

ELEMENTS

Research. Knowledge. The future.



Happy End

**Probiotic feed additives keep poultry intestines healthy
and reduce the use of antibiotics → p. 10**

High-tech membranes make green hydrogen more cost-effective → p. 22

Chemical recycling: Innovative adsorbents for pyrolysis → p. 36

Probiotic

A preparation containing live microorganisms for stabilizing the microbiome

The name “probiotic” is derived from the Latin word *pro* (“for”) and the ancient Greek word *bios* (“life”). A probiotic is a preparation containing live microorganisms—usually lactic acid bacteria or yeasts—that is added to foods, dietary supplements or medications. Unlike antibiotics, probiotics are intended to stabilize the balance of the microbiome. They can suppress disease-causing germs, produce antimicrobial substances, influence the pH, and activate the immune system. Probiotics are used for the prevention and supportive treatment of various diseases.

Microorganism A microscopically small living organism that cannot be seen with the naked eye as an individual entity; often also referred to as a microbe

Antibiotic Metabolic products of microorganisms; antibiotics fight infections by killing bacteria or inhibiting their growth

Microbiome The totality of all microorganisms colonizing a living organism, understood as a complex community



DEAR READERS,

Until a few years ago, “resilience” was a term that only physics nerds or materials scientists could make sense of. These days, it pops up everywhere; in many circles, it’s used just as liberally as “sustainability.” Originally, resilience referred to a body’s ability to return to its original shape after being deformed. When there is a particularly large number of crisis-related developments, such an approach naturally becomes more important.

By now, the figurative meaning has come to predominate: resilience as the ability to overcome problems on one’s own and thus be robust. In this issue, we present three examples. One of them concerns the physical resilience of breeding poultry. All too often, the animals are given antibiotics, which indirectly becomes a problem for humans as well. An innovation from Evonik offers a solution and enables resilient feeding systems.

A second case takes us into the world of energy. Green hydrogen produced from solar or wind power is considered a key to the defossilization of industry. But this sustainable raw material is still too expensive. A new membrane developed by our experts in Marl makes its production more cost-effective, thereby facilitating the transition away from fossil fuels. This is another valuable contribution that increases resilience.

The same applies to a development from Evonik for the petrochemical industry, which is increasingly relying on pyrolysis oil derived from plastic waste. The problem here is the contaminants contained in the recycled product. Evonik has invented something that removes many unwanted substances from this oil. In this case, the path to greater resilience leads through purity.

Evonik is convinced that no matter which systems we want to make more resilient, sustainability will not lose its importance. For us, resilience and sustainability are two sides of the same coin, as the examples in our current issue show.

I wish you fascinating insights. If you have any questions, recommendations or criticisms about this issue, please write to me at elements@evonik.com

Jörg Wagner

Editor in Chief

All of the articles from the printed magazine, as well as additional current content, are also available on the Internet at elements.evonik.com



A healthy sip: The turkey poults in this growout house receive Ecobiol® Fizz through their drinking water. This probiotic from Evonik improves the balance of the animals' gut microbiome and makes them less susceptible to bacterial infections. In this way, the use of antibiotics can be significantly reduced

PROBIOTICS

10 Reducing resistance

Antibiotics are a boon for humanity. However, more and more often, their therapeutic use is no longer effective. The reason for this is the growing resistance of bacteria—caused by the excessive use of the medications, including in animal husbandry. With the probiotic Ecobiol®, Evonik is offering breeders and farmers an effective alternative that avoids unwanted side effects

DATA MINING

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Antibiotic resistance is on the rise worldwide. An overview of the situation in figures

GREEN HYDROGEN

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Water electrolysis is the key technology for producing green hydrogen. AEM technology, which combines the advantages of several processes, is considered especially promising. Evonik has developed polymer membranes that can now be produced in large quantities for this process

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The expansion of the hydrogen economy requires technological innovation and government regulation. Ann-Kathrin Klaas, an expert in energy systems engineering, explains what matters most

On a roll: Evonik is producing a newly developed high-performance membrane at a pilot plant in Marl. It's the key to more cost-efficient green hydrogen

PYROLYSIS

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If plastic waste cannot be sorted by type, pyrolysis is often used. To ensure that the oil recovered in this process can be reused in plastics of the highest possible quality, it must be freed of impurities—using innovative adsorbents

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Landfill or incineration are not options. This is how shredded plastic waste is turned back into a valuable raw material for new products



Here we go again: Arcus Greencycling produces pyrolysis oil for use in the production of new plastic from shredded plastic waste

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The world is full of challenges. Evonik is working on innovative solutions that are both economical and sustainable. We present them here.

The problem: Paints and coatings protect surfaces and make life more colorful. They frequently contain siloxanes, which ensure that the products spread evenly over a surface and repel water and dirt after curing. They also improve weather and UV resistance. Paints and coatings containing siloxanes can also contain small amounts of impurities that the European Union classifies as Substances of Very High Concern (SVHC)—that is, substances with particularly worrying properties.

The solution: Evonik manufactures a wide range of siloxane-based additives. In 95 percent of these products, the SVHC content is less than 0.1 percent, making them suitable for use in paints and coatings with Ecolabel certification. Careful selection of raw materials and optimized manufacturing processes have led to significant reductions in contamination by problematic siloxanes.

The former fishing village of Punta Brava on Tenerife is known for its brightly colored houses. The relatively humid climate and the salty air on the north coast of this Atlantic island take a particularly heavy toll on the paint on the facades and rooftop terraces.

Winds of change

Repairable rotor blades make wind turbines even more sustainable

Wind turbines are a key driver of the energy transition. However, once they reach the end of their service life, the rotor blades—made of glass-fiber reinforced plastics—have a significant environmental impact. Incinerating or shredding them to mix their components into other materials—such as cement—are not sustainable options; sending them to landfill is prohibited in the EU. And there's another problem: The blades, which are tens of meters long, often have to be completely replaced, even though only individual parts of them are damaged. This is because the structural layers are permanently bonded together, making them difficult or impossible to separate. As part of the EU project Recreate, researchers at the Fraunhofer Institute for Machine Tools and Forming Technology (IWU) are developing

Dismantling a wind farm in the Netherlands. To date, wind turbine rotor blades have been difficult to recycle

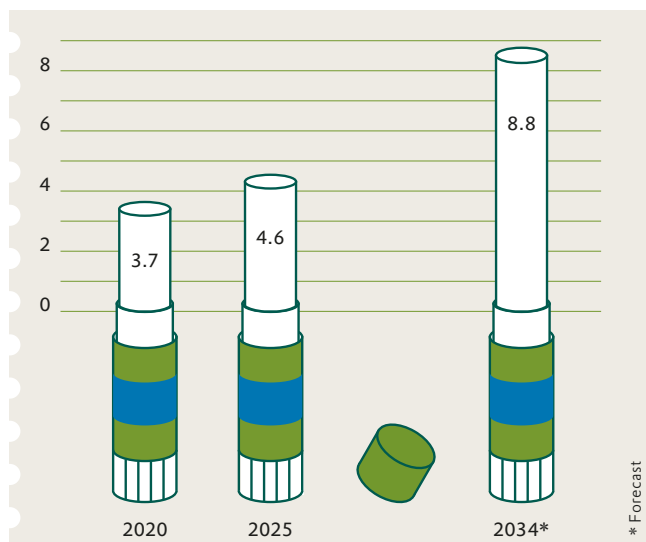


rotor blades with a modular design. Additional components are attached to a continuous load-bearing spar by removable adhesive bonds. For example, this makes it possible to replace the leading edges, which are subject to particularly heavy wear. In addition, natural-fiber thermoplastics that are easier to recycle are replacing glass-fiber reinforced plastics. In this way, wind energy can not only generate climate-friendly electricity, but can also be produced and used in a more sustainable manner.

THAT'S BETTER

Green force

Global sales of sustainable adhesives, in billions of US\$



Sustainable adhesives are becoming increasingly important worldwide in the packaging, construction, automotive, electronics, and consumer goods industries. The market for bio-based, recyclable, and low-emission products is growing steadily and is projected to increase by 7.6 percent annually through 2034. Advances in polymer and materials chemistry are driving this development. Bio-based raw materials, optimized polymer architectures, and new cross-linking concepts enable high-performance alternatives to fossil-based adhesives.

Source: fortunebusinessinsights.com

6,000

CHARGE-DISCHARGE CYCLES

An iron redox flow battery developed by researchers at the Chinese Academy of Sciences achieves this without any loss of capacity. That's equivalent to about 16 years of daily use. Until now, unstable iron ions and material losses have shortened the service life of such batteries. This problem has now been solved using a combination of protective mechanisms in the electrolyte. Large organic molecules shield the iron ions from hydroxide ions that would otherwise decompose them. At the same time, their high negative charge causes them to be repelled electrostatically by the hydroxide ions, which are also negatively charged. This technology enables durable and cost-effective large-scale storage solutions for electricity from renewable sources.

DIFORMYLXYLOSE...

...is a catalyst derived from plant cell-wall sugars that researchers at the Swiss Federal Institute of Technology in Lausanne are combining with lignin—a component of wood—to replace the harmful bisphenol A (BPA) and bisphenol S (BPS) in thermal paper coatings. When heated, the coating made from plant-based biomass produces clear, stable printed images and, unlike BPA or BPS, shows no detectable toxic effects or disruption of hormones. It enables the production of more environmentally friendly receipts, tickets, and shipping labels.

PEOPLE & VISIONS

“We want to electrify the chemical industry”

THE PEOPLE

Martin Baumgärtl and Gianluca Pauletto share a passion for chemistry and sustainable energy technologies. Baumgärtl, who was born in Altötting, Germany, studied chemistry at the Technical University of Munich (TUM) and earned his doctorate with a dissertation on heterogeneous catalysis. Pauletto is from Castelfranco Veneto, Italy; he studied chemical and process engineering at the University of Padua and earned his doctorate in Canada. His research into more efficient uses of natural gas led to the idea of using electricity to heat chemical processes. Drawing on Baumgärtl's expertise, they further developed the approach and founded the TUM spin-off Sybox.

THE VISION

“We want to drive forward the electrification of energy-intensive chemical processes,” says Baumgärtl, describing Sybox's goal. The company's technology replaces fossil fuels in high-temperature industrial processes with electricity to heat the reactors. As a result, synthetic fuels (e-fuels), as well as hydrogen, methanol, and other basic chemicals, can be produced with significantly lower emissions in the future. The founders are currently working on their first commercial, electrically heated 10-megawatt reformer, which is intended to produce synthesis gas for methanol production in Denmark.

