is only useful as a stopgap technology, what does your strategy for exiting from it look like?

CHATZIMARKAKIS Mr. Fell is absolutely right when he says that the decarbonization of blue hydrogen costs a lot of money. In the future it may become even more expensive. We can even establish policies that define this increase, as well as the decrease in the costs of green hydrogen. At some point, industries would make the switch, purely because of their own economic interest.

FELL My experience tells me something different—namely, that the greenhouse gas-emitting technologies will gain the upper hand and thwart the expansion of alternatives.

What would a smart policy for promoting the right kind of hydrogen look like, Mr. Fell?

FELL The most important element would be framework conditions that encourage private companies to profitably invest their capital in zero-emission technologies. The model for that is the German Renewable Energy Sources Act and the fixed rate of feed-in remuneration. These things have strongly stimulated investments. First came private individuals with their solar panels, followed by cooperatives with wind turbines, and then industry caught up.

Why are you against a tax on carbon dioxide emissions such as the one that was passed in Germany? It would certainly help to price in the external costs of protecting the climate.

FELL If the price of oil drops precipitously, as it is doing this spring, a CO_2 tax is worthless, and if it

“In the past I’ve seen oil companies simply greenwashing themselves over and over again”

HANS-JOSEF FELL

doesn’t include methane, it’s less than worthless. Setting a price on carbon dioxide can make sense in individual cases, but the effect of that always depends on other market developments. That’s why it shouldn’t be our most important tool.

CHATZIMARKAKIS The German price for CO_2 is really a joke. Switzerland is doing things better. Both of the major Swiss retail chains are now investing in 1,600 hydrogen-powered trucks, and they are doing this voluntarily because this is cheaper for them than paying the CO_2 tax would be.

FELL Yes, the Swiss have had their CO_2 tax for a long time now, and everyone is praising it. Nonetheless, they won’t reach the emissions reduction target they’ve set for themselves—which is only 20 percent.

Mr. Chatzimarkakis, your association also represents conventional energy companies. Are these companies really interested in expanding the hydrogen economy?

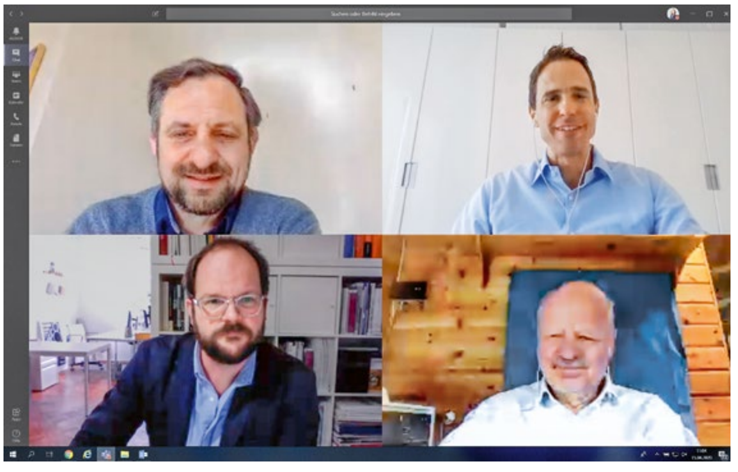
CHATZIMARKAKIS Shell was one of the first strong players in the area of hydrogen. Shell needs hydrogen itself, for its refineries and for other processes. So does BP. Shell is currently implementing its NorthH2 project for the ten-gigawatt offshore production of hydrogen from wind energy. Its total investment in this project is €15 billion. That refutes the argument that the fossil-fuel industries are relying on blue hydrogen to safeguard their future, Mr. Fell.

FELL I’m happy about Shell’s green hydrogen project, but in the past I’ve seen oil companies simply greenwashing themselves over and over again. Even though it costs €15 billion, it’s still a green fig leaf. That’s because the companies are basically holding on tight to their business model, which is based on fossil carbon. If a crisis occurs, like the coronavirus pandemic we are experiencing today, it will be accompanied by the demand that everything else should be put on hold. The Economic Council to the CDU political party in Germany has just called for a reduction of the climate protection goals.

CHATZIMARKAKIS I absolutely agree with you on that. I think that the calls for rolling back climate protection goals are disruptive. Those who make such demands are guilty of an offense against future generations. But the major project of the European Commission, the Green Deal, is controlled in Brussels. Mr. Fell, I cordially invite you to visit us and take a look at what we’re starting up here. But before that can happen, we have to be able to travel again.

Distanced debate

How can you have a debate via a videoconference? Quite well, as it turns out. The *Elements* talk between Jorgo Chatzimarkakis and Hans-Josef Fell took place in mid-April, at the preliminary peak of the coronavirus pandemic in Europe. That’s why it was moved to a virtual conference room at short notice, although the original plans called for a lively discussion with a small group of participants in Essen. This experience is being shared by millions of people who can see their colleagues, family members, and friends only on the monitors of their laptops during these weeks. Jerky video images, cut-off audio, views of strangers’ studies and bookshelves, children screaming in the background—these may be our memories of the working world of 2020. This ultimately became an exciting discussion between two experts who are striving to reach a shared goal via very different routes. And the circumstances of this talk made it clear to everyone involved that in spite of our differences of opinion all of us are sitting in the same boat.



UNDER POWER

Huge amounts of green hydrogen will be needed to create a sustainable economic system. As a result, Evonik is working together with partners to develop a new membrane that will make environmentally friendly water electrolysis competitive

TEXT **GEORG DAHM**

"This technology combines the advantages of previous electrolysis processes"

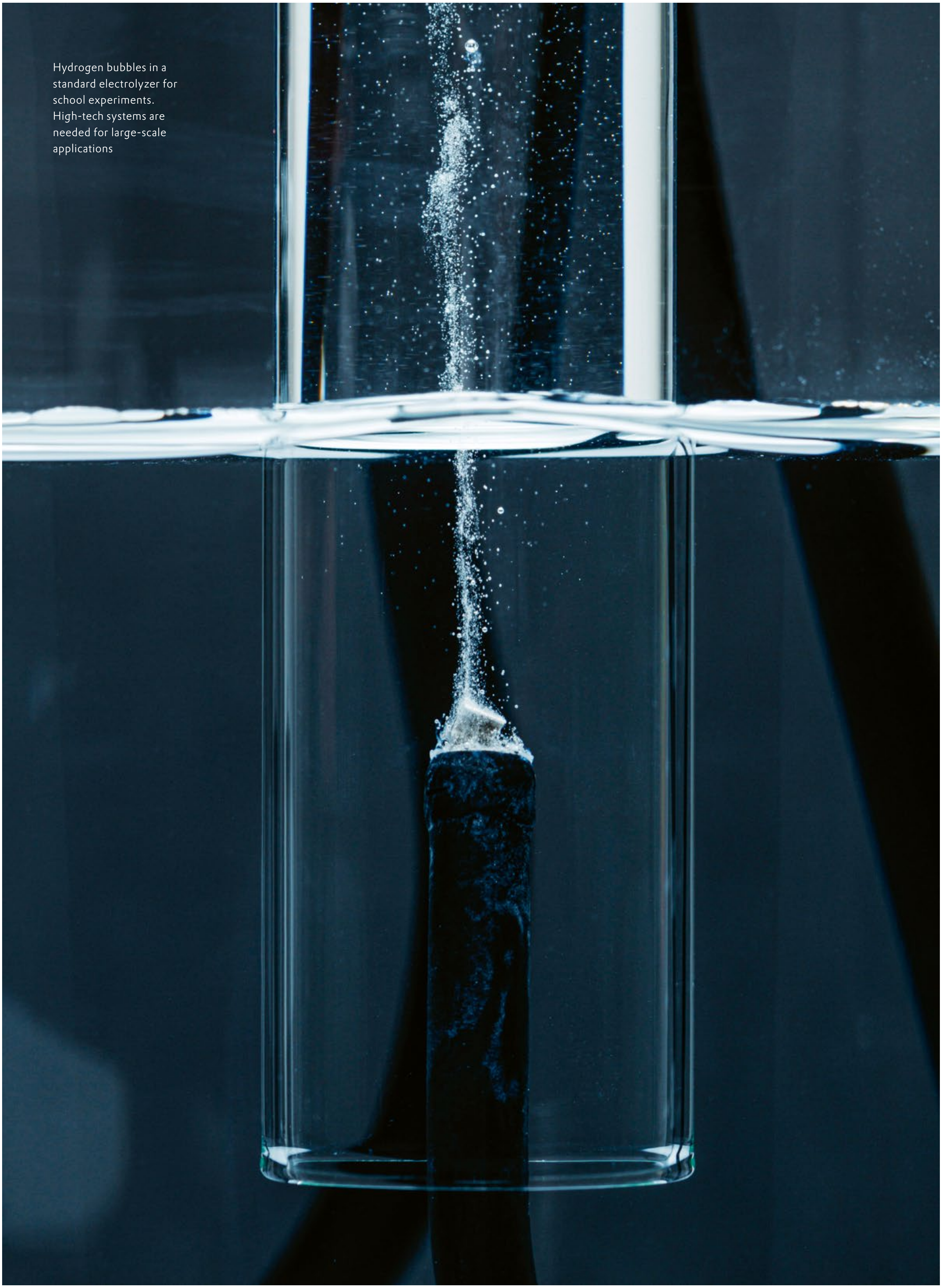
OLIVER CONRADI, CREAVIS

Sebastian-Justus Schmidt became an energy entrepreneur by accident. Since 2014, Schmidt, who owns an IT firm, has been supplying his sustainable estate in Thailand with hydrogen that is produced with green electricity. The associated electrolyzer comes from the Italian startup Acta. Although the system worked wonderfully, Acta's German parent company went bankrupt in 2017. "So we bought up the technology, took over the team, and created our own startup, Enapter," recounts Schmidt's son, Jan-Justus, Chief Operating Officer of the young family-run enterprise.

This step not only enabled the Schmidt family to safeguard the energy supply of its property but also to take a leading role in a technology that could make entire sectors carbon-neutral in the coming decades. According to experts, AEM (anion exchange membrane) electrolysis could make the production of hydrogen from renewable electricity feasible on a large scale.

"This technology combines the advantages of the previous hydrogen electrolysis processes," says Oliver Conradi, who is in charge of the Membranes innovation field at Creavis. This strategic innovation unit at Evonik is cooperating with Enapter in an EU-funded research project in order to develop new membrane materials for AEM electrolysis. "If it works as well as it already has in the lab, we will make the industrial-scale production of environmentally friendly hydrogen economically viable," says Conradi.