Founders Gianluca Pauletto (left) and Martin Baumgärtl in front of a demonstration unit from their startup, Sybox



This way, please

Innovative “signposts” direct chemical reactions to hard-to-reach locations within a molecule

A research team at the University of Vienna, led by Prof. Nuno Maulide, has developed a new method—known as “cation sampling”—for precisely modifying carbon-hydrogen bonds. The targeted functionalization of C-H bonds in complex molecules is a core task of modern synthetic chemistry. However, many reaction sites are difficult to access and require complex multi-step processes or the use of expensive catalysts. In cation sampling, positive charges

migrate along a molecule's carbon chain and are guided by specific ketone groups that act as molecular “signposts.” This enables especially precise control of the reaction. The method opens up new approaches for a more efficient and sustainable synthesis of complex molecules and, among other things, simplifies the development of pharmaceutical active ingredients and high-tech materials.

GOOD QUESTION



Mr. Schreiner, will hexanitrogen solve our energy problems?

That's an ambitious and far-reaching question. Hexanitrogen (N_6) is not a finished product, but a scientific breakthrough with revolutionary potential. When it decomposes into atmospheric nitrogen, no CO_2 is produced. As an energy source, N_6 would be clean and nontoxic, with an exceptionally high energy density.

However, we are only at the beginning of our research. The biggest challenge is the stability of N_6 . We must learn to handle this extremely high-energy molecule safely—in its production, storage, and controlled decomposition. N_6 won't solve our energy problems overnight, but it could be the key to new concepts for clean, highly efficient energy storage. This is a high-risk scientific project with the potential for enormous ecological and economic returns.

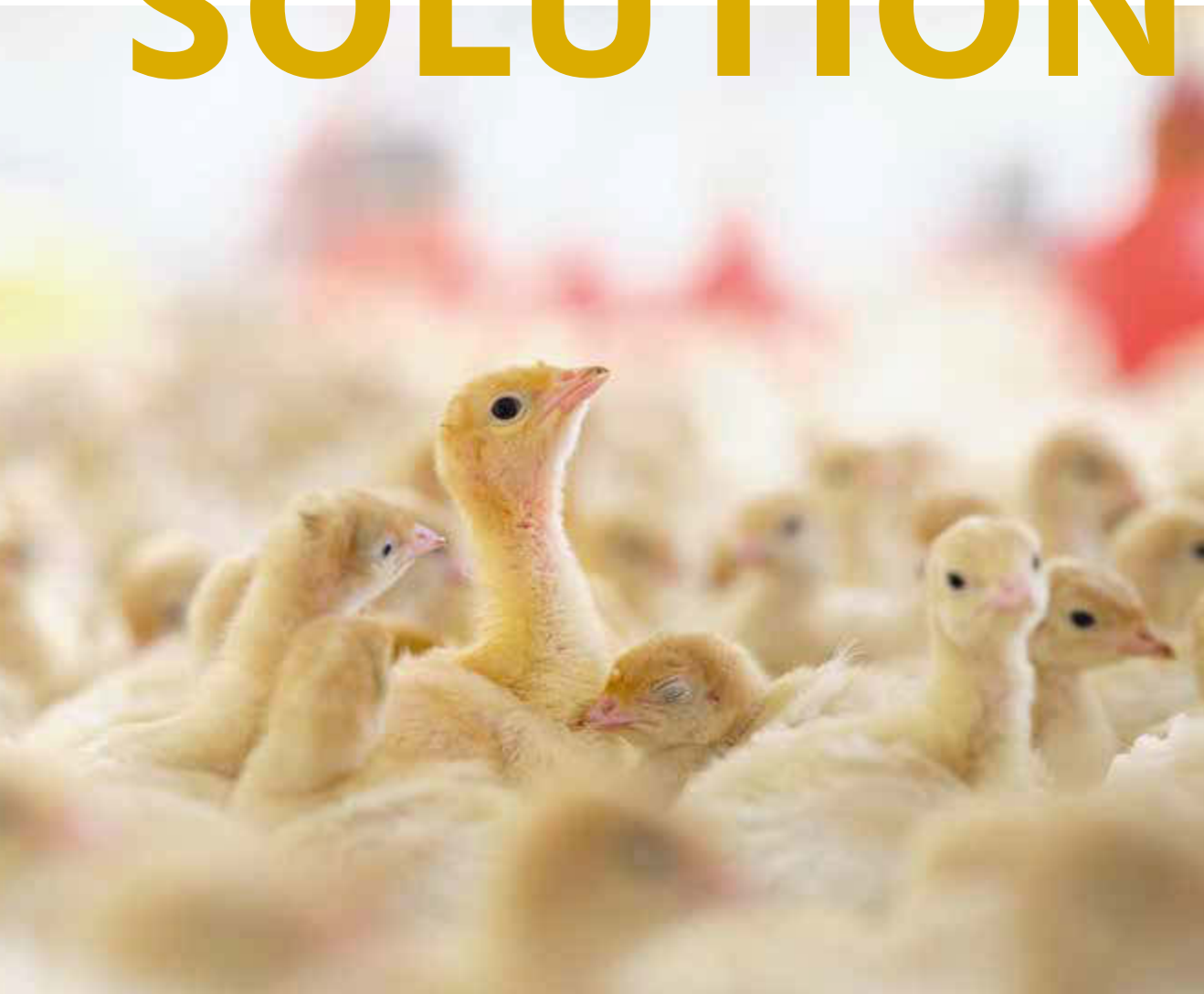
Dr. Peter Richard Schreiner is a professor of organic chemistry at Justus Liebig University Giessen (JLU) and director of the Institute of Organic Chemistry



Bacillus bacteria are cultivated on an agar-based culture medium in a Petri dish at Evonik's Halle-Künsebeck site (this page). Eight-day-old turkey poults on Corinna Wilke's poultry farm in the district of Oldenburg, Germany (right)



SPORE SOLUTION



Evonik's latest probiotic feed additive not only keeps poult healthy; its use in poultry farming makes an important contribution to the fight against antibiotic resistance. How Ecobiol® Pro is produced and why it benefits people around the world

TEXT **SINA HORSTHEMKE**



The poults have moved into their new home in Corinna Wilke's barn (right). The animals receive Ecobiol® Fizz via the water in the red drinking troughs

When visitors step through the door of the turkey house, excitement spreads through the well-lit hall. The previously gentle peeping of individual poults swells into an orchestra of twittering; fluffy yellow baby turkeys with beady black eyes stretch their necks curiously towards the door. They run towards the visitors from all sides, fearlessly examining their rubber shoes with their beaks. The air is as warm and humid as before a summer thunderstorm, it smells of wood shavings and feed.

With all the hustle and bustle, it's impossible to estimate the number of animals, some of which head for the red drinking troughs while others gather around the yellow feed dispensers. But Corinna Wilke knows exactly how many animals she moved into the brood house eight days ago: 4,800 hens and 8,800 toms, all freshly hatched, were delivered to the farm. The farm that Wilke, a veterinarian, runs with her husband is located in the district of Oldenburg, where half-timbered houses are thatched, wind turbines stand on the horizon, and people greet each other with the North German greeting "Moin." The Wilkes have specialized in turkey rearing: They raise the poults, which initially weigh around 60 grams, for six weeks. When the young animals weigh more than two kilos, they are passed on to the grow-out farm, where they remain for four months until slaughter.

Losing birds to disease not only means animal suffering; it is also bad for business. This is why hygiene regulations are strict. Anyone entering Wilke's barn has to slip plastic covers over their feet and lower legs, put on rubber shoes and a blue disposable overall, disinfect their hands, and change their shoes again before taking their first step into the sawdust. "Keeping all the animals healthy at all times is not that easy," she explains. "If you notice an infection too late, the entire rafter could be put at risk in the worst case." That's why she checks on her "turkey kindergarten" four to six times a day, cleans the drinking troughs, takes water samples, monitors the birds' behavior, and examines their droppings in the laboratory of the veterinary practice where she is employed. "Diarrhea is a common problem," says Wilke. "Young turkeys are particularly susceptible, as their intestinal flora quickly gets mixed up."

STRICT GOVERNMENT REGULATIONS

Livestock farmers have been using antibiotics both therapeutically and metaphylactically to combat infections in barns for decades. While only sick animals are treated during therapy, metaphylaxis also permits the administration of therapeutics to healthy animals in the same herd. However, it is now clear that antibiotic use urgently needs to be reduced. The problems caused by resistant

“If you notice an infection too late, the entire rafter could be put at risk in the worst case”

CORINNA WILKE, POULTRY FARMER AND VET

germs have become too extensive worldwide (see p. 16). The veterinary office’s guidelines for antibiotic use in livestock barns have therefore become more restrictive over the past 20 years. For example, Corinna Wilke is now required to take samples beforehand in order to clarify which pathogen she is dealing with. Distributing a broad-spectrum antibiotic as a precaution has been severely restricted in animal husbandry since 2022. In addition, using such antibiotics to compensate for poor husbandry conditions is now prohibited. “I also have to document exactly how many turkeys were given which quantities of a medication on which days,” Wilke says. If the same disease occurs twice in succession in the same rafter, a resistance test with pathogen identification is required. Moreover, anyone who uses an above-average amount of antibiotics in their turkey houses has been required to work out countermeasures with their vet since 2014. Using the drugs as growth promoters—which used to be common practice and is still done in some countries because animals then put on more meat—has been banned throughout the EU since 2006.

The Wilkes’s records show that they have needed less antibiotics than before for about a year now. Since their turkeys started regularly receiving Ecobiol® Fizz, they are no longer sick as often as they were before. The effervescent tablets, which are dissolved in water, contain a probiotic from Evonik that is also available as a feed additive. The product has now been optimized and Ecobiol® Pro is being launched on the market. Regardless of whether livestock owners and feed mills add it to drinking water as a tablet or to feed pellets as a powder, the principle is the same: Among other things, the

product stabilizes the intestinal microbiome of poultry and inhibits the spread of dangerous intestinal pathogens such as *Clostridium perfringens*. This bacterium often leads to infections in chickens. It not only causes diarrhea but also severe damage to the intestinal mucosa, which adversely affects the animal’s well-being and growth and can also be fatal. Droppings from infected birds can quickly infect other birds as well. Farmers suffer considerable economic damage due to intestinal diseases in their livestock. Experts estimate that this damage amounts to up to six billion US dollars a year worldwide.

Thanks to a modified production process, the effectiveness of Ecobiol® has now been increased. According to a feeding study conducted by Oklahoma State University, Ecobiol® Pro improves the survival rate of broilers by 50 percent compared to a commercially available product. Wilke reports that she noticed the effect in her barn from the very first use: “Turkeys are very sensitive and react to changes in the weather or feed, for example. Since we started giving them Ecobiol®, everything has become more relaxed. Our animals are healthier and even reach a higher weight.” →



“The world has a huge problem with antibiotic resistance”

STEFAN PELZER, HEAD OF
MICROBIOME RESEARCH AT EVONIK



Stefan Pelzer heads microbiome research at Evonik. His team in Halle-Künsebeck is developing new probiotics using the chicken intestine model DAISy

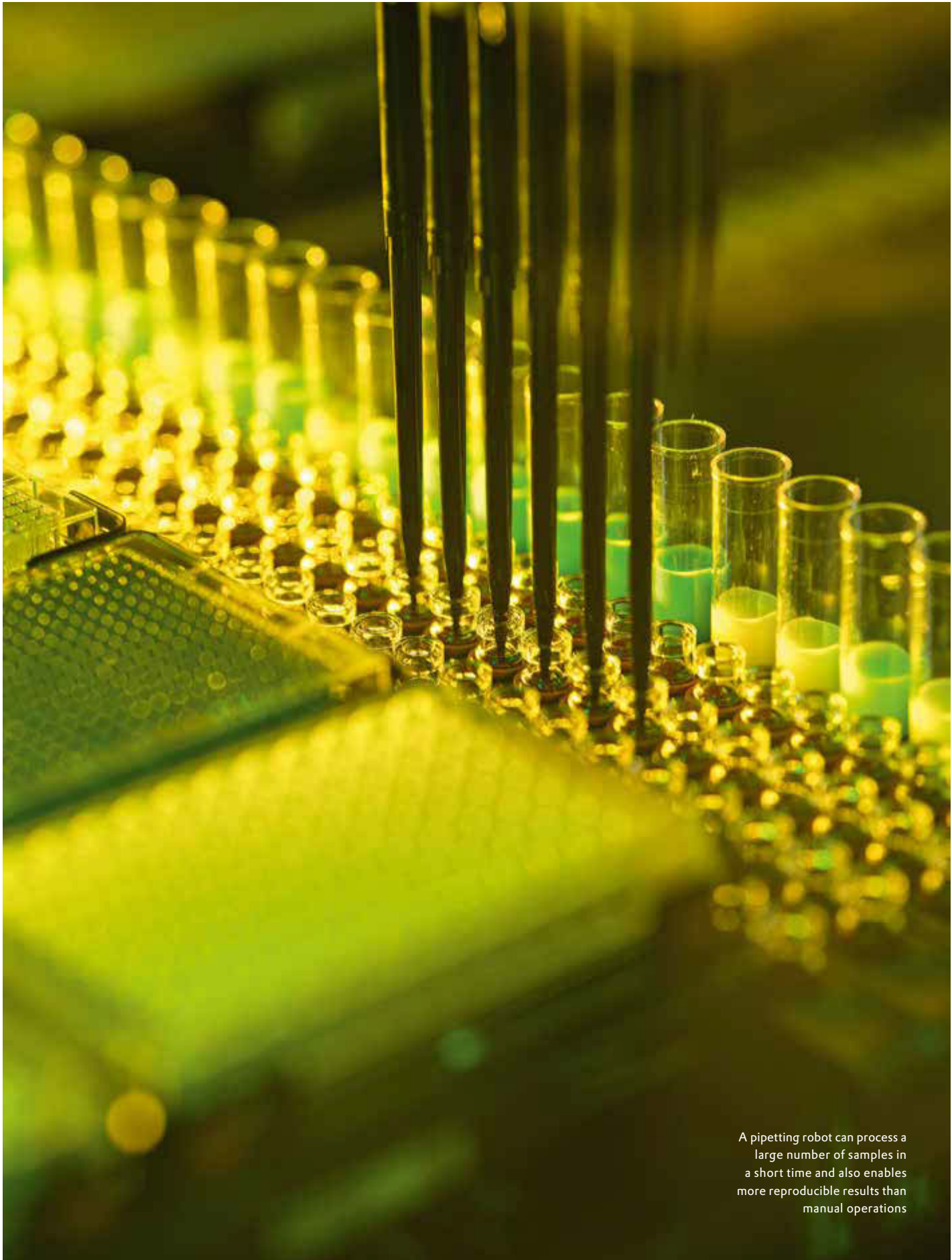
What makes Ecobiol® products special is that this probiotic, which supports a healthy intestinal flora with beneficial bacteria, contains spores rather than active cells. Bacteria of the genus *Bacillus* produce these so-called endospores when nutrients become scarce. The spores are resistant to heat and cold and can withstand acid, radiation, and high pressure. In short, they can survive for millions of years under the most adverse conditions and wait for better times. Only when living conditions become suitable do the spores outgrow and develop back into active bacteria that can multiply.

Evonik made use of the microorganisms' survival strategy when developing Ecobiol® Pro, whereby the spores of the *Bacillus velezensis* CECT 5940 strain of beneficial intestinal bacteria are not supposed to become active when the pellets are pressed, during feed storage,

in the feed trough or the upper gastrointestinal tract of a chicken; instead they should become active only after they reach the small intestine. But things have to move quickly there: Depending on the age of the animal, feed passes through the entire intestinal tract in three to five hours, and the spores outgrow in the duodenum within one hour. The timing is crucial in order to ensure that the probiotic can work there effectively.

TESTS IN THE POULTRY INTESTINE MODEL

Stefan Pelzer, Head of Microbiome Research at Evonik, and his team investigated what Ecobiol® does in the chicken intestine. At the chemical company's Biotech Hub in Halle-Künsebeck, Westphalia, scientists have been working for several years with the “Dynamic Avian Intestine in vitro System” (DAISy) poultry intestine simulation model, which has already proven its value in the development of other products. The conditions in each of the system's glass vessels are the same as those in the respective sections of a chicken's digestive tract—the pH, oxygen content, enzyme activity, and microbial composition correspond to the conditions in the animal. “We can put in different feed mixtures and let DAISy digest them,” Pelzer explains. “The model also enables us to take samples from each section of the gut, which would otherwise require us to euthanize a chicken.” A pipetting robot does some of the lab work for the humans →



A pipetting robot can process a large number of samples in a short time and also enables more reproducible results than manual operations

DANGEROUS RESISTANCES

The discovery of antibiotics revolutionized medicine—and at the same time sowed the seeds of a global crisis. That’s because it is increasingly the case that bacteria can no longer be combated with the available means

If Alexander Fleming had tidied the laboratory before his vacation in 1928, antibiotics would not have been discovered so soon. On his return, the London physician and bacteriologist found a moldy Petri dish. He was astonished to see that no bacteria were growing near the *Penicillium notatum* mold. Did the blue-green microbe secrete something that inhibited the single-celled organisms—an antibacterial substance perhaps? Fleming pursued the matter—and since the publication of his research results in 1929, he has been regarded as the discoverer of the world’s first antibiotic. It took more than ten years until Howard Florey and Ernst Boris Chain succeeded in preparing Fleming’s “penicillin” in a manner that made it possible to inject it into patients. However, pharmaceutical companies were already producing tons of the active ingredient by 1943. This saved thousands of lives, as penicillin made it possible for the first time to cure infections that were previously often fatal.

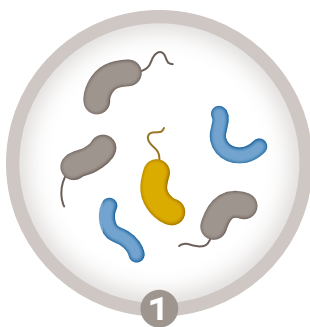
Fleming, Florey, and Chain were awarded the Nobel Prize in Medicine in 1945 for their work. In his acceptance speech, Fleming spoke of the dangers: “It is not difficult to make microbes resistant to penicillin in the

laboratory by exposing them to concentrations not sufficient to kill them, and the same thing has occasionally happened in the body.” He warned that this could lead to the resistant bacteria infecting other people who penicillin would no longer be able to help. Every antibiotic inhibits most of the bacteria it is targeted at. However, sometimes some bacteria survive—if they are resistant due to a random mutation—and then multiply. Bacteria are also able to exchange genes with each other. This means that resistance can spread quickly. Sometimes germs develop their own resistance mechanisms as well. After some time, they manage to break down the antibiotic or transport it out of their cells. The more widely and more frequently antibiotics are used, the more likely it is that resistant bacteria will develop and spread.

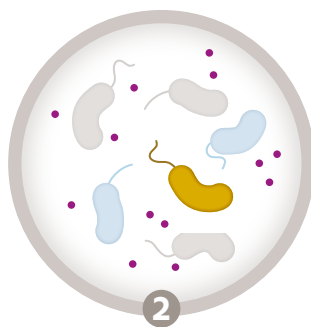
After Fleming’s penicillin, numerous other antibiotics were developed between 1940 and 1970, and there are now more than 80 such active pharmaceutical ingredients. However, the once sharp weapon against pathogenic bacteria has been blunted because antibiotics are increasingly often proving ineffective. Due to the inflationary or often incorrect use of antibiotics in human medicine and livestock farming, many germs have changed over time and become resistant to the once effective substances. Antibiotics are already no longer available for one in six bacterial infections, which is why around 1.3 million people die every year (see Data Mining, p. 21). Since 2022, the World Health Organization (WHO) has classified antibiotic resistance as a “global threat”—partly because the development of new substances is lagging behind. In addition, WHO Director-General Tedros Adhanom Ghebreyesus has warned that “antimicrobial resistance is outpacing advances in modern medicine.”

It starts with the bacterium

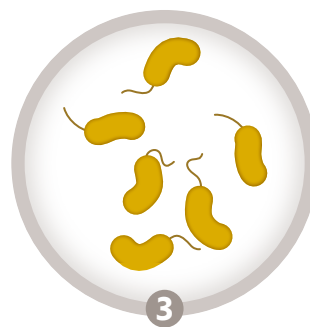
How resistance to antibiotics develops



In the body (and elsewhere) “good” bacteria live that protect against disease, but also harmful bacteria that cause illness, and a few bacteria that happen to be resistant.



An antibiotic kills almost all bacteria, i.e. the “good” and the pathogenic ones. The bacteria that happen to be resistant survive, however.



The resistant bacteria can multiply unhindered because the antibiotic does not affect them.



They are even able to pass on their resistance to other bacteria. This is how the resistance spreads.



Microbiologist Stella Molck counts the bacterial colonies on an agar plate in the laboratory. Under good conditions and warmth, each spore in the sample outgrows into a visible colony containing around one million bacteria



and dilutes the semi-digested feed residues from DAISy to the desired concentration. “The spores survive the crop and then pass through the proventriculus and gizzard,” Pelzer explains. “In the small intestine, enzymes break down the feed further, producing amino acids and sugar.” Both of these serve as a signal for the spores to start outgrowth. By the time the digesta has finally reached the lower part of the small intestine, almost all the spores have turned into active cells.

FERMENTATION AS THE KEY TO SUCCESS

Ecobiol® Pro is not the only probiotic feed additive on the market. However, the experiments using the DAISy model showed that many other products never become active bacteria at all in chicken intestines. Instead, the birds excrete the spores unused because they do not outgrow in time. This means there can be no effect. “In other words, it’s not enough to count the spores in the feed to determine the effectiveness of a product,” says Pelzer, who has been carrying out research for Evonik for 14 years and teaches at the University of Tübingen. “The decisive factor for the probiotic effect is that the spores outgrow in the right place in the intestine at the right time.”