The collaborative project is called CHANNEL. Besides Evonik and Enapter, the participants include the energy company Shell, Forschungszentrum Jülich, and the Norwegian research institute SINTEF. Their goal is to create a demonstrator by 2022 that will prove AEM's capabilities. The project's main feature is a new ion-conducting membrane from Evonik, which is being tested in Enapter's facilities. →



Hydrogen bubbles in a standard electrolyzer for school experiments. High-tech systems are needed for large-scale applications

Enapter still makes its electrolyzer modules in Italy. However, plans call for series production to start soon in Germany

The electrolyzers can be combined into bigger systems as needed

"We have learned that we greatly benefit by working together with small companies such as Enapter because they are flexible and can very quickly try out new things," says Conradi. "Moreover, having direct contact to the people involved is very helpful when you want to validate and implement a technology."

Enapter's AEM electrolyzers aren't big systems. Instead, they look rather like server cabinets with slide-in modules arranged one on top of another. Each of these modules is a separate unit that produces half a cubic meter of hydrogen per hour. "This makes the technology so easily scalable," says Jan-Justus Schmidt, who studied aerospace engineering and is now setting up series production in Germany.

In water electrolysis, electricity is used to split water into oxygen and hydrogen. However, most hydrogen is currently still produced from carbon-based sources such as methane by means of steam reforming. This is mainly due to the fact that this traditional process is much less expensive than electrolysis (see the article on the hydrogen energy economy, beginning on page 10). "One of the reasons for this is the relatively high price of electricity," says Conradi. "Another reason is that electrolysis systems require a very high level of investment." Evonik wants to help reduce the cost of the equipment by introducing an innovative membrane technology.

PROVEN TECHNOLOGY WITH SOME WEAKNESSES

The workhorse of the established processes is alkaline electrolysis (AEL). It is the method that is most like those illustrated in schoolbooks, consisting of two electrodes that are inserted into a highly concentrated potassium hydroxide solution (pure water is not conductive enough). At the cathode, the water molecules split into hydrogen and hydroxide ions. The hydrogen rises as a gas while the hydroxide ions move through the alkaline solution to the anode, where they react to create water and oxygen. To ensure the products of the reaction remain apart and don't recombine with a bang, a porous membrane—a diaphragm—separates the anode side of the electrolyzer from the cathode side.

"The technology is robust and the cell material is pretty inexpensive," says Conradi. For example, the catalysts that cause the reactions to start at the electrodes include nickel, cobalt or iron, while the housing components are made from stainless steel. The investment costs amount to about €800 per kilowatt of power and experts think that the amount will drop to as low as €600 by 2025.

“Our technology is easily scalable”

JAN-JUSTUS SCHMIDT, COO ENAPTER

AEM technology is already being used at a residential site in Thailand

One problem with AEL is that the diaphragm is porous. This means that it lets gases through so that the possibility of operating the facility under pressure is limited. As a result, the hydrogen has to be compressed so that it can be stored and transported further, consuming a lot of energy in the process. In addition, the porous membrane can only be operated at low power densities: The diaphragm can handle a maximum of 600 milliamperes per square centimeter of membrane surface. The other well-established method, PEM (proton exchange membrane) electrolysis, can operate at three times the current density, or 2,000 milliamperes per square centimeter of membrane surface. In practice, this means that a much smaller electrolyzer can be used to produce the same amount of hydrogen.

In PEM electrolysis, membranes are more than just separators. They replace the entire bath because they consist of an electrically conductive polymer that ions can move through. The electrodes lie right on top of the membrane. In this system, the water to be split flows across the anode. The hydrogen ions that are released move from the anode through the membrane to the cathode side, where they combine to form hydrogen molecules. A PEM electrolyzer is not only operated at higher current densities than an AEL system, it can also handle greater load fluctuations. And because it can be operated under pressure, less energy is subsequently needed for hydrogen compression.

However, despite its technological advantages, the high investment costs of PEM systems pose a considerable barrier to market entry. “PEM cells operate in an acidic environment, which means that the materials need to be very robust,” says Conradi. “The catalysts have to be made of precious metals such as platinum and iridium, while the cells have to consist of titanium or even of platinized titanium. Investment costs are calculated to be €1,000 or more per kilowatt of power using today’s technology.”

HIGHER OUTPUT, LOWER COSTS

This is where the promising AEM process comes into play. Over the medium term, Evonik hopes to develop a system that costs €500 to €600 per kilowatt. An AEM cell has the same structure as a PEM cell. It can also be operated under pressure and with a high level of power output. The centerpiece of this system is also a membrane made of an ion-conducting plastic known as an ionomer. Electrodes lie on both sides of the membrane. They are also made of an ionomer and are permeated with catalyst particles. “However, AEM lets us use non-precious metals such as nickel for this purpose, which is significantly less expensive,” says Conradi. This is possible because the process operates in an alkaline environment. As is the case with the AEL process, the water is split on the cathode side. Two H_2O molecules give rise to one hydrogen molecule and two hydroxide ions (OH^-). The hydroxide ions then move through the membrane to the anode, where they react to form oxygen and water (see the illustration on page 33).

To achieve such a combination is a real challenge. “An alkaline environment is aggressive as well,” says Alejandro Oyarce Barnett from the Norwegian re- →

First it's solid, then liquid, then flexible: In the Creavis laboratory, researchers create a polymer powder (top right), which is then turned into a liquid (bottom right) that is cast into endless membranes (above)

search institute SINTEF, which chose the partners for CHANNEL and coordinates the consortium. "Developing a membrane that can operate under such conditions is no trivial matter. Only a few companies in the world can do this and Evonik is one of the key players in this field."

SINTEF operates similarly to Germany's Fraunhofer Society: The government supplies only some of its budget, as the society's business model focuses on partnerships and funded projects that produce commercially exploitable intellectual property. SINTEF now wants to forge ahead with the construction of a two-kilowatt system. It would be a first step, says Barnett: "If it works, it would be only logical to think about building a 100, 200 or even 500-kilowatt facility."

Although the membranes from the Creavis laboratory already exceed most of the team's targets, the teams are still working with prototypes about the size of an A4 format sheet of paper. Before the material can be series-produced in endless sheets, the team at Creavis will have to optimize the coating process, among other things. Before the year is out, the team plans to conduct tests in a pilot plant in order to determine how a constant level of quality can be ensured in a roll-to-roll process. Creavis has been working together with experts from High Performance Polymers to research ion-conducting membranes for electrochemistry for several years now, enabling it to amass extensive know-how in this field. "Our knowledge of polymer chemistry in this field ideally supplements our expertise with membranes for separating gases and liquids," says Goetz Baumgarten, who is responsible for the Membranes innovation growth field at Evonik.

A great deal of preparatory work was done during the development phase. Creavis has been researching ion-conducting membranes for electrochemistry for several years—it's another promising field for the company besides the hollow-fiber membranes that have been the mainstay of the business to date. "We need completely new methods and skills for measuring the properties of the membranes, for example," says Conradi.

DEVELOPMENT TARGET: AN ENTIRE SYSTEM

The focus is currently still on optimizing the membrane's formulation. "An important factor for its efficiency is the contact resistance between the membrane and the electrode, for example," says Conradi. "To make it as small as possible, we need a good ion connection between the two. As a result, we not only have to continue optimizing the polymer formulation for the membrane but also develop a custom electrode paste that is then applied to the membrane." The aim is to develop an entire system that can be supplied to electrolyzer manufacturers such as Enapter.

Project manager Barnett expects that a whole series of membrane and electrode formulations will have to be tried out until an optimal combination is found. It will include the right catalyst systems, which are currently being developed by Forschungszentrum Jülich and the Norwegian University of Science and Technology (NTNU). Experts at Evonik will develop further generations of catalysts once the new membrane technology goes into commercial series production.

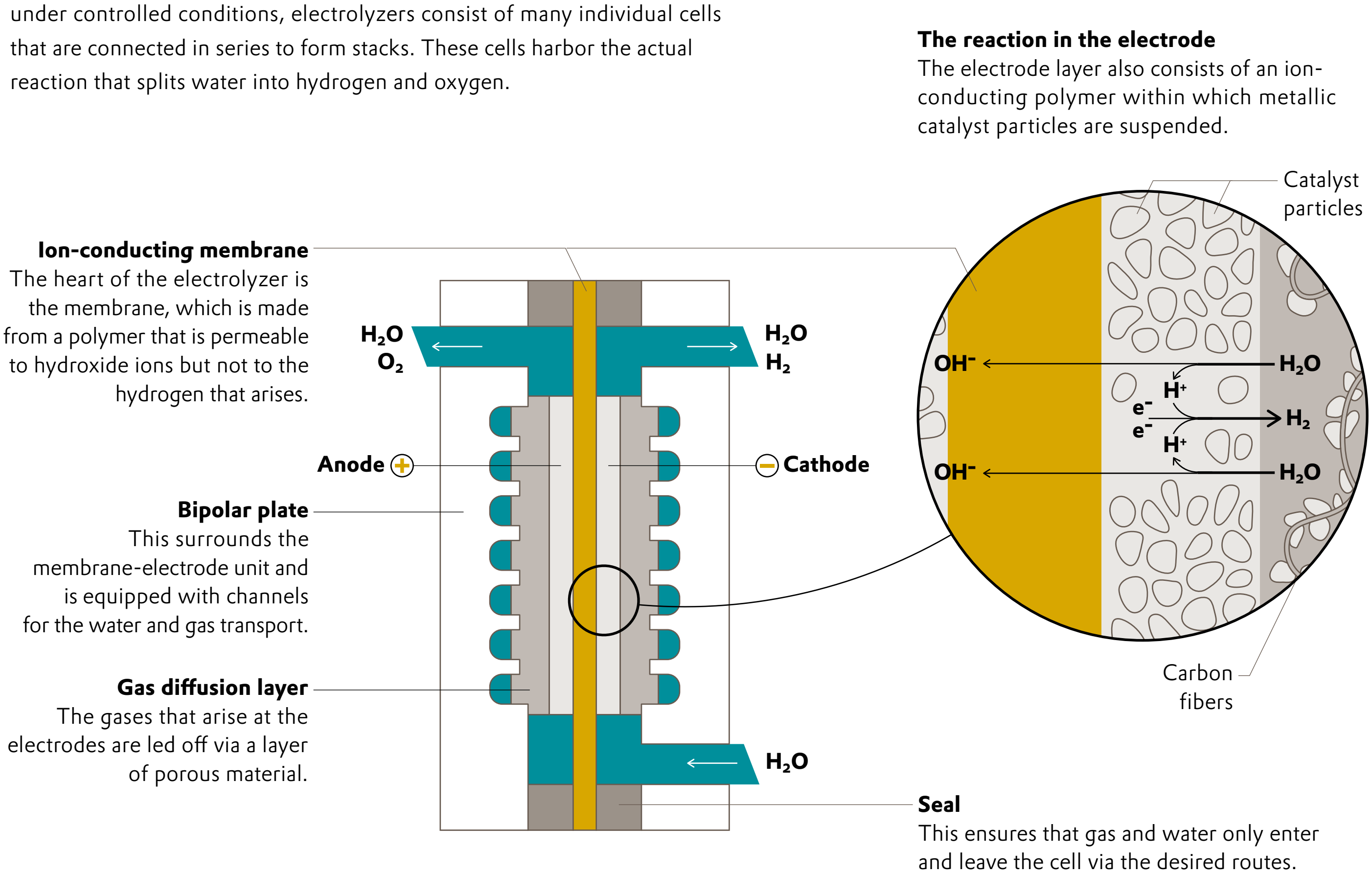
"For the formulation of the electrode pastes, we are benefiting greatly from the fact that the colleagues at Evonik know a lot about polymers and their properties," says Barnett. This means that the team doesn't have to start from scratch, but can instead use proven components to quickly develop and test new materials.