Like many successful Evonik products, the spores for Ecobiol® Pro are produced by fermentation, one of the company’s specialties. This biotechnological process utilizing selected bacteria on an industrial scale initially provides perfect living conditions for the microorganisms. The temperature, pH, pressure, oxygen content and nutrient supply are all optimized in such a manner that the bacteria multiply within a short time. Only when large amounts of biomass have been produced and the nutrients have been fully consumed does sporulation begin: The bacteria form their persistent dormant form, the endospore. “We discovered that we can use the production conditions in the fermenter to influence the memory of the spores and thus the outgrowth kinetics in the intestine,” says Pelzer. “With this knowledge, we optimized the manufacturing process and the effect of our probiotic without having to change the bacterial strain.” Compared to the average of the competing products tested, the new Ecobiol® Pro outgrows significantly faster. “This puts Ecobiol® in the top league of probiotic products,” says Stella Molck, a microbiologist in Pelzer’s team. →



The largest tank in the fermentation hall at the production facility in Onzonilla, Spain, has a capacity of 8,000 liters

Since Ecobiol® Pro is added to different types of feed all over the world, the team in Halle-Künsebeck also used the DAISy model to test how the spores behave in different mixtures, for example with maize, soybean meal or wheat. “Not all feeds are the same,” Pelzer points out. “The quality of the raw materials constantly varies and the formulations differ from region to region.” Still, laboratory tests have shown that the outgrowth rate of Ecobiol® Pro is amazingly stable. “It works consistently well with all feed mixtures, while the competitor products display greater variations,” Pelzer explains.

Pelzer also believes it is important to point out that probiotic feed additives benefit not only broilers and turkeys: “Humanity has a huge problem with antibiotic resistance, and if we don’t address it, the number of deaths that result will continue to rise tremendously.” Livestock farming accounts for 73 percent of the antibiotics used worldwide—far too much, Pelzer believes: “In line with the World Health Organization’s One Health concept, which sees health risks for humans, animals, and the environment as being closely linked, we should not be indifferent to the massive use of antibiotics in animals. After all, this also affects our lives.”

The high informational value of the tests in the chicken intestine model enables the targeted evaluation of probiotic efficacy under customer-specific feed conditions. Stefan Pelzer and Stella Molck offer customers

close cooperation on this basis. For example, customers can send in feed to have the outgrowth rates of various probiotics tested individually. “Firstly, we compare the outgrowth behavior of Ecobiol® Pro with other products in customer-specific feeds and give the customers tips on how they can improve the effectiveness of the probiotic,” Molck explains. The aim here is to learn more about Evonik’s own product and better understand which factors influence the outgrowth of the spores. In the future, the company intends to use these findings to determine how the outgrowth behavior and thus the effectiveness of Ecobiol® Pro can be further improved.

STORAGE AT MINUS 80 DEGREES CELSIUS

How Ecobiol® Pro is produced on an industrial scale can be seen in the northwestern part of Spain, where Molecular biologist Pilar Honrubia manages a small production facility in Onzonilla, south of León. Twenty-nine people are employed here; a long row of windows in the laboratory provides a view of the fermentation hall. Two new fermenters have been in place there for four years, with the largest tank holding 8,000 liters. The fermentation process for Ecobiol® Pro takes five days and begins every Monday as soon as an employee has carefully carried a fresh starter culture from the laboratory into the hall and added it to the first tank.

Each starter culture is prepared in a glass flask in the facility's production laboratory on the basis of bacterial stem cell banks that were established in Halle-Künsebeck. After they have been delivered to Onzonilla, the bacterial cultures are stored in a freezer at minus 80 degrees Celsius. Several cultivation steps are required before the large fermenters can be inoculated. "The biggest enemy of successful fermentation is contamination with other microorganisms," says Honrubia. "We therefore pay strict attention throughout the entire process to ensure there is no contamination. Otherwise, in the worst case, we would have to get rid of the entire batch." The plan is to continue to ramp up production in Onzonilla and soon have it running around the clock in two fermenters simultaneously, including on weekends.

Pumps and engines roar in the hall and there is a malty smell. A forklift truck drives past, two men wearing safety goggles heave a thick blue hose upwards to an opening in the fermenter. The other end is submerged in a tank containing liquid glucose, which the men are now pumping into the fermentation vessel, which is around four meters high. Sugar is the most important ingredient in fermentation. It serves as the nutrient for the bacteria while they multiply behind the stainless-steel wall of the tank. Once the glucose has been used up, the lack of nutrient triggers sporulation. Once this is complete, the biomass consisting of the nutrient solution, water, and spores can be harvested. →

"We pay strict attention to ensure there is no contamination"

PILAR HONRUBIA, HEAD OF ECOBIOL® PRODUCTION
AT EVONIK



Pilar Honrubia (left) manages the Evonik plant near León. New bacterial cultures are regularly delivered from Halle-Künsebeck and stored at minus 80 degrees Celsius.



After fermentation, the biomass is centrifuged, shock-frozen into plates, and freeze-dried

After centrifugation, a thick brown pulp remains. The pulp is poured onto trays, shock-frozen at minus 35 degrees Celsius, and stored in the hall's freezer container. The next step, drying, takes place just a few meters further on. The frozen water is removed by sublimation in two large freeze dryers, leaving behind dry slabs consisting mainly of spores. The boards are crushed and sieved, after which the powder is mechanically mixed with various excipients and filled into bags—Ecobiol® Pro is ready.

In order to ensure that each bag contains the specified amount of spores, the laboratory staff test up to 40 samples from ongoing production every day. Samples are taken from the nutrient solution several times during the entire incubation period; after they are dried, the concentration of the Ecobiol® biomass is determined. This is done because the end product must contain a defined concentration that is guaranteed to the customer. To count the spores, the biologists dilute the samples in the laboratory and spread them out on agar plates, where the spores outgrow again. Each one grows into a bacterial colony on the culture medium in the incubator; the colonies are then visible to the naked eye or can be digitally scanned and counted.



The plates with the spores are crumbled by a machine, mixed with excipients, and filled into bags for transport to customers

The employees in the Spanish laboratory also test finished pellets to which Ecobiol® Pro has been added in feed mills; a new delivery has just arrived. However, the facility doesn't just employ humans, as a separate building on the site has space for 475 chickens on which feed mixtures are tested—under the strict supervision of two veterinarians.

Although the new Ecobiol® Pro has only just been launched on the market, one thing is already clear: It will help reduce the use of antibiotics in livestock farming. The animals will be the first to benefit—for example Corinna Wilke's turkey poults, which are doing better with probiotics. Their owner is not only pleased in her role as operations manager: "As a veterinarian, it's important to me that we can use antibiotics more responsibly thanks to products like these." Because this will also help people all over the world. —



Sina Horsthemke is a science journalist based in Munich. She has a degree in biology and writes primarily about health-related topics and biotechnology

LIFE AND DEATH

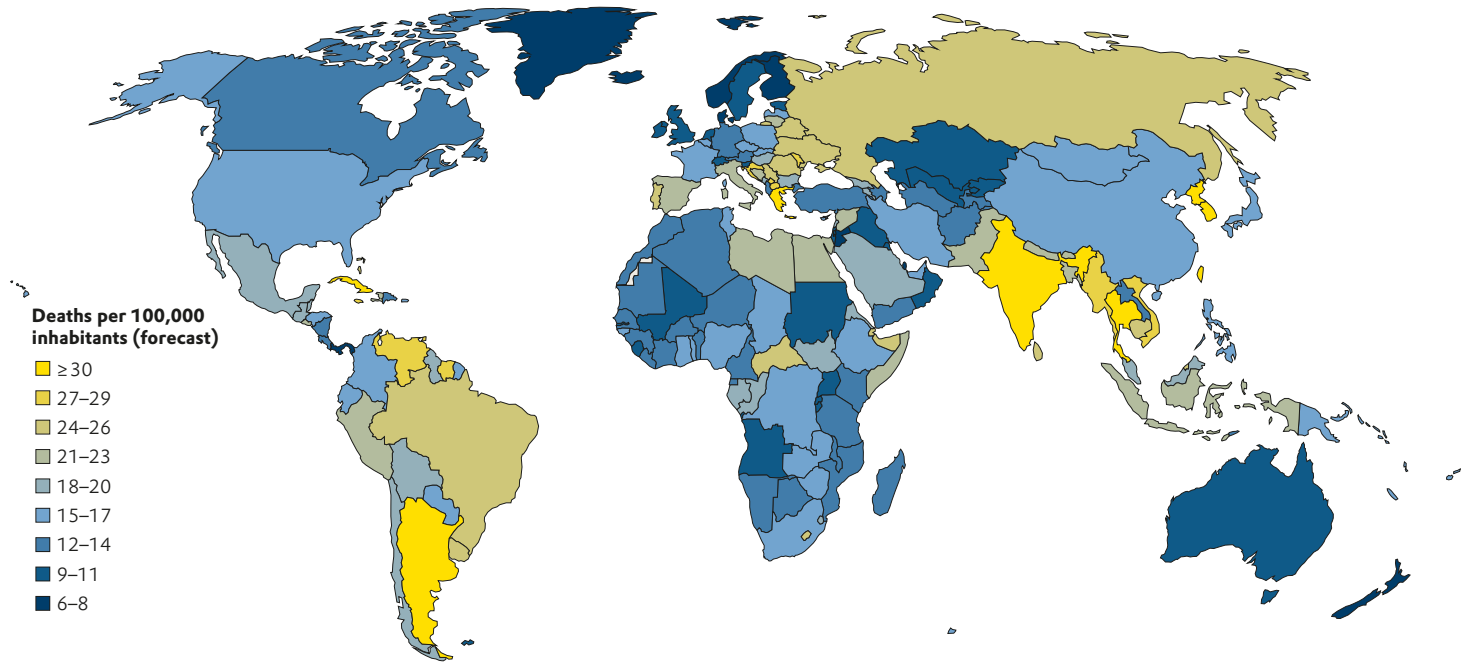
Antibiotics help save millions of lives. However, they pose a problem when added to animal feed in particular, as their mass use promotes resistance. An overview of the situation in figures

Sources: FMI, Statista

INFOGRAPHIC **MAXIMILIAN NERTINGER**

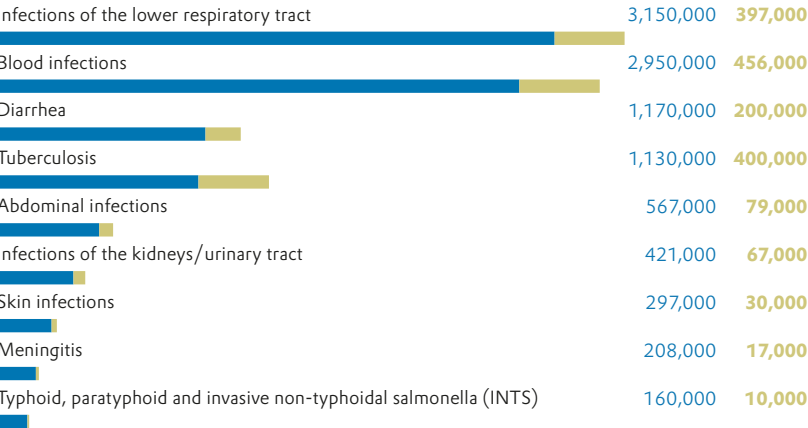
Where it gets dangerous for people

Antimicrobial resistance (AMR) arises when microorganisms no longer respond to medication. In some regions of the world, the resulting mortality will increase significantly, *estimated number of AMR-related deaths per 100,000 population in 2050*



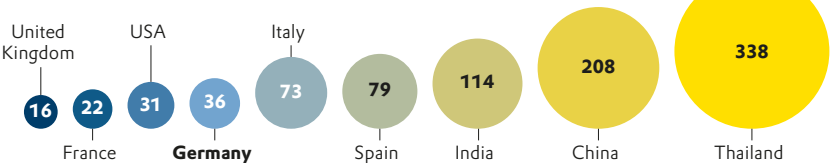
Less favorable chances

Non-AMR-related deaths and AMR-related deaths, by selected types of disease, 2021



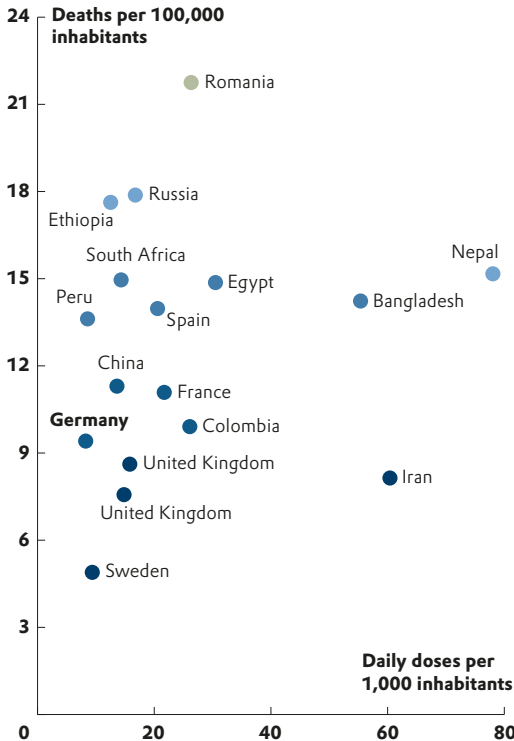
Disastrous additive

Use of antibiotics in livestock, in selected countries in milligrams per kilogram of body weight, 2023



Risks and side effects

Ratio of AMR-related deaths to daily doses of antibiotics, in selected countries, 2021



A FINE ADVANTAGE



Green hydrogen is seen as a great hope for the energy sector in the future. A team from Evonik has put a pilot plant into operation in which new high-performance membranes for water electrolysis are now being produced on a large scale. These hold the key to more cost-efficient production of green hydrogen, which industry needs as a building block for decarbonization, and for energy independence as well

TEXT **TIM SCHRÖDER**

Bright prospects: The DURAION® membrane is the key to more cost-efficient green hydrogen. Evonik is now producing it on a commercial scale at its new pilot plant in Marl





“If we want to stop using fossil fuels, there’s no getting around hydrogen”

CHRISTIAN DÄSCHLEIN, HEAD OF NEW GROWTH AREA
AEM AT THE EVONIK INNOVATION FACTORY

Before the coated film is rolled up, cameras scan the surface. No scratches, no air bubbles, not even pinhead-sized holes should be visible in the polymer layer. Perfection is required because the component must deliver top performance in its later use—as the heart of an innovative electrolysis technology with which green hydrogen can be produced efficiently and relatively inexpensively.

PROVEN TECHNOLOGIES WITH WEAKNESSES

Hydrogen, a colorless and odorless gas, is considered to be an environmentally friendly energy source for the future if it is produced using green electricity. The global demand for hydrogen is already around 100 million tons per year. This hydrogen is usually made from natural gas. Using electrolysis is more sustainable. Here, electricity from renewable energy sources is used to split water into its hydrogen and oxygen components. Switching to green hydrogen would thus reduce CO₂ emissions by around one billion tons. This corresponds to around one third of the EU’s energy-related emissions.

However, the current electrolysis processes have drawbacks: Depending on the technology involved, the facilities needed for them have to be very large or else equipped with components made from expensive raw materials. The new polymer membrane from Marl, which is known as DURAION®, is now set to pave the way for an electrolysis technology that combines the advantages of established processes and avoids their weaknesses: AEM electrolysis. AEM stands for anion exchange membrane—a layer that separates two electrolysis half-cells in which hydrogen and oxygen are respectively produced. The hydroxide ions (OH⁻) formed during electrolysis pass through the membrane (see diagram on p. 26). →

The facility in the factory building on the Evonik site in Marl is the size of a double truck-trailer combination. When Production Manager Florian Roghmans explains what goes on here, he has to speak up against the noise of the ventilation system: “This is where the carrier film is drawn into the machine,” explains the chemical engineer, pointing to a transparent roll on the left-hand side of the unit. The web, which is one meter wide and just a few micrometers thick, passes under a container filled with a honey-yellow liquid—the polymer solution. A squeegee gently applies the liquid to the web so that a thin film is visible. Wet with the polymer and stretched taut, the web runs into the center section of the large system, to the dryers. Inside these, nozzles blow warm air against the film until it emerges dried at the other end after a few minutes. “It all looks very simple, but it’s quite sophisticated,” says Roghmans. “The polymer must dry slowly and evenly on the carrier film, otherwise there will be cracks or defects—and that means rejects.”

At the start of membrane production, cameras measure the wet film thickness of the polymer solution



The chemist Christian Däschlein is certain that hydrogen will play an important role in the transformation of industry toward greater sustainability and resilience. “If we want to stop using fossil fuels in the future in order to reduce CO₂ emissions, there’s no getting around this energy carrier,” says Däschlein, who works at the Evonik Innovation Factory. “It’s also essential for making our energy system more resilient and thus making Europe more independent.” Däschlein got the membrane ready for the market with his team of more than 30 people. The chemical and steel industries need hydrogen, and gas-fired power plants will also increasingly be operated using it. “It’s crucial that the electrolyzers are supplied with electricity from renewable sources,” says the Evonik expert. “That’s because only green hydrogen makes sense when it comes to decarbonizing processes and products in these industries over the long term.” Around 100 million tons of hydrogen are currently required worldwide each year. According to estimates, demand is set to rise to between 300 and 700 million tons by 2050, depen-

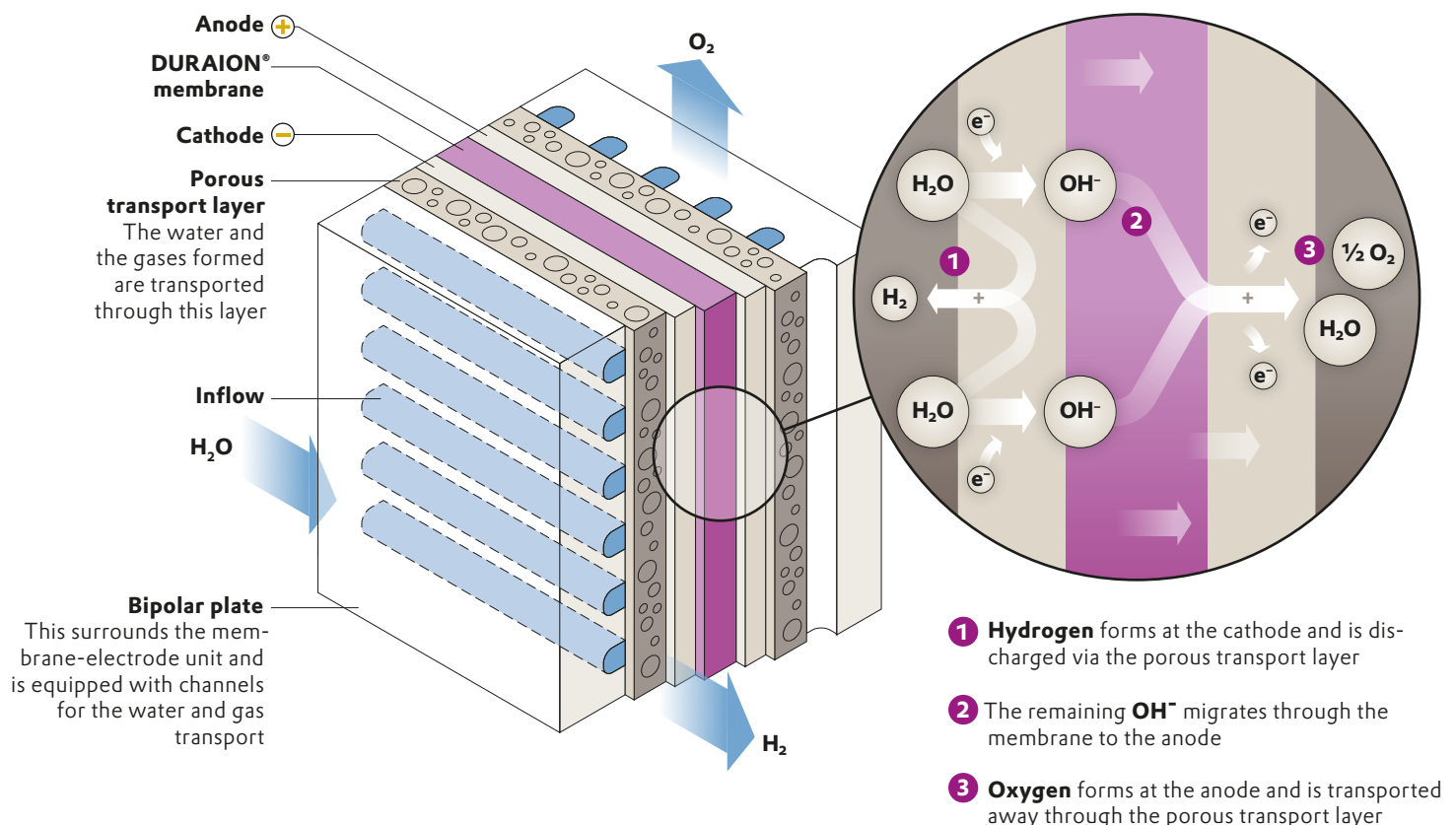
ding on the scenario. Consulting firms predict that 60 to 70 percent of this hydrogen will be green hydrogen. The new DURAION® membrane could give the hydrogen economy an additional boost. Moreover, with the new pilot plant in Marl, a facility is now available that can meet the growing global demand for membranes for AEM electrolysis.