Each new formulation of the membrane electrode assembly (MEA) affects the design of the cell. The ultimate aim is to combine five of these cells into a stack. The cells' components include the bipolar plates—solid metal structures that enclose the membrane electrode assembly on both sides in order to channel the inflow and outflow of liquids and gases. The porous transport layers at the electrodes, through which the gas from the electrodes is led off, are another example. "These are a key component that isn't yet available on the market," says Barnett's colleague Thulile Khoza. "Although we are building on the experience gained from the production of PEM cells, we are working with completely different materials and have to continuously compare costs and performance."

The new modules are being tested in Enapter facilities. "We can test new materials on a small scale before quickly using them on a larger scale," says Jan-Justus Schmidt. In this way, a private technical pastime could turn into a product that will take the world by storm.

The AEM water electrolysis

High pressure and an aggressive environment: The AEM process puts great demands on the material. To enable hydrogen production to take place under controlled conditions, electrolyzers consist of many individual cells that are connected in series to form stacks. These cells harbor the actual reaction that splits water into hydrogen and oxygen.



Christian Kullmann is the Chairman of the Executive Board of Evonik

Making Use of the Crisis

by Christian Kullmann

The consequences of the coronavirus pandemic have made it necessary to reorient European economic policy. In order to cope with the crisis, we don't need any Green Deals. Instead, we need a comprehensive Sustainable Future Deal

Our old certainties are suddenly no longer certain. Yesterday's everyday activities have suddenly been forbidden. The lightness of being has given way to insecurity, fear of infection, and fear of unemployment, economic decline, and bankruptcy. Our health and our prosperity are under threat from a novel virus that has already caused several hundred thousand deaths all over the world within a few weeks. And the virus is still far from being defeated.

The "coronavirus spring" of 2020 has opened our eyes in many respects. It's showing us what achievements people and companies are capable of when an emergency inspires them to transcend their own limits in order to help others. It's showing how quickly governments can make decisions and act when they are called on to prevent the worst from happening. And it's unsparingly revealing how robust—or how fragile—our companies and national economies really are.

In Asia, Europe, and the Americas, national economies are plunging into a recession, countless companies will go bankrupt, and many millions of people will lose their jobs. The problems are global, but the struggle against them is initially being waged by each country for itself alone, at the national level.

International institutions that seemed so important to us when times were good are now being exposed as powerless in the current situation. In some cases their situation is due to structural deficits; in others, the institutions are still being purposely weakened by central players. In both cases, the result is the same: The World Health Organization (WHO) probably won't be able to ensure a fair worldwide distribution of a Covid-19 vaccine in the future. And the World Trade Organization (WTO) is unable to fulfill its function as the arbitrator of international trade conflicts. Unfortunately, the conventional mechanisms of cooperative global conflict resolution are often only useless templates.

As a result, international competition will not ease up after the coronavirus has been defeated. On the contrary, it will become even fiercer. Every industrialized country and every major economic region will try to bolster its own economy in every way possible. In the USA, this could lead to even more protectionism. Countries in Asia will engage in a merciless competition with Europe and the Americas in order to secure future investments for themselves and dominate strategically important markets and value chains.

The responsibility to act now lies with national states—or strong regional alliances. For the European Union, which was already in a deep crisis before the coronavirus pandemic, it's now a question of all or nothing. The virus is forcing us to finally take a binding position: Do we want an EU that is strong and capable of acting in severe crises? Or when the going gets rough do we want to continue relying on a scenario in which German problems are solved in Berlin, Italian ones in Rome, and Swedish ones in Stockholm?

The principle that has paid off in the urgent response to the wave of infections is even more relevant to the economic restart:

“What we now need is a growth program that takes into account not only environmental goals but also social and economic aspects”

We Europeans can summon up the strength to withstand this severe crisis only if we act together. Let’s hold fast to the European spirit and the original idea of a unified Europe in which wars will never again be waged and raw materials will never again be selfishly hoarded—a Europe in which people live in peace, freedom, and prosperity.

What would we gain if individual countries in northern Europe took advantage of their relative strength in order to get their economies through the crisis but the countries in the south and the east couldn’t get back on their feet? Nothing would be gained. On the contrary, Europe would effectively be a thing of the past. And Germany would be harder hit than any other country.

Let’s make use of this crisis to improve Europe’s ability to act! Let’s make use of the crisis to become more successful together. The rebuilding process offers opportunities to do just that. Whenever a government invests huge amounts of money, one result is the power to shape developments. What should our economy and our industry look like in the future? What models and technologies should be systematically promoted?

NO MORE BURDENS!

But nothing will be possible without growth. Of course climate protection is still a guiding principle of targeted development. Here the Green Deal of the European Commission is setting the trend. However, according to everything that is known so far, it falls far short of what is needed. And that’s especially true with regard to the coronavirus pandemic. What we now need is a genuine and sustainable growth program that takes into account not only the justified environmental goals but also social and economic aspects and assigns equal importance to all of them. We need a program that makes growth possible and systematically avoids putting additional burdens on companies at this time.

What Europe now needs is entrepreneurship and momentum for growth, rather than interventionism, prohibitions, and additional regulations. Let’s continue developing the Green Deal—into a Sustainable Future Deal. Energy plays a central role in this development. The decarbonization of power generation is the key to climate protection. At the same time, industrial companies need huge amounts of energy, and this will continue to be the case in the future, in spite of all increases in efficiency. This industrial power must be available and remain affordable in Europe. Otherwise, the key sectors that play an important role in the economic revival cannot survive.

In order to address environmental, economic, and social requirements adequately, we need incentives and goals on a European scale. The promotion of climate-friendly types of generation must be linked with target prices that offer investment security to companies. With regard to issues that are much more easily tackled by a cross-border alliance, such as the creation of a hydrogen economy, the infrastructure must be planned on a European scale from the very start. That reduces startup costs and increases the impact.

The chemical industry is already making crucial contributions to the decarbonization of our energy supply today. There’s no wind turbine that spins without lightweight rotors and no solar panel that can exist without chemical products. The mechanical engineering sector is also making valuable contributions. If we combine these skills and this expertise and give free rein to the creativity of our engineers, we will arrive at solutions that are fully conducive to our sustainability goals—for the environment as well as the economy and society in general.

This kind of restructuring of the European economy requires clear schedules. In terms of the environment, the framework is provided by the benchmarks of the Paris agreement on climate change. At Evonik we explicitly commit ourselves to this framework. We will have cut our absolute CO_2 emissions in half between 2008 and 2025. Especially in recent months, the chemical and pharmaceutical industries have demonstrated their ability to react quickly to new challenges—as producers and suppliers of disinfectants, as manufacturers of fast tests and pharmaceutical active ingredients, and, last but not least, as developers of a vaccine that we hope will soon be available. Together, we will beat Covid-19. And the chemical industry will help us do it.

CLIMATE PROTECTION IS PROFITABLE

But a really sustainable reorientation will be successful only if companies are not overstretched. The upheaval caused by the coronavirus is unprecedented. And the full extent of the crisis will only be revealed to us in the months and years ahead. A truly sustainable new beginning can therefore only succeed if neither the public nor companies are overstretched by the speed of the change or by new burdens.

One thing is clear: Sustainability has been an important principle of corporate management for the chemical industry for a long time. We have a triad of goals: making social prosperity and economic growth possible, ensuring social equilibrium, and preserving the natural foundations of life for future generations. We are doing this because we are convinced that in our pursuit of economic utility the factors of environmental protection, sustainability, growth, and profitability are all interdependent. Ecology and economy are after all not mutually exclusive! Climate protection can be extremely profitable in every sense of the word. We know that. If this realization also informs the spirit of the new beginning in Europe with which we want to leave the period of insecurity behind us, we will not only overcome the crisis but also emerge from it strengthened as the European Union.

CLEAN AND GREEN

Without surfactants, dishwashing detergents, shower gels, and shampoos would be ineffective. In cooperation with Unilever, Evonik has now developed an especially efficient surfactant based on rhamnolipids. It comes from biological sources and is completely biodegradable. According to the experts, there is a huge demand in emerging economies in particular

TEXT **CHRISTOPH BAUER**

"Biosurfactants are game changers in household cleaning applications and beyond"

HANS HENNING WENK, HEAD OF RESEARCH & DEVELOPMENT AT CARE SOLUTIONS

For dishwashing testers, activities that most people consider tedious kitchen work are scientific research protocols. Dishes, glasses, and cooking pots are carefully prepared to simulate the challenges faced daily at the kitchen sink: müsli residue sticking to a bowl, dried-out leftover rice in a pot, congealed fat in the frying pan. The test items are then cleaned with various dishwashing detergents under identical conditions and the results are compared.

One important aspect of the results is the "mileage"—a value that, for cars, quantifies the range of travel with a defined amount of fuel. In the dishwashing lab, the mileage is the amount of dishes that the testers can clean before the foam disappears from the dishwater. "The sooner the foam breaks down, the more often the consumer changes the dishwashing water," says Dr. Hans Henning Wenk, who heads the Care Solutions unit's research department at Evonik. That means the consumer is using additional water, energy, and dishwashing detergent.