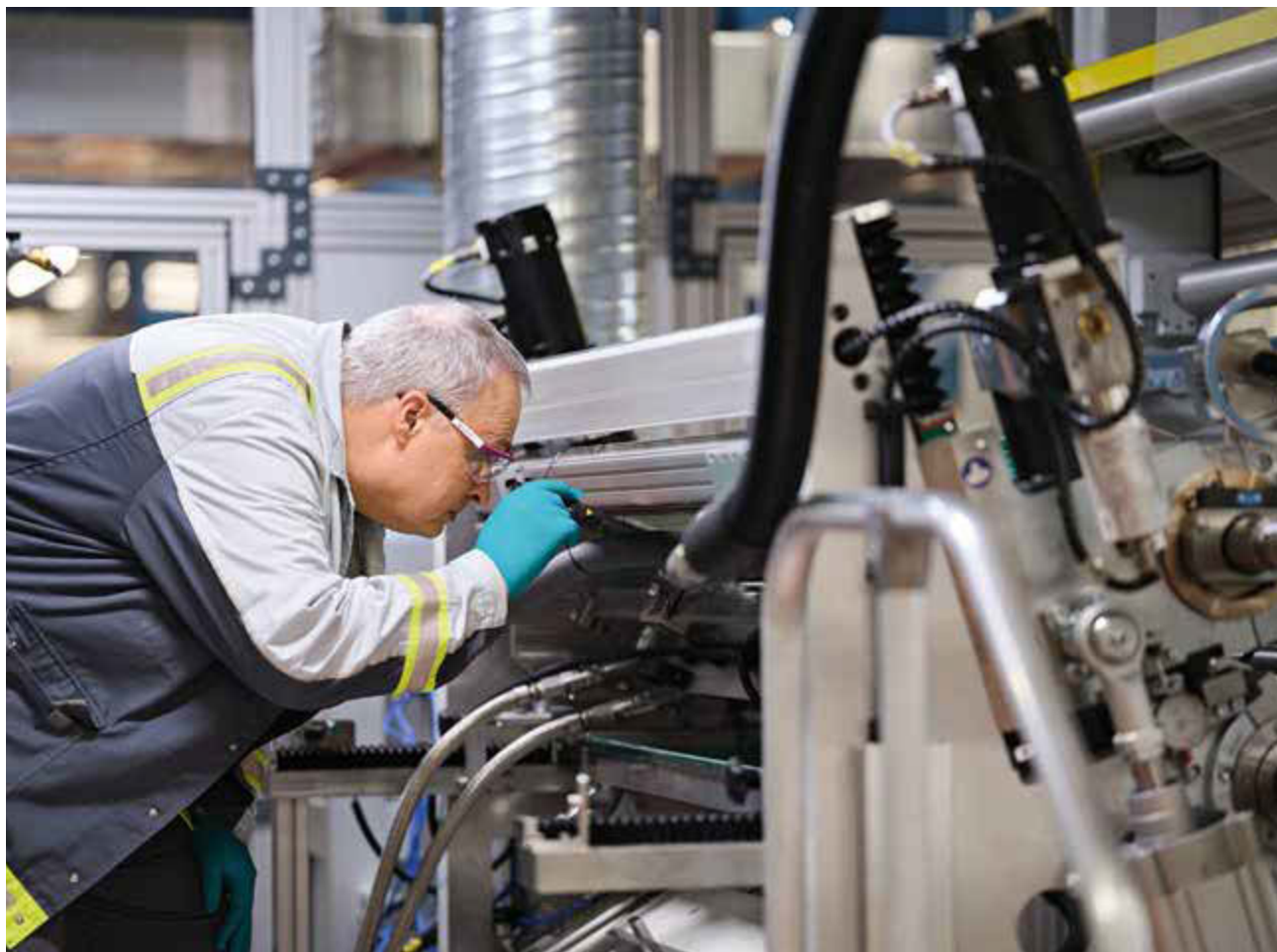
The advantages offered by AEM electrolysis become apparent when it is compared with conventional processes—AEL (alkaline electrolysis) and PEM electrolysis (proton exchange membrane). What all electrolyzers have in common is the fact that the hydrogen and oxygen are cleanly separated from each other in the two half-cells so that the explosive oxyhydrogen reaction familiar from chemistry lessons does not occur. This requires a separating layer such as the DURAION® membrane.

AEL is the classic method that has been used to produce hydrogen for decades. For technical reasons, however, the electrolyzers used here only work with moderate current densities and do not operate under pressure,

THE MEMBRANE MAKES THE DIFFERENCE

How electrolysis splits water into hydrogen and oxygen using an anion exchange membrane (AEM)





The technician Thomas Schrief checks whether the polymer solution is being evenly applied to the carrier film

as otherwise too much hydrogen would accumulate on the oxygen side. So they must be very large in order to produce economically relevant quantities of hydrogen. In addition, the gas must then be compressed—which requires a great deal of energy—so that it can be stored and transported.

PEM electrolysis works with higher current densities and under pressure and delivers significantly more hydrogen than an AEL system of the same size. Water is split here under highly acidic conditions. Corrosion-resistant materials must therefore be used—for example precious metals such as iridium. This makes the electrolyzers expensive. The membrane must also be able to withstand the acid. It is usually made of resistant PFAS. However, this group of fluorine compounds has been criticized for years because they accumulate in the environment and are suspected of being potentially harmful to health. This is precisely where DURAION®'s market opportunity lies, as no PFAS are added when the membrane is manufactured. The membrane is therefore an efficient alternative that already offers electrolyzer manufacturers planning security with respect to future environmental regulations.

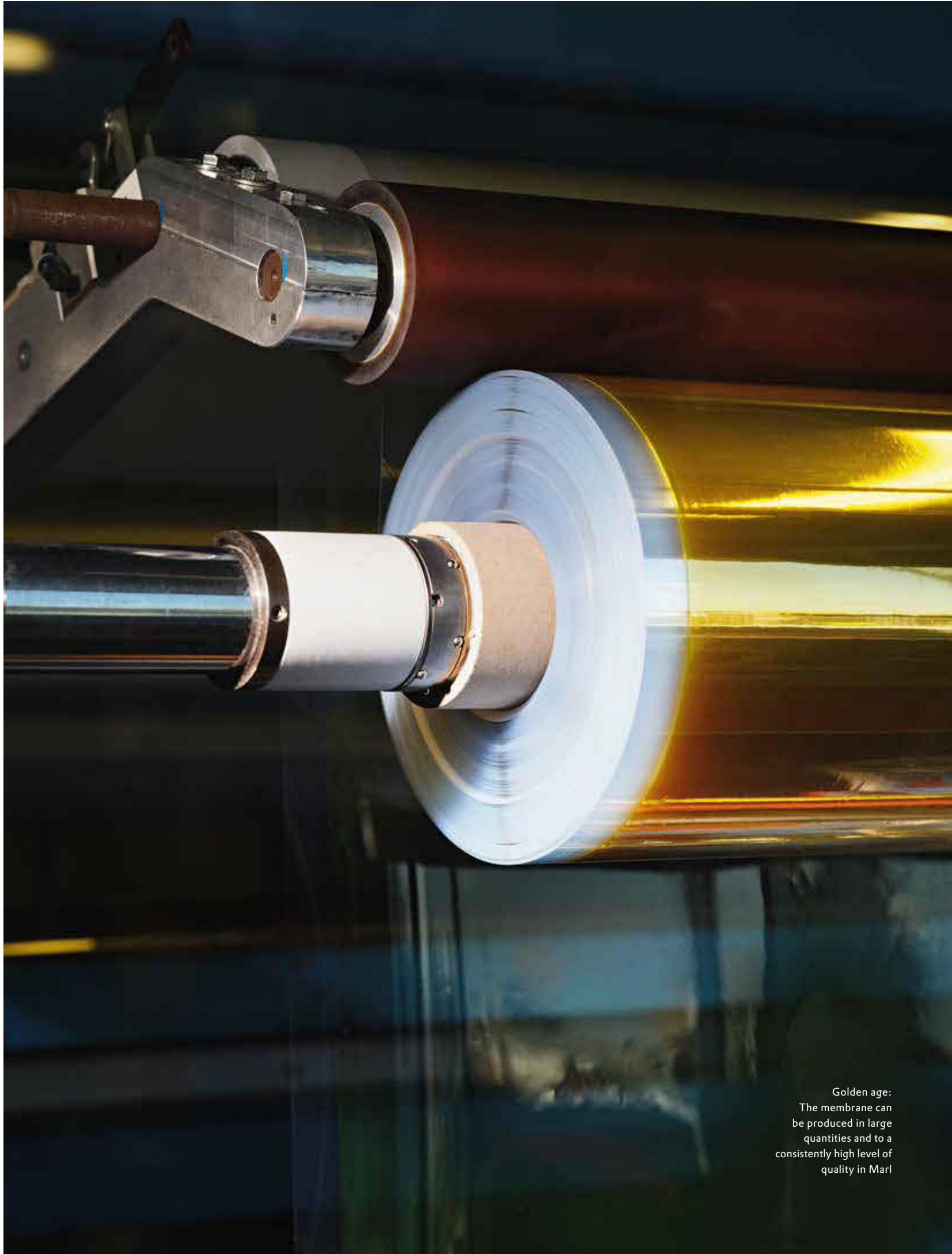
THE BEST OF BOTH WORLDS

AEM technology avoids the disadvantages of AEL and PEM. It works with higher current densities and under

pressure, thus delivering a high hydrogen yield. In addition, the membrane works in an alkaline environment, not in an acidic one. Precious metals are therefore not required for cell design or for use as catalysts; less expensive metals such as nickel can be used instead. The investment costs for AEM technology are thus lower—an important factor for large-scale applications such as those that are being planned in China.

In addition, AEM electrolyzers can be started up more quickly than AEL systems, for example. The technology is therefore very well suited for cushioning the fluctuating supply of solar and wind energy. If there is a lot of electricity available on a sunny and windy day, AEM electrolyzers can ramp up their output at short notice and produce hydrogen. Up until now, the surplus has been diverted to neighboring countries via the European power grid, or power plants have actually been shut down. The resulting compensation and grid congestion costs are borne by the grid operators and ultimately the electricity customers. “We could instead use the surplus electricity to produce hydrogen at virtually zero cost,” says Christian Schnitzer, who is responsible for DURAION® at the High Performance Polymers business line.

Despite these advantages, AEM remains more of a niche technology. Until now, there has been a lack of efficient and reliable membranes that can be produced in large quantities. Various start-ups have launched →



Golden age:
The membrane can
be produced in large
quantities and to a
consistently high level of
quality in Marl



“Evonik has a lot of expertise with membranes”

CHRISTIAN SCHNITZER,
BUSINESS MANAGER FOR DURAION®
AT HIGH PERFORMANCE POLYMERS

a number of anion-conducting membranes on the market in recent years. So far, however, no one has been able to supply membranes in the consistent quality and sufficient quantities that would enable a breakthrough for AEM technology. Thanks to its complete backward integration—from the starting molecules to the finished membrane roll—Evonik can meet both requirements with DURAION®. With the plant now in operation, the membrane is available on a large scale. “With our coating width of 100 centimeters, we will be able to supply even the largest AEM electrolyzers with membranes,” says Schnitzer.