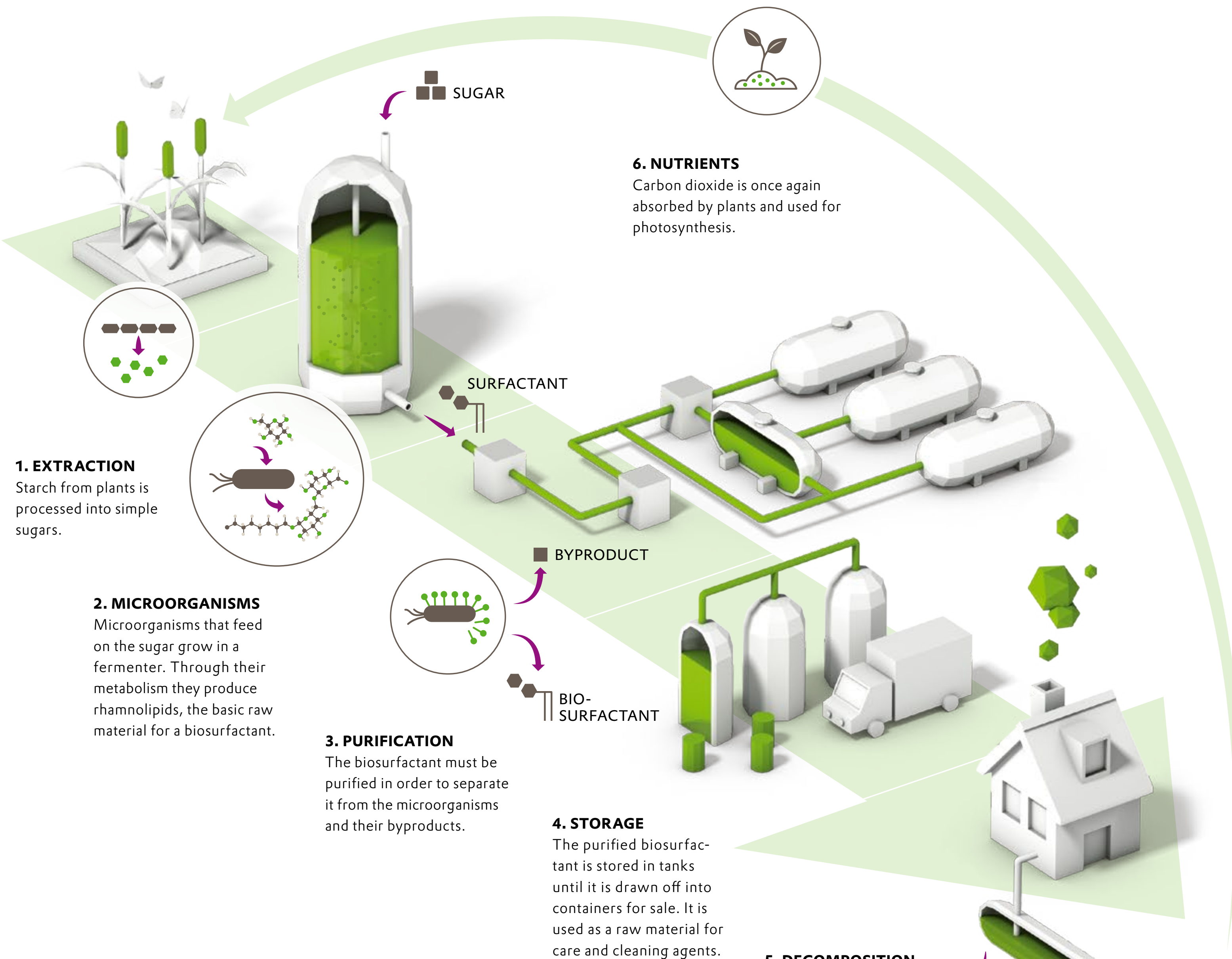
Surfactants are responsible for the formation of foam. Depending on the brand and type, they comprise between five and 30 percent of the contents of a bottle of dishwashing detergent. They are crucial to the product's efficiency and environmental friendliness. Effective surfactants are thus an important factor in a cleaning product's sales success.

The annual worldwide sales of surfactants based on biological raw materials amount to more than US$4 billion. The experts expect to see this amount increase to $5.5 billion in 2022 (see Data Mining on page 41). This growth is being driven by consumers who are assigning increasing importance to environmentally friendly solutions, as well as by regulatory bodies that are setting significantly higher standards for the biodegradability of cleaning substances. Europe is an important production location for surfactants—and Evonik is an important player. Together with the consumer goods group Unilever, specialists from Evonik have developed a novel surfactant that not only cleans very well and cares for the skin but is also completely biodegradable. "Biosurfactants are game changers in household cleaning applications and beyond," says Wenk. "And thanks to our technology, we have the potential to fundamentally change the way cleaning products are manufactured."

Surfactants work according to a simple principle: They have one end that is attracted to water and another one that bonds with fat (see the graphic on page 39). That's how they ensure that dissolved dirt doesn't end up on the dishes again. The new biosurfactant is based on substances called rhamnolipids, which are much better tolerated by aquatic organisms than the surfactants used to date.

A PIONEERING BACTERIUM

The starting point of the cleaning agent is a bacterium that likes to live in dirt: *Pseudomonas aeruginosa*. It lives in the soil and feeds on fats. It was discovered in 1900 but initially attracted little attention. That may also be due to the fact that it is categorized as a pathogen: If it is ingested in large amounts, it is detrimental to human health. Not until the 1960s did researchers discover that this bacterium produces useful rhamnolipids, even →



A natural cycle

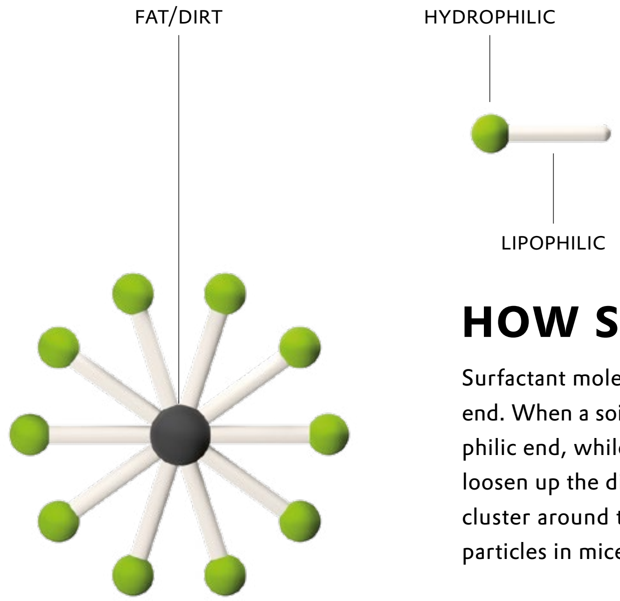
Producing biosurfactants based on rhamnolipids

though the amounts are very small. The idea of taking advantage of these lipids' cleaning abilities initially remained just a vision. But after the genome of this bacterium was decoded in 2000, researchers took up this idea again.

There is one surfactant that people have already been using for thousands of years: soap. Eventually soap was replaced by surfactants based on petrochemical raw materials. However, the first generation of these products formed huge mountains of foam on the surface of wastewater and in rivers. The surfactants were not degraded by water purification processes; they escaped into the environment and damaged the organisms living in it. Today surfactants are legally required to be mostly degradable within four weeks in wastewater treatment plants.

Customers have increasingly expressed their desire to use sustainable products that are just as effective as conventional ones. That's why Hans Henning Wenk and a team of researchers in Essen launched a project in 2008 to develop a new generation of surfactants for cleaning and care products. "Consumers initially accepted the fact that environmentally friendly products were not as good as standard ones," he recalls. "But today all that is over."

The researchers decided to use rhamnolipids because they are completely biodegradable, both with and without the presence of oxygen. Besides, they remove dirt just as reliably as very good synthetic surfac-



HOW SURFACTANTS WORK

Surfactant molecules have a hydrophilic (water-loving) and a lipophilic (fat-loving) end. When a soiled surface is washed with water, the dirt particles attract the lipophilic end, while the hydrophilic end points toward the water. These opposing forces loosen up the dirt particles and dissolve them in the water. There the surfactants cluster around the dirt particles by means of their lipophilic ends and enclose the particles in micelles, which are thrown out together with the wastewater.

tants. What's more, they are gentle to the skin—a property the professionals call "mildness." After washing the dishes, showering or bathing, the user's skin feels pleasantly cared for.

Wenk and his colleagues searched for an alternative bacterium that can produce rhamnolipids without posing any risk to human health and gives manufacturers the highest possible yield. They also decided that sugar should serve as the basis of the process, because it is available everywhere from regional sources that are not competing with sensitive ecosystems. "That was a bet on the future," says Wenk as he looks back at the time and money that were invested in the project. "We really took on something big."

AN INTERNATIONAL PARTNERSHIP

For production purposes, the team chose a strain of bacteria from the *Pseudomonas putida* family that is already used in other industrial applications. This is a well-researched safe strain that is not harmful to human beings, animals or plants and that multiplies strongly only under artificial conditions. The strain was then engineered to have the properties needed in the initial bacterium. Step by step, the researchers successfully increased the bacterium's production capacity to the point where commercial use of the rhamnolipids they produced seemed possible.

Under the microscope, the bacterium does not look spectacular: It has an elongated structure with a couple of filaments at one end. However, rhamnolipids proved to be highly attractive for research purposes. Unilever were aware of this too. In 2015 it became clear that the Dutch-British consumer goods producer was also working to develop surfactants based on rhamnolipids. Thanks to its business relationship with Evonik, a joint development project was born. "Our research and development team has been familiar with rhamnolipids for years. However, the technology and the science had not yet reached the point when industrial production would have been possible," says Peter Ter Kulve, the President of Unilever's Home Care business, which is based in London. Evonik contributed its expertise for this "scale-up." The market potential is tremendous: 2.5 billion people use Unilever products every day. The Home Care division alone posts more than €11 billion in sales annually.

→

The fermenter hall of the Evonik plant in Slovenská Ľupča. This location has vast experience in the production of biosurfactants

The market launch was preceded by years of research and development work. In Slovakia the work concentrated on reducing foam formation during the production process

Environmentally friendly and effective: This was the product promise used by Unilever in Chile for the launch of Quix, the first dishwashing detergent based on rhamnolipids

The successful breakthrough to large-scale production was reached in 2016 at the Evonik plant in Slovenská Ľupča, Slovakia. There the Group has for many years employed fermentation specialists who are responsible, among other things, for the production of surfactants based on biological raw materials.

THE CHALLENGE OF FOAM

"If you're producing 5,000 liters instead of ten liters of a substance, it's not enough to simply multiply the values," says Wenk. The pressures, processes, and temperatures must also be adapted. The biggest problem turned out to be the very thing that makes rhamnolipids so attractive to end users: the foam. The product should foam when it's being used, but not while it's being produced. If the parameters are correct, production proceeds smoothly (see the graphic on page 38). Simple glucose is used as the raw material in the fermenters in Slovenská Ľupča. The strain of bacteria converts the sugar into rhamnolipids inside the fermenter at room temperature.

The rhamnolipids have been on the market since 2018. Initially a solution for care products was developed under the name RHEANCE® One. The product was very popular with consumers, and the team of researchers received in-house and external awards for it. But Unilever is aiming at another market: the one for dishwashing detergents. The Group pays special attention to the sustainability of its products and the situation in the emerging economies. There the desire for hygiene and cleanliness is growing, but only a few households have a dishwasher. As a result, there is a big demand for hand dishwashing detergents. What's more, in many of these countries wastewater is not processed as intensely as it is in industrialized countries. Thus a completely degradable ingredient is an especially big advantage.

The experts from Unilever decided to launch this product on the market in Chile under the very popular brand Quix (see the interview on page 42). The most important selling point was the product's environmental friendliness—a quality that Chileans prize highly when they make shopping decisions. Unilever evaluates the market launch as a success, and the product will now be introduced in other countries.

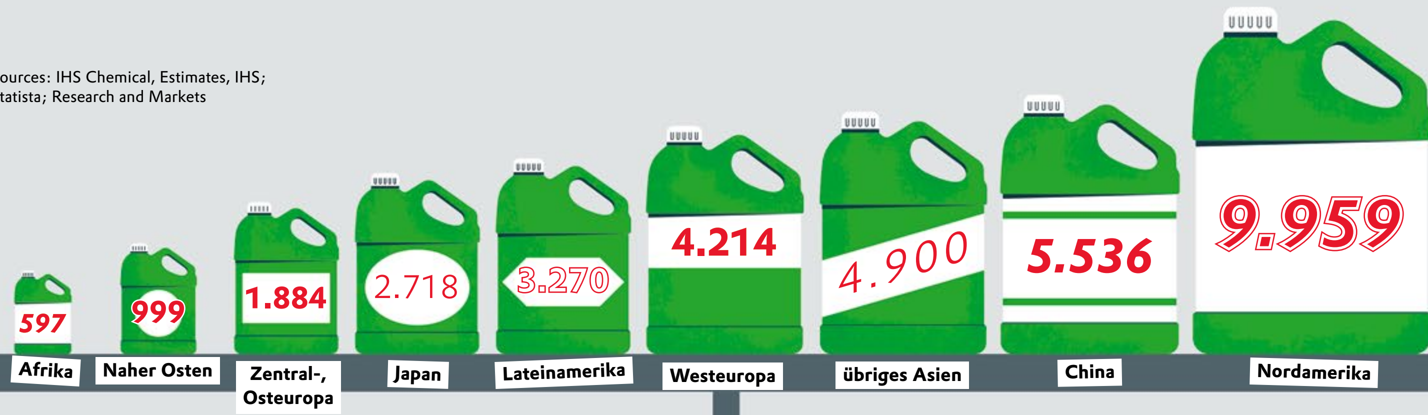
Meanwhile, Evonik is considering the construction of a new major production plant. The experts are sure that the need for rhamnolipids will grow by leaps and bounds in the future.

BIG CLEANING

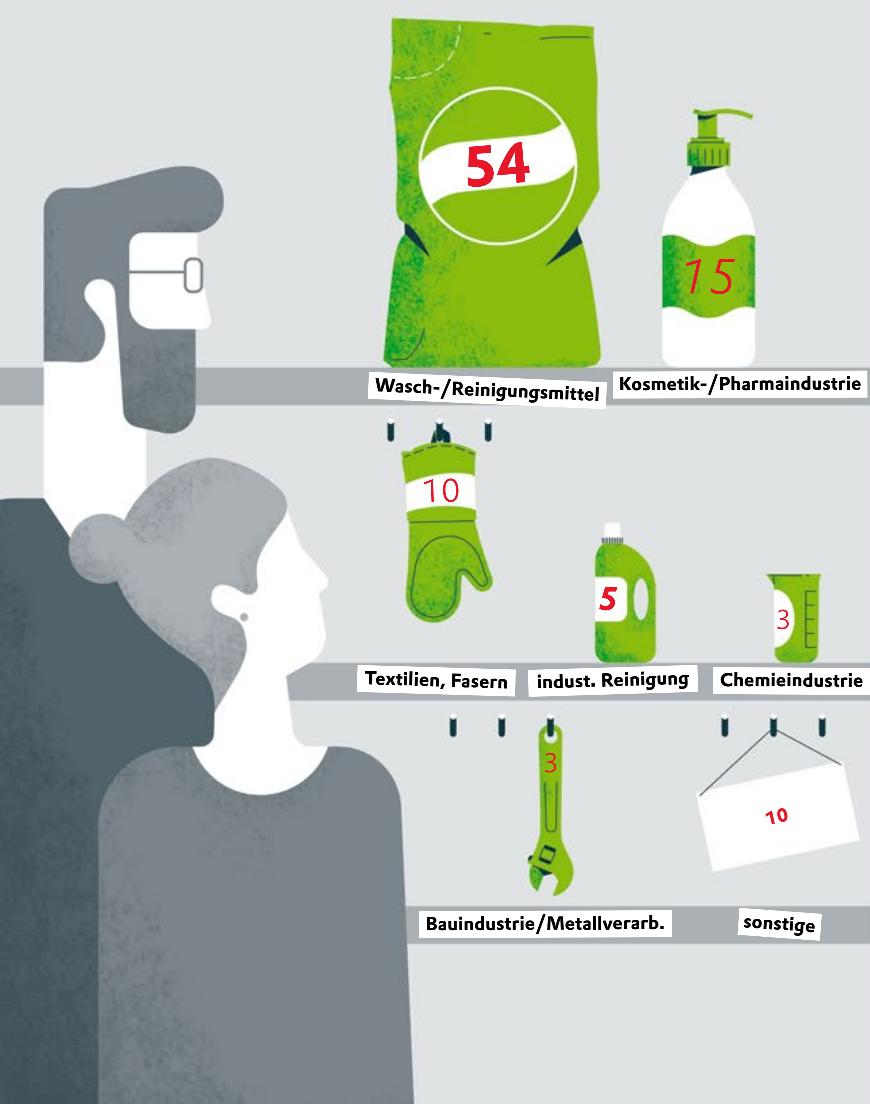
Surfactants can be found in countless products in daily use all over the world. But the sales markets are changing—and so are the customers' requirements. An overview of the facts and figures

Asia and North America dominate the market
Sales of surfactants in selected markets in millions of US$, 2015

Sources: IHS Chemical, Estimates, IHS; Statista; Research and Markets



The biggest buyers are manufacturers of washing and cleaning products
Use of surfactants by sector in percent, 2015



Backlog demand in emerging economies
Predicted annual sales per capita of dishwashing detergents in selected countries, 2020

Biosurfactants are gaining ground
Annual sales (2022 forecast) of bio-based surfactants

Bert Nijhuis (48) is based in Rotterdam, from where he heads the research and development team for hand-dishwashing and machine-dishwashing detergents at the Unilever consumer goods group. A Netherlands native, he has a doctorate in analytical chemistry and has worked in the area of cleaning agents at Unilever for the past 16 years. In the course of his career, Nijhuis has lived and worked in different countries leading R&D teams across the globe.

"This is only the start of the journey for biosurfactants"

The Unilever expert Bert Nijhuis explains what consumers expect in a dishwashing detergent—and why Chile is the perfect test market for the biosurfactants jointly developed by Unilever and Evonik

INTERVIEW **CHRISTOPH BAUER**
ILLUSTRATION **ORIANA FENWICK**

Mr. Nijhuis, if Unilever decides to launch a product such as the Quix Hand Dishwash with a new composition, what criteria do you apply?

No matter what product we launch anywhere in the world, it has to perform—and for a dishwashing product, performance means above all that it has to clean. It has to remove grease, remove stains, and leave plates and glasses shining. It must also produce the right amount of foam. But that's not all. People are increasingly concerned that their cleaning products might have a negative impact on the environment, so making our top-performing products environmentally friendly and offering additional benefits, such as noticeable mildness to the skin, creates the sweet spot for a successful new launch.

“Environmentally friendly products must deliver the same performance as conventional ones or even better”

Why did you choose Chile as a test market?
Our data show that environmental awareness is growing there and thus the demand for more sustainable products is increasing.

…and the dishes are still mostly washed by hand.
Exactly. Dishwashers are particularly common in the USA and Europe. In the rest of the world, washing dishes is still done mainly by hand every day, and that means people spending a lot of time with their hands in soapy water. In Chile, we already had a product formulated for sensitive skin. This seemed to us a great opportunity to launch rhamnolipids as surfactants in Quix, as it is renewable, biodegradable, and very mild on the hands.

What makes rhamnolipids so attractive for Unilever?
We have observed that there is a tension between “clean and green.” Green products are often expected to clean less well and that is sometimes true for traditional technologies. With rhamnolipids we have a green solution that cleans and is gentle on the skin and good for the planet.

Is sustainability an equally important driver for your company in all markets?
There are certainly differences from country to country. The level of air or water pollution as well as the economic environment affects consumer awareness. But in opinion polls, environmental concerns are very often high on the list of priorities in most countries. And our market research shows that a sustainable product is preferred to a conventional one—if it works well. But for us as at Unilever, sustainability is not just a growth driver. We also want to play our part in tackling the big problems of our world such as climate change or environmental pollution.

Unilever has a strong presence in emerging markets. What are the special requirements of these markets?
Many households have tight budgets. It is therefore important that we offer consumers very good value for money. That means an excellent product at a price people can afford.

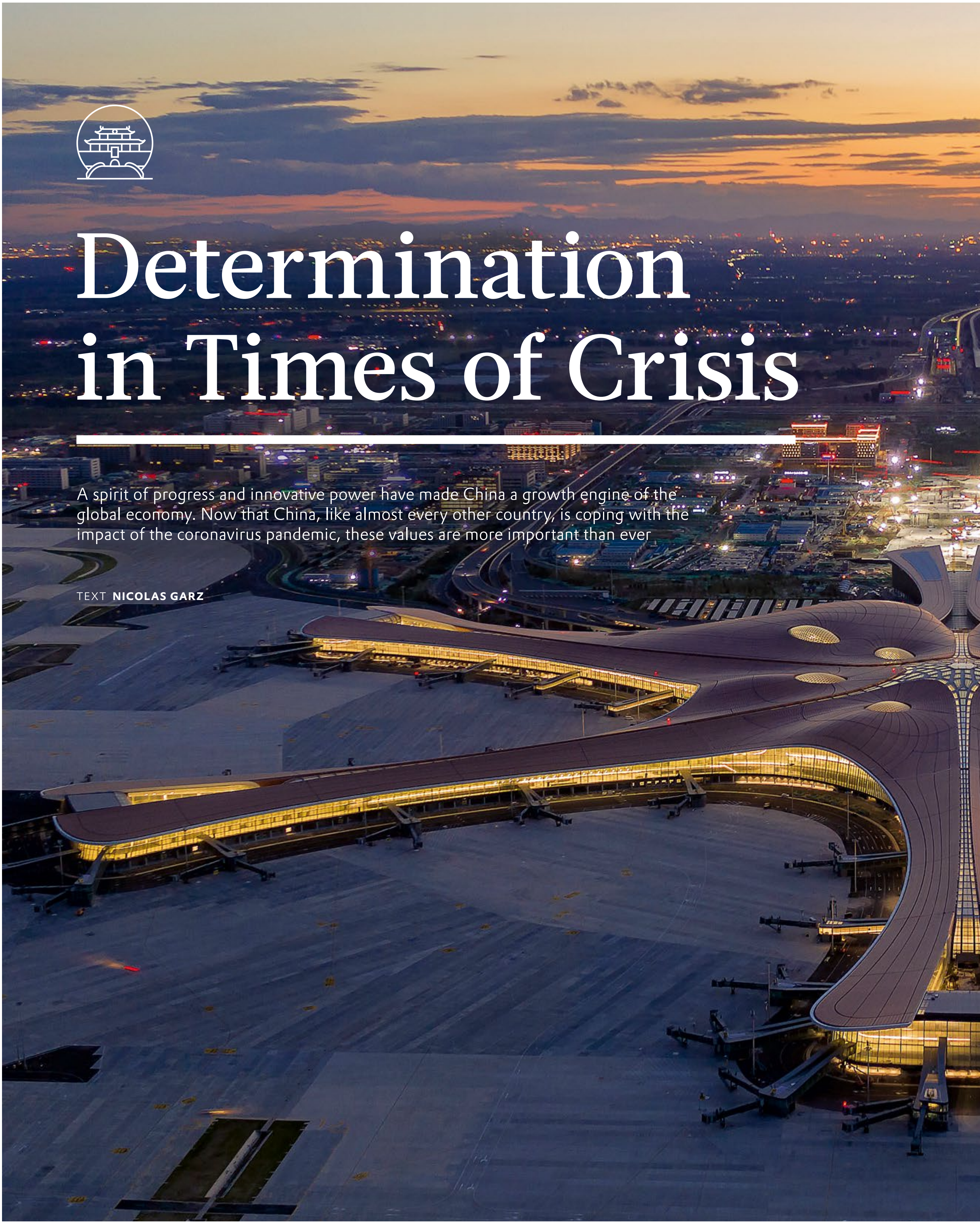
Do consumers accept a weaker performance if a product is more environmentally friendly in return?
Very few consumers are ready to do that. If we want to make sustainability an everyday reality, environmentally friendly products must deliver the same performance as conventional ones or even better. This is how we believe we can be successful in the marketplace.