Following initial tests, customers praised the overall package of availability, quality, and properties of the membranes, which are chemically and mechanically stable as well as very good anion conductors. They are also gas-tight, which means they can withstand high pressures.

The road to series production of the high-performance membrane was a long one. “The idea came about more than ten years ago, when we made the decision to focus on hydrogen,” says Schnitzer. “Evonik has a lot of expertise with regard to membranes, for example in

products for the treatment of gases. So it made sense to also address electrolysis.” The team began by developing the polymer. It was clear that the material had to fulfill many requirements, and the right building blocks—the monomers—also had to be found. The chemical structure of DURAION® was established around five years ago. “Back then, we were already testing the properties of the developed polymer in membrane form,” says Däschlein. Two years later, the team also developed a version with fabric reinforcement in order to meet all customer requirements. “In the beginning, we manufactured both products by hand as films in approximately A4 format,” Däschlein explains.

The next step was the scale-up—the step from laboratory scale to bulk production—in this case of both the polymer solution and the membranes. There is a huge difference between producing 100 grams of a polymer in a small glass flask in the laboratory and producing hundreds of kilos in a large vessel. The components are quickly mixed in the laboratory flask and the heat is distributed evenly. In a large vessel, uniform mixing and heating become a challenge. “Fortunately, we have the necessary expertise in-house—everything from basic chemistry to plant construction,” says Däschlein. “For the scale-up, we brought together specialists from various locations.”

GROWING STEP BY STEP

However, it still took some time before roll-to-roll production in the 20-meter unit became possible. The team approached the big solution slowly. Initially, the experts produced 13-cm-wide membranes on a laboratory system the size of a living room wall unit. This allowed them to test how well the polymer can be produced in a con- →



Production Manager
Florian Roghmans and
Marketing Manager
Franziska van Krüchten
monitor membrane pro-
duction in the coating
plant

tinuous process in order to perfectly match the machine and material. About three years ago, Roghmans and his team started planning the next expansion stage: “We then had an idea of how the membrane could be produced roll-to-roll, but a large system is something completely different,” he says. “For example, the air flow and heat are distributed very differently than in a small system.”

MARL MEETS SHANGHAI

Evonik’s new application technology center starts operations in China

Demand for hydrogen is growing in China—and with it interest in AEM technology. Evonik is positioning itself strategically here. Parallel to the start of membrane production in Germany, the new AEM Center Shanghai has commenced operations in China. This is the company’s first technology-oriented application technology center in Asia with a focus on AEM electrolysis and its integration into the hydrogen infrastructure. Experts there test the membranes produced in Marl together with local partners and customers under real operating conditions. The center is aimed at global customers and is also closely linked to the Chinese market—with the goal of quickly transferring AEM technology to industrial applications and promoting its dissemination.

In addition, it had to be possible to combine the liquid polymer layer with a thin reinforcing fabric. This fabric ensures that the membranes swell less during operations in the electrolyzer and therefore do not wrinkle the way human skin does after a long bath. Ion-conducting polymers absorb water, which means that they expand by 10 to 20 percent in a wet environment. If a water-repellent fabric is embedded in the polymer, it reduces water absorption and prevents the membrane from creating waves in the electrolyzer. “This is primarily an issue with large electrolyzers in which the membranes installed occupy a large area,” Roghmans explains. The plant in Marl therefore had to be able to position the reinforcing fabric precisely in the polymer so that it is embedded exactly in the middle of the wafer-thin honey layer and does not protrude from the top or bottom of the membrane. To do this, the system unwinds the carrier film and the fabric from two rolls at the same time. At the point where the fabric and the coated web meet—the lamination point—it is pressed into the polymer solution.

LARGE-SCALE PRODUCTION.

The pilot plant began operating recently. “This is no longer a research unit, but instead the actual starting point for bringing our product to market,” says Däschlein. “In the current expansion stage, we are able to produce membranes for an electrolysis capacity of up to 2.5 gigawatts.” This corresponds to a quarter of Germany’s planned electrolysis capacity for the year 2030. The first manufacturers of AEM electrolyzers are already using DURAION® membranes in pilot production and demonstration plants. “We



The interplay between materials science and polymer chemistry is crucial in the production of DURAION®—for example with regard to the precise embedding of the fabric reinforcement in the polymer solution

can now supply not only large quantities but also consistently high quality,” says Däschlein. This is the be-all and end-all for manufacturers of electrolyzers.

The DURAION® membrane, and with it AEM technology, could bring new momentum to hydrogen production. The technology is reliable and robust, reduces investment costs for electrolyzers, and can now be brought to market on a large scale thanks to roll-to-roll mass production. The expansion targets in Germany and Europe have been set high in recent years. For example, in its update of the National Hydrogen Strategy, the German government set a target of 10 gigawatts of electrolysis capacity for 2030—that corresponds to around 12 percent of the installed wind turbine capacity in Germany. The expansion has stalled, however, and only 7.2 gigawatts are now firmly planned, according to the German Gas and Hydrogen Industry Association. “Numerous electrolysis projects have been postponed or canceled, particularly on the production side, as the funding conditions are inadequate,” says the association’s Managing Director, Timm Kehler. In addition, it is not certain that the hydrogen produced will also be accepted (see the interview with Dr. Ann-Kathrin Klaas starting on p. 32).

Germany and Europe are facing a chicken-and-egg problem, according to Kehler: Does the hydrogen have to be there first, or does the demand? “We need practical and reliable conditions for the production of hydrogen—especially green hydrogen,” says Kehler. “This means that the government has to set a binding target for the expansion of electrolysis, arrange long-term purchase agreements, and ensure competitive electricity prices.” Only then would companies have the investment security they need, and only then could the ramp-up be accelerated. The DURAION® membrane could make a significant contribution to this process. After all, it has the potential to make electrolysis more cost-efficient than before. In addition, Evonik is a reliable supplier of AEM technology.

The hydrogen market currently displays a much greater degree of momentum in China. While regulatory barriers are still being debated in Europe, hydrogen is already firmly anchored in the national strategy in China. The dynamics there are not a distant scenario for Evonik, but instead a direct business development: AEM electrolyzers are already widely used in Asia and the demand for high-performance membranes is enormous. “The technology is already being scaled up to industrial proportions there,” Schnitzer reports. Asia is therefore an interesting market for the membranes from Marl.

Schnitzer is optimistic that hydrogen will prevail, sooner or later, initially in Asia and Europe—and its use will expand accordingly: “When this becomes the case, we will be there to produce large quantities of membranes—at an attractive price.” —



Tim Schröder is a science journalist who lives in Oldenburg



“We need more planning security”

The market for green hydrogen is developing more slowly than expected in Germany and Europe. Dr.-Ing. Ann-Kathrin Klaas from the Institute of Energy Economics at the University of Cologne explains how government regulation and innovative technology can help ensure things pick up speed again

INTERVIEW TIM SCHRÖDER

Ms. Klaas, in its hydrogen strategy, the previous German government set itself the goal of establishing a domestic electrolysis capacity of 10 gigawatts by 2030. In a recent study, you came to the conclusion that this goal is unlikely to be achieved—why?

Because many announced projects will probably not be realized by then. At the end of 2025, electrolyzers with a total capacity of just under 200 megawatts were in operation in Germany. This corresponds to the installed capacity of around 80 wind turbines. There are also currently 22 projects with a total of 1.3 gigawatts for which companies have already made the final financing decisions. These projects are to be realized within two years, so that we will end up with around 1.5 gigawatts nationwide in 2027. The financing decisions on other, larger projects will soon be taken. However, people are now hesitant due to the uncertainty about whether the hydrogen produced will actually find buyers. We're talking here about several projects of 100 megawatts each, many of them in northern Germany. If these are not implemented, the ramp-up of hydrogen power in Germany is likely to take considerably longer than was previously assumed.

Is this concern about hesitant demand for green hydrogen justified?

Green hydrogen is currently still much more expensive than expected. Forecasts and studies previously assumed that production costs would fall to €2 to €3 per kilogram in the long term. Our current analyses show that

we could be at around €5 to €6 per kilogram in 2030. Costs for storage and transport must be added to this. In the long term, the production costs for green hydrogen could fall to €3 to €4 per kilogram, which is still a lot. The operators of the electrolyzers cannot conclude offtake agreements—and hardly any electrolyzer projects will be launched without such a contract.

How did this discrepancy come about?

A few years ago there was a lot of hydrogen hype. However, the market has developed much more slowly than expected. In the beginning, the costs of building large electrolyzers were simply underestimated, especially in terms of the ancillary costs—the connections to the electricity and hydrogen grids, and all the engineering involved. If you add it all up, the current investment costs for an electrolyzer are around €2,000 per kilowatt.

Could new efficient electrolysis technologies help reduce the price of hydrogen?

You need to distinguish between the investment costs for the electrolyzer and the total production costs for the hydrogen. The investment accounts for around half of the hydrogen price. New, efficient technologies and innovations can certainly lead to savings here, but the other half is the cost of the green electricity needed for the electrolysis.

Can the government exert any influence to accelerate the ramp-up of electrolysis?

Yes, above all by ensuring more planning security. Many project developers see the current debate on electricity grid charges as a real stumbling block. At the moment, electrolyzers that will go into operation before mid-2029 are exempt from grid charges. As things stand today, →



“We will not achieve climate neutrality in Europe without green hydrogen”



Expensive project: Experts have calculated that the installation of an electrolyzer costs around €2,000 per kilowatt of power (above). Building transport infrastructure with pipelines and tankers is also expensive (middle). These costs must fall if green hydrogen is to become attractive to consumers—with regard to mobility as well

conventional grid charges will then be paid for all systems that go into operation after then. That could mean additional costs of up to 20 percent. A reform of electricity grid charges is currently under discussion. There are also discussions about continuing the electrolyzer exemption from charges after mid-2029. Everything is still open, which is why there is a great deal of uncertainty on the market. This state of affairs with the electrolyzers also shows that politicians had expected the hydrogen market to ramp up much more quickly, and they then intervened with regulations. From the viewpoint of the project developers, an exemption beyond 2029 would make sense.

Are these difficulties a purely German phenomenon?

We have a total of around 600 megawatts of electrolysis in operation in the EU. With almost 200 megawatts, Germany has the largest share. In addition, electrolyzers are currently in operation in Denmark, Spain and Norway in particular. There are various initiatives to build Europe-wide, cross-border infrastructure—for example the European Hydrogen Backbone. The German gas transmission system operators have entered into many cooperative ventures with all the surrounding countries. However, the hydrogen ramp-up in other European countries is basically at the same point as in Germany and is also facing similar problems.

And these would be?