How closely does Unilever monitor the market? What do you know about consumers before you put a product on the market?
We invest a considerable amount of time in talking to consumers to understand their needs and desires. Much of Unilever’s success is based on our ability to respond quickly to consumer needs.

Biosurfactants still play a relatively small role. Will these ingredients ever be more than just a market niche?
We think we are only discovering the potential of biosurfactants in the home. As more consumers look for top-performing products that are better for the environment, this is only the start of the journey for biosurfactants.

What role do suppliers like Evonik play in keeping their ecological product promises?
Our suppliers are often more than just suppliers. They are our technology partners—like Evonik. Any improvement in the performance and sustainability of our products requires a certain amount of technology. That’s why our suppliers are essential to the implementation of our sustainability agenda.

Right up to the joint marketing of products?
Yes, of course. Unilever and Evonik are jointly researching and developing in the field of biosurfactants. From a business point of view, joint commercialization makes perfect sense.



Determination in Times of Crisis

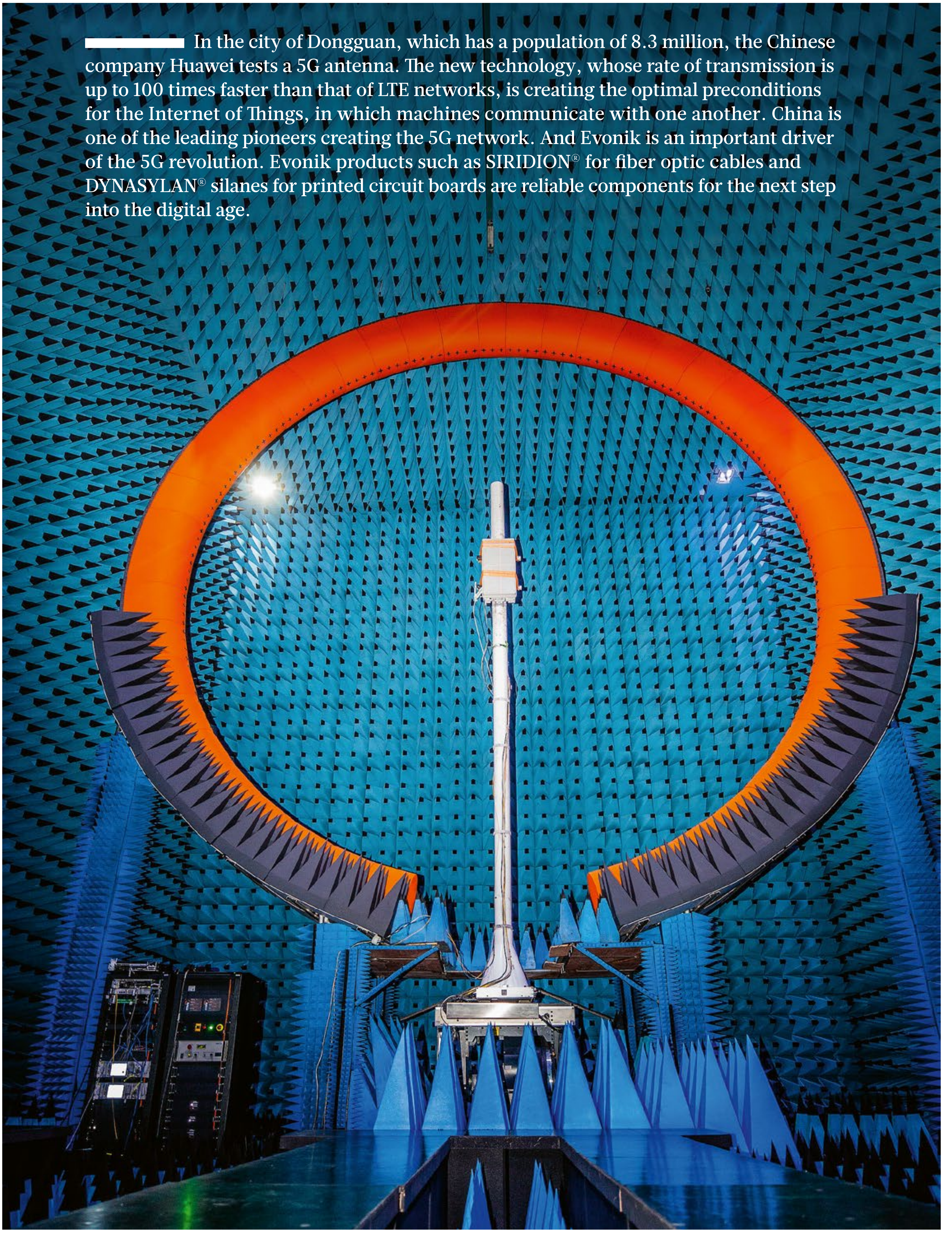
A spirit of progress and innovative power have made China a growth engine of the global economy. Now that China, like almost every other country, is coping with the impact of the coronavirus pandemic, these values are more important than ever

TEXT **NICOLAS GARZ**

Beijing's new Daxing Airport, nicknamed "Starfish" because of its side arms, was opened in the fall of 2019. Air traffic is currently limited because of the coronavirus pandemic, but in the future Daxing is set to be a hub for airplanes from all over the world. It's a symbol of China's new self-confidence and its ambitions in the field of aviation. What matters in airplane construction is performance, comfort, and sustainability—and that makes weight a major factor. The lighter a plane is, the less fuel it consumes. ROHACELL® from Evonik makes airplanes light and stable—and makes resource-conserving travel possible.

For many Chinese, shopping at a mall, like this one in Shanghai's Lujiazui financial district, is an expression of economic advancement and a better quality of life. However, because of the COVID-19 pandemic very few shoppers have ventured out to the malls in recent months. Today more customers are entering the shops again, thanks to the maintenance of strict standards of hygiene. Here disinfectants are playing a crucial role. Evonik products including hydrogen peroxide, peracetic acid, and biocidal active ingredients such as REWOCID® WK30 are responsible for the disinfectants' effectiveness. They are helping to restore a bit of normality during the state of emergency.

In the city of Dongguan, which has a population of 8.3 million, the Chinese company Huawei tests a 5G antenna. The new technology, whose rate of transmission is up to 100 times faster than that of LTE networks, is creating the optimal preconditions for the Internet of Things, in which machines communicate with one another. China is one of the leading pioneers creating the 5G network. And Evonik is an important driver of the 5G revolution. Evonik products such as SIRIDION® for fiber optic cables and DYNASYLAN® silanes for printed circuit boards are reliable components for the next step into the digital age.



Good food occupies a very special place in Chinese life. Traditional dishes, such as these shumai dumplings, are every bit as popular as modern fusion cuisine. The prosperity of the last few decades has made it possible for more and more of its citizens to afford high-quality food. China's livestock farming industry is reacting to the growing demand. To make sure that farm animals grow up healthier and provide better-quality meat, the farmers are increasingly relying on sustainably produced feed additives. Evonik is supporting this trend with its DL-methionine amino acids for chickens, pigs, dairy cows, and shrimps, as well as probiotics which improve the gut health of poultry and pigs.

Health is the foundation of a long life—and in the current emergency situation this becomes plainly apparent. In an aging society like China's, medical care is especially important. It saves lives and also helps people have a good life in old age, as for example in this nursing home in Sanya. Modern medical technology is also needed to achieve this. For example, in China the demand for prosthetics and dentures is growing. Evonik provides products such as VESTAKEEP® and RESOMER® for high-quality medical implants that help the recipients to have a healthy and dignified old age.

FARSIGHTED COMMITMENT

Evonik's predecessor companies opened their first representative office in China back in the 1930s. Since then Evonik has expanded its investments step by step. The financial metropolis of Shanghai is playing a key role in this process. This is where Evonik operates an R&D center and a multi-user site (MUSC) where more than 200 different products are manufactured today.

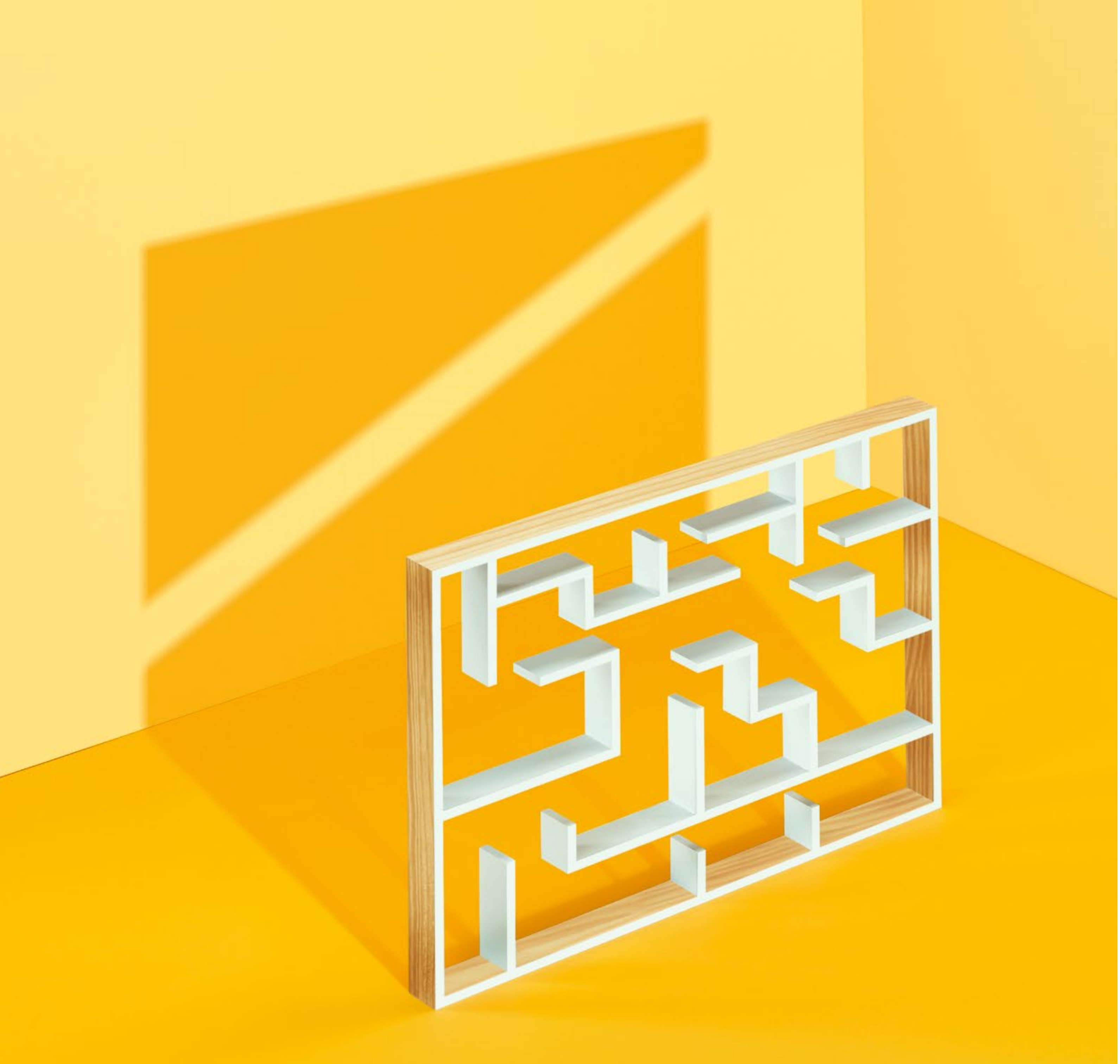
About

2,500

employees work at

14

locations.



A FANTASTIC SHORTCUT

“It’s not necessarily a bad thing if you don’t try to directly achieve extremely challenging targets”

ROBERT FRANKE, HEAD OF HYDROFORMYLATION RESEARCH AT EVONIK

The more efficient reactions are, the more sustainable chemistry becomes. Working together with partners from the Leibniz Institute for Catalysis, a group of researchers at Evonik have recently achieved a notable feat—the direct production of the important industrial chemical adipic acid. This breakthrough was even showcased in an article in the journal *Science*

TEXT **KARL HÜBNER** ILLUSTRATION **SAMY LOEWE**

It’s been more than 60 years since Schalke 04 won Germany’s soccer championship. That was back in 1958, when Professor Robert Franke had not even been born. However, as a Schalke fan, Franke dreams of seeing the team becoming the German champion once again. Franke also has dreams as a researcher. Among other things, he would like to carry out some chemical reactions that no lab on earth has managed to achieve to date. Some of these reactions are as unrealistic as the likelihood that Schalke’s neighboring team, VfL Bochum, which is in the second league, could soon become the German champion. Other reactions are at least conceivable—and about as likely as Schalke becoming champion.

Chemists really do refer to them as “dream reactions.” For one of these reactions, Franke recently achieved a breakthrough in cooperation with partners from the Leibniz Institute for Catalysis (LIKAT) in Rostock. The dream of achieving this reaction is about as old as that of Schalke fans regarding their team’s championship, because the literature concerning such research extends back to the 1950s.

The aim is to directly convert butadiene into adipic acid. The latter is a dicarboxylic acid and an important starting material for many other products (see the box on page 56) such as nylon. Several million tons of adipic acid are produced worldwide each year. To date, manufacturers have only been able to produce it by way of several chemical detours and the use of aggressive chemicals such as nitric acid. Moreover, they have to →

“We’re delighted whenever we can apply our academic research to concrete examples from industrial operations”

MATTHIAS BELLER, DIRECTOR OF THE LEIBNIZ INSTITUTE FOR CATALYSIS (LIKAT)

deal with the byproduct nitrous oxide, a molecule that is around 300 times more damaging to the climate than carbon dioxide. It would therefore be much more sustainable if adipic acid could be produced from butadiene in a single step. So it’s no wonder that the recently achieved breakthrough even had an article devoted to it in the renowned journal *Science*.

When chemists write out the equation for this reaction, it looks pretty simple: A carboxyl group (COOH) is attached to each end of a butadiene molecule. The result is adipic acid. In practice, things aren’t quite so easy. That has been demonstrated by the many attempts made in past decades that at best achieved no more than partial success. “One problem is the many possible side reactions, which produce other, unwanted substances,” says Franke. Another obstacle is that the attachment of each COOH group occurs in two separate steps, which to date have only been achieved independently of one another. “As a result, you need to laboriously separate and purify the substances in a variety of steps. This makes the whole thing rather uneconomical,” states Franke.

As is often the case in chemistry, the recent breakthrough was achieved by means of a suitable catalyst. “We couldn’t have done it without the help of the colleagues at LIKAT,” adds Franke. This joint success isn’t the first in the 23-year partnership between LIKAT and Evonik. The two partners have already transferred eight jointly developed processes to technology-center scale and registered more than 140 patents. For many years, they have also been sending staff members to each other on temporary assignments so that they can benefit from one another’s expertise. “It’s a very fruitful partnership,” says Franke.

AN ACCIDENTAL BYPRODUCT

However, it’s rather unusual that Franke, as an industrial researcher, is interested in adipic acid, given that it hasn’t previously played a role at Evonik. Franke likes to call such side trips “serendipitous,” which means that the discovery was important but not aimed for. It’s an accidental byproduct.

“It’s not necessarily a bad thing if you don’t try to directly achieve extremely challenging targets but still keep them in the back of your mind,” he says. Dream reactions such as the one that converts butadiene into adipic acid are something that an industrial chemist always has at the back of his or her mind. And at some point a few years ago, the time eventually came for Franke to remember the idea and make his own attempt.

The reason for this was that the hydroformylation research that Franke heads at Evonik had achieved a breakthrough. Hydroformylation is a tried and tested method for reacting unsaturated hydrocarbons, known as olefins, with synthesis gas—a mixture of carbon

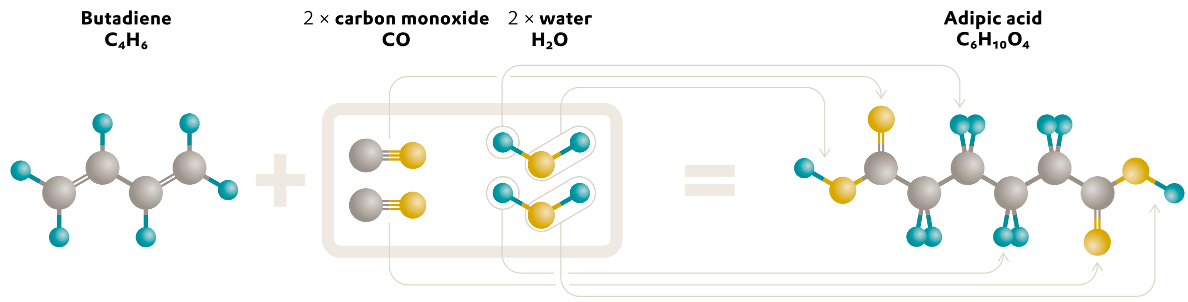
Adipic acid is a starting material for many products, including polyamide 6.6, which is better known as nylon. Among other things, the synthetic fiber is used in tear-resistant fabrics and ropes as well as in the strings of some musical instruments

monoxide and hydrogen—in order to incorporate carbonyl groups (CO) into the molecules. At the Marl Chemical Park, where Franke has his office, Evonik uses this method to turn hundreds of thousands of tons of petrochemical raw materials into intermediates every year.

However, it's always worthwhile to look for ways in which even well-established processes can be optimized. Can a process be made even more efficient and more sustainable? "These are the kinds of questions that drive my work," says Franke. Among other things, he has been spending the past ten years working on alkoxy carbonylation, which might one day replace hydroformylation. In this process, the olefins' double bonds are treated with a mixture of carbon monoxide and an alcohol. This results in esters. Because many products of hydroformylation are converted into esters for later use, the ability to synthesize them directly would be elegant as well as sustainable.

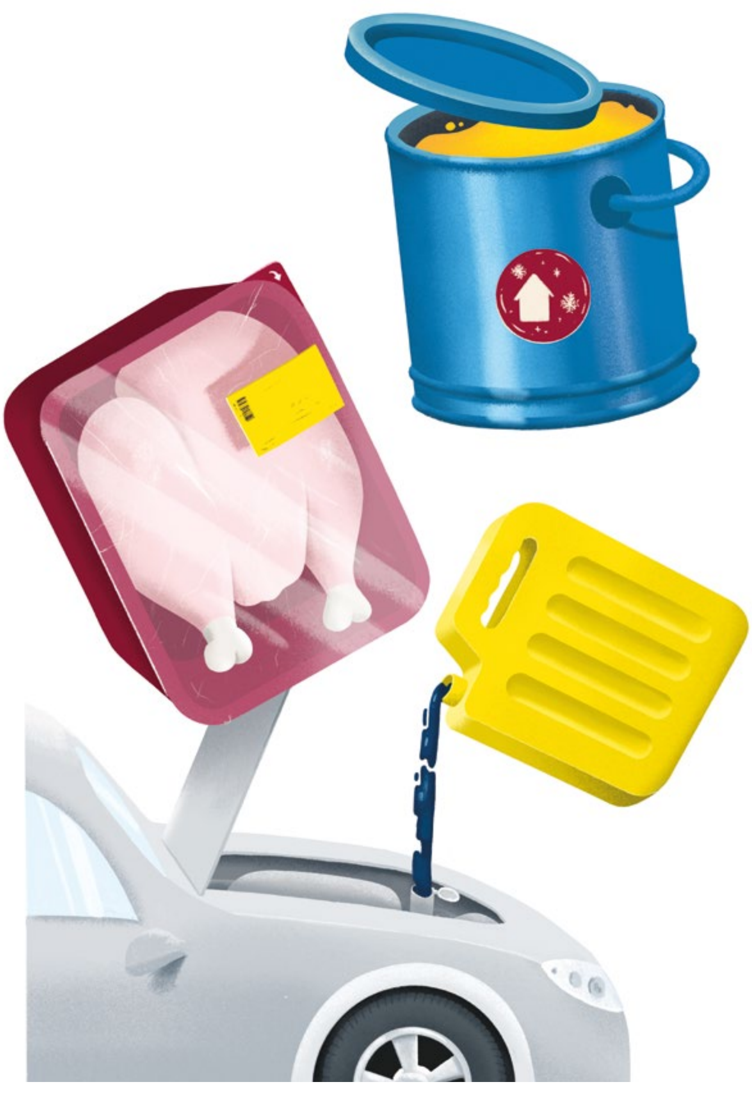
LOOKING FOR A "MATCHMAKER"

One of the biggest challenges that the researchers faced was the search for a suitable catalyst. Catalysts are often referred to as "chemical matchmakers" because they bring molecules together and help to overcome existing energy barriers. Catalysts are often complex molecules that perform a variety of tasks. For example, the planned alkoxy carbonylation of an olefin goes through four to five transition states. The catalyst has to support the process at each transition. As a result, Evonik launched another partnership with the specialists at LIKAT in 2015. The institute's director, Professor Matthias Beller, immediately agreed. "We're delighted whenever we can apply our academic research to concrete examples from industrial operations," he says. →



An acid for many uses

Adipic acid is an important intermediate for the chemical industry, which produces several million tons of it every year. By far the biggest portion of the output is used to produce polyamide 6.6 (nylon), which is turned into fibers for lightweight fabrics that are tear and abrasion-resistant as well as into strings for plucked instruments, tennis racket strings, and wear-resistant parts such as cogwheels. In addition, adipic acid is used as a raw material for certain polyurethanes, which are found in ski boots, sports shoe soles, golf balls, foams, coatings, and adhesives, for example. Adipic acid is also used to produce plasticizers for cables, hoses, foils, and food packaging made of PVC. Other applications include the use in additives that make paints and coatings resistant to low temperatures and as components of lubricants. Adipic acid itself is also approved for use as an acidulant in food (E355). The name is based on the Latin word *adipes* (animal fats). Adipic acid used to be produced by oxidyzing fat. This natural starting material was later replaced by petroleum-based raw materials. Until now, its synthesis required several steps. In the recently achieved reaction, researchers succeeded in producing adipic acid directly from butadiene for the first time. The scientists accomplished this using a catalyst they had developed specifically for this purpose. In the new process, carbon monoxide and water are used to attach two carboxyl groups to a butadiene molecule in a single process step.



Esters of adipic acid are used, for example, as plasticizers in PVC food packaging and as additives in coatings and lubricants

For its starting point, Beller's team chose a catalyst that is well-established in industry, but unsuitable for Evonik's purposes. The specialists at LIKAT changed molecular groups in such a way that the reaction's second stage, the addition of the alcohol, can proceed more rapidly. The team headed by Franke and Beller published this breakthrough in 2017. Thanks to the new catalyst, monounsaturated olefins can be converted into esters with a good yield. Evonik is now preparing the first conversions to the new process on a commercial scale.

This success automatically brought Robert Franke's dream reaction back to mind—serendipitously. The question was: Could the catalyst also work with butadiene? After all, that process also involves a carbonylation, although it has to incorporate not one but two CO groups.

And lo and behold, it worked quite well. However, it produced too many interfering byproducts. The researchers wanted to improve this unsatisfactory selectivity, so to this end they then combined molecular groups from the industrially well-established system with their new candidate. This led to the breakthrough.

Science published the findings shortly before Christmas 2019. It added a one-page expert commentary that stated that the selectivity and product yield of the process were outstanding.

However, the reaction still had one minor drawback: It initially “only” produced an ester of adipic acid. Water had to be added to create the acid itself. Adipic acid could only be produced in one go if water could be used for the reaction instead of alcohol. Although this was difficult at first, the team has also made progress in this regard. “A different solvent enables us to achieve that as well,” says Matthias Beller about the follow-on success, which has not yet been published.

However, this result is not yet adequate for industrial applications. “The synthesis of the catalyst is very complicated and uneconomical as well,” says Franke. In addition, parts of the complex molecule decompose during the process. Beller’s team in Rostock is currently working on developing a similarly effective catalyst that would be easier to produce and more stable.

FROM THE LAB TO LARGE-SCALE TECHNOLOGICAL APPLICATIONS

At the same time as it is enhancing the catalyst, Franke’s Evonik team is also working on transferring the reaction to large-scale technological applications. To date, the tests have only been conducted on the laboratory scale, with only a few hundred grams of the various substances. The next stage will take place in a mini plant in order to determine whether the process is permanently stable in such a reactor, says Franke.

At some point, Evonik will decide whether it should produce adipic acid itself or market the process in other ways. The most important raw material for this process, butadiene, would be supplied by the company’s own C4 production network at the Marl location. This production network is based on C4 hydrocarbons from petroleum cracking. The name “C4” refers to the fact that these hydrocarbons contain four carbon atoms. Butadiene is one such hydrocarbon.

No matter who uses this process one day, it will make the production of adipic acid simpler and, above all, more sustainable. It avoids “ugly chemistry” (Franke) and all of the starting substances end up completely incorporated into the product, so no waste is produced. In the future, some of the starting materials could also be produced from renewable resources. An example of this is the synthesis gas, from which the carbon monoxide is separated for the production of adipic acid. According to Franke, at least it would allow two of the six carbon atoms in the end product to be created in a green manner.

As a result, the dream reaction has almost become a reality. It would be a great feat if the success in the laboratory could be turned into a large-scale process that replaces the conventional process for producing adipic acid. Robert Franke would be so thrilled that he could even get over it if it took a while for Schalke to become Germany’s soccer champion again.

Adipic acid is also used during the production of certain thermoplastic polyurethanes from which ski boots, skateboard wheels, animal eartags, and other items are made

KEEPING CLEAN

We live in an era of high-performance medicine. But even today, a long and healthy life would be unthinkable without progress in the area of hygiene

TEXT **BJÖRN THEIS**

Since the beginning of human history, our longevity has continually increased. This effect was especially accelerated during the twentieth century. About 1900, the average lifespan of German men was 45 years; for women, it was 48 years. Since that time those figures have almost doubled.

This development has been largely due to improvements in hygiene, which prevents the outbreak of diseases. Such long human lifespans have been made possible by the modern era's expansion of public hygiene measures ranging from well-functioning sewage systems to mandatory vaccination, as well as efficient private hygiene due to products such as effective cleaning agents, toilet paper, and toothpaste.

The history of hygiene dates back to Greek mythology. Its very name is derived from Hygieia, the goddess of health and the daughter of Asklepios, the god of medicine. One of her best-known devotees was Hippocrates, a physician who recommended conscientious personal hygiene as a means of avoiding disease. The citizens of the Roman Empire were also extremely hygiene-conscious: Public baths and toilets were familiar parts of the urban landscape. Even back then, the scientists of that era suspected that "tiny creatures" invisible to the eye caused diseases. But these microorganisms only became visible more than 2,000 years later, when the Dutch merchant Antony van Leeuwenhoek observed bacteria under a microscope for the first time in 1675.

THE FIGHT AGAINST BACTERIA

In the 19th century, the development of hygiene was accelerated by leaps and bounds. Ignaz Philip Semmelweis discovered the immense utility of hand disinfection and thus dramatically decreased the maternal mortality rate. Meanwhile, Sir Joseph Lister was introducing the use of carbolic acid (phenol) as a disinfectant for the antiseptic treatment of wounds, which put an end to deaths caused by wound fever. Louis Pasteur discovered the effectiveness of heating foods to make them germ-free, and shortly thereafter Robert Koch isolated the tuberculosis pathogen and joined Pasteur as the cofounder of modern bacteriology. However, all of these measures were still not sufficient to effectively cure bacterial infections. It was not until 1929 that Alexander Fleming discovered the first antibiotic, penicillin.

The history of hygiene is still not over today. It's true that we can now treat diseases such as plague and tuberculosis, but today there are still many infectious diseases for which no medicine is yet available—including Covid-19. As a result, strict hygiene regulations are the best weapon in the struggle to maintain human health.

In the Western world, the provisions needed for compliance with the principal rules of hygiene are generally available. However, in the developing countries the situation is very different. More than 50 percent of households in India do not have their own toilet, and half of the world's people wash their laundry by hand. Very many women still have no access to menstruation hygiene products.

Björn Theis heads the Corporate Foresight department at Evonik's innovation unit Creavis. His ELEMENTS column appears regularly at elements.evonik.com

A GLOBAL CHALLENGE

However, diseases do not respect national borders, and in today's globalized world they are spreading faster than ever before. Because of climate change, we also have to prepare for larger numbers of infections: Rising temperatures are expanding the range and the seasonality of mosquito species and the viruses they transmit. In developed countries, the widespread use of antibiotics has also meant that more and more strains of bacteria are resistant to the medicines that are currently available. As a result, even today strict hygiene measures are often the best way to prevent the spread of diseases.

Nor will the challenges in the area of hygiene diminish in the future. That's why the Corporate Foresight team and the scientists at Creavis are analyzing new approaches and concepts in hygiene, such as antimicrobial surfaces and coatings and the use of phages—viruses that attack and destroy specific bacteria. The goal is a clean and healthy future.

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Fe
Iron

"Iron forms the solid basis of my collection"

Hermann Sicius (61) has a degree in chemistry and works at the Liquid Purification Technologies Business Unit of the chemical company Lanxess. He is responsible for researching patents at the research department in Leverkusen

LOG **ANNA SCHRIEVER**
ILLUSTRATION **ORIANA FENWICK**

I haven't always been passionate about chemistry. At school, I didn't understand much of it at first. Chemical formulas were incomprehensible to me. However, I gradually understood that everything around us consists of chemical elements. Our surroundings are a form of tangible chemistry! When I was 14, I began to collect chemical elements. My first element was iron, which came from my chemistry kit. It forms the solid basis of my element collection.

I now own 56 of the 118 elements in the periodic table. You need to know, however, that only 81 elements are accessible and only 70 can be included in a collection. Some elements are very unstable and decay extremely quickly due to their radioactivity. Others are toxic and can't be collected as a result.

My collection is unique from today's standpoint. Many elements have become so rare and valuable that private individuals are no longer able to simply buy them. By far the most expensive element in my collection is without a doubt europium. In 1982 I paid more than 50 deutschmarks for half a gram. Today it would cost many times that. It's obvious that most chemical elements can't be bought at every street corner. I purchased most of them through the former company Degussa or from the specialist chemical trade.

I'm particularly fascinated by how the various elements were discovered and got their names. For example, the shiny silvery-white transition metal rhenium was named after the Rhineland in 1925. Sometimes elements are also named after famous researchers. An example is meitnerium, which was named after the Austrian physicist Lise Meitner.

In addition to chemical elements, I also "collect" foreign languages. I speak ten of them, most of which I taught myself. These languages range from English, French, Spanish, Portuguese, Italian, Danish, Dutch, Serbian, and Romanian (I should brush up on the last two) to Norwegian, Swedish, and Afrikaans, which I know how to read. I'm currently combining my passion for chemistry and languages by writing a handbook for industrial chemists. The book is about all of the elements and will be more than 1,000 pages long. It is scheduled to appear next year.

Masthead

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“Water will be the coal of the future

I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable.”

FROM THE NOVEL *THE MYSTERIOUS ISLAND* (1874) BY JULES VERNE