The European RFNBO criteria are currently the main obstacle. The abbreviation stands for Renewable Fuels of Non-Biological Origin. There are strict requirements for the purchase of electricity for electrolyzers here. Operators are only allowed to produce if they enter into a direct contract with a renewable energy facility such as a wind

farm—a so-called power purchase agreement, or PPA for short. Furthermore, the electrolyzer may only consume as much electricity per month as the energy facility in question generates. This “monthly simultaneity” is to be tightened to hourly simultaneity starting in 2030. This makes the operation of an electrolyzer inflexible because it is very closely tied to the availability of electricity over time. Today, an electrolyzer cannot participate directly in the electricity market, but is instead bound by direct contracts. Here, too, a rapid hydrogen ramp-up was expected and the aim was to regulate the market. This is now proving to be an obstacle.

What else can be done to accelerate the ramp-up of electrolysis capacity and the hydrogen economy?

Basically I believe there are three approaches: Firstly, you can try to reduce costs on the production side, for example through innovation. Secondly, you can try to increase the willingness to pay on the demand side. This could be achieved by making fossil fuels more expensive—for example through CO₂ pricing. However, in the current tight energy market, this would increase the pressure on industry even further and could lead to energy-intensive production being relocated abroad.

And the third approach?

Coupling hydrogen producers and consumers via intermediaries—so-called midstreamers. These traders bundle supply and demand and thus aggregate larger quantities. This is already the case in the electricity and gas markets. In the future, this bundling can lead to savings through economies of scale, as large quantities of hydrogen will be traded, stored, and transported. There is currently talk of providing regulatory financial support via the midstreamers. H2Global offers a good example of such a stakeholder in the hydrogen market. This foundation coordinates auctions for the import of green hydrogen on behalf of the German government. One auction round was won by a project in Egypt, where green ammonia is produced. Ammonia can be used to chemically store and transport hydrogen. Deliveries of the green ammonia to Germany are scheduled to begin in 2027. The project is being subsidized with funds provided by the German government. These funds are managed by the midstreamer that organizes the auction.



Dr.-Ing. Ann-Kathrin Klaas is an expert for energy systems technology at the Institute of Energy Economics at the University of Cologne (EWI), where she heads the Energy Commodities research area. She is responsible for topics relating to the hydrogen and natural gas economy and the heating transition. Her focus is on techno-economic analyses, the natural gas and heating sector, and the hydrogen market. Klaas completed her doctorate at the Institute of Electrical Power Engineering and Energy Systems at Clausthal University of Technology with a dissertation on the subject of hydrogen storage

How will the hydrogen market, and with it electrolysis, develop in the coming years?

All current climate neutrality studies show that we will not achieve climate neutrality in Germany and Europe without green hydrogen. There are industries and production processes that rely on hydrogen as a green energy source—for example the steel industry. Until now, steel-makers have smelted metal ores using coking coal in blast furnaces. In the future, direct reduction furnaces using hydrogen will provide a climate-neutral alternative. At the moment, however, the high cost of hydrogen production means this is often not an economical option. Changing this situation will require an extensive package of measures. Targeted government funding could also accelerate the ramp-up. Steel manufacturers in Germany, for example, receive a subsidy to support investment in new facilities such as direct reduction furnaces. However, it's also clear that every subsidy must have a fixed term because the government cannot afford to provide subsidies indefinitely. —



CRACKED PLASTIC



More plastic is to be recycled worldwide. Pyrolysis, which is the liquefaction of plastic waste, creates new possibilities here. Evonik offers additives and technologies that improve the quality of pyrolysis oil in a manner that makes it suitable for the production of polymers

TEXT **KARL HÜBNER**



Chemical recycling in operation: The Arcus Greencycling pyrolysis plant in Frankfurt's Höchst district

Plastics have played a role at Frankfurt's Industriepark Höchst for almost 100 years. The Hoechst company began producing polyvinyl acetate here in 1928. Later, polyethylene (PE) was added, a polymer that is still found in many different forms in every household today.

Up until recently, the plastics industry did not pay much attention to the circular economy. Industriepark Höchst is one of the places where you can see how this is changing. Trucks regularly drive up to Arcus Greencycling Technologies, which has been based here since 2021, and unload big bags containing compressed plastic waste. "This is our raw material," explains Daniel Odenthal, the Managing Director of Arcus Greencycling Technologies. The shreds in the bags include material unsuitable for mechanical recycling that has been disposed of in the standard yellow containers that German house-

holds use for recyclable trash. But Arcus is also happy to accept industrial waste such as used films from agriculture or production waste.

In Germany, however, most of this waste has thus far ended up in incinerators. Elsewhere it is also sent to landfills. Arcus wants to recycle these materials so that other companies can use them to manufacture new plastics, which would make an important contribution to the circular economy. For this type of processing to succeed, the quality of the intermediate products must be assured—and this is where Evonik is playing an important role.

The recycling rates for plastic are still very low. Of the 431 million tons of plastic produced worldwide in 2024, not even one tenth came from recycled material. Moreover, the quantities of plastic waste are vast. In 2022, for example, almost 270 million tons of plastic waste was produced worldwide, and a good ten percent of that in the



The plastic pellets for pyrolysis are delivered in flexible intermediate bulk containers (FIBC), known as big bags. To ensure consistently high quality, employees constantly adapt individual processes and systems



EU. Only slightly less than 38 million tons of this waste was recycled globally. By contrast, 90 million tons were thermally recycled—i.e. burned to generate energy—and a little more than 103 million tons ended up in landfills. Only few kinds of plastic are collected and returned by type. Beverage bottles made of polyethylene terephthalate (PET) are one of the rare exceptions. The recycling system here is quite successful at keeping this material in circulation by cleaning, shredding, and melting old bottles and then using them to make new ones. Experts use the term mechanical recycling when the material in question remains chemically unchanged throughout the recycling process.

CHEMICAL HODGEPODGE

Chemical recycling is used for the large remaining amount of mixed plastic waste that is unsuitable for mechanical recycling. In this process, the polymers are broken down into constituents from which new plastics can be obtained.

So far, this technology has hardly played a role in terms of volume, but companies like Arcus want to change that. To do this, they have to deal with colorful plastic mixtures that contain not only various classes of polymers, but also additives such as dyes, stabilizers, plasticizers, and flame retardants. Impurities and met-

als or paper from caps and labels are also part of the mix. It's a chemical hodgepodge—and completely unsuitable for mechanical recycling.

At Arcus, these mixtures are treated with nitrogen and then transported via a suction hose into the pyrolysis furnace, which is the heart of the system. Here, the shredded used polymer mixture is heated to several hundred degrees Celsius in the absence of air. Due to the lack of oxygen, the long molecular chains are broken down into smaller building blocks without being burned. The result of the pyrolysis is a mixture of hydrocarbons in gaseous, liquid, and solid forms, depending on their chain lengths.

The liquid—pyrolysis oil—is the largest of these fractions and is an important intermediate product in chemical recycling. “Depending on the feedstock, we get around 600 to 650 kilograms of oil from one ton of waste,” says Dr. Marco Tomasi Morgano, the Technical Director (CTO) of Arcus. The company earns its →

NOT JUST A QUESTION OF TECHNICAL FEASIBILITY

The role that pyrolysis oils from plastic waste can play in the production of new plastics in the future is not just dependent on purity and technical feasibility. The political environment is also a factor here and can provide incentives to promote chemical recycling—or not. It therefore makes sense to take a look at the EU, the United States, and China, which together account for around three quarters of global steam cracker capacity



In the **United States** the individual states have different requirements for the reuse of plastics. States such as California and New York, for example, have severely restricted the use of disposable cutlery and food containers, which creates incentives for degradable or recyclable alternatives. There is currently still a debate in the United States as to whether pyrolysis should be classified as a recycling technology. To date, pyrolysis oil from plastic waste has been used almost exclusively as a fuel. Regardless of legislation, however, companies are increasingly committing themselves to greater sustainability. This in turn promotes approaches relating to the circular economy.



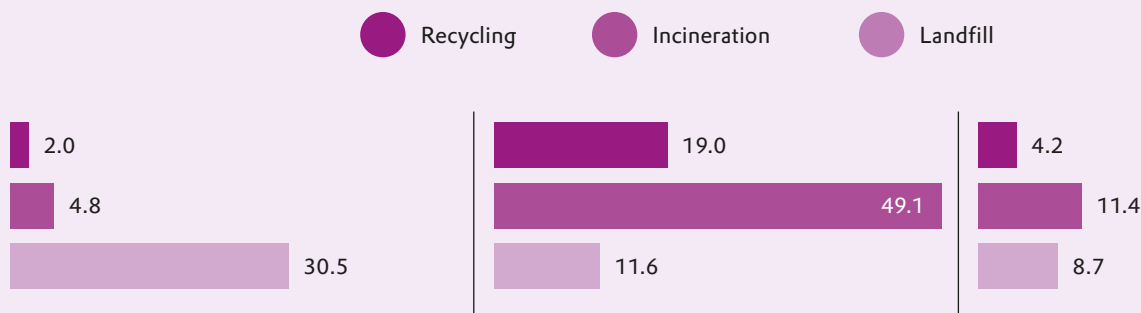
In **China** the current five-year plan (2026–30) is also driving the transition to more environmentally friendly production and lifestyles. CO₂ emissions are to be reduced by 2030 at the latest, and Beijing wants to be greenhouse gas neutral by 2060. So far, there have only been a few specific stipulations regarding recycling percentages in production. Films used in agriculture, for example, now have to consist of 85 percent recycled materials. Sorting and collection systems are only now being set up. In addition, certain companies are increasingly incorporating sustainability targets into their strategy. PetroChina, for example, which is the country's largest oil company, wants to at least partially replace fossil raw materials in polymer production with recycled materials. Europe is an important export region for China. Experts therefore expect that the stricter EU regulation of recycle content in new products could also stimulate recycling in China.



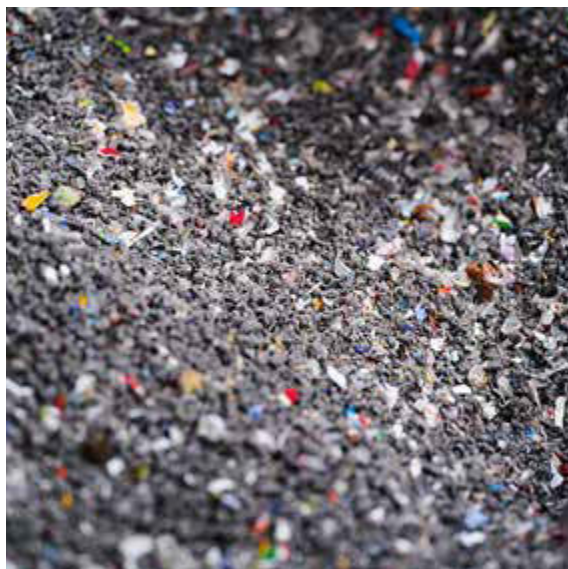
In the **EU** there are initial specific targets for plastic recycling rates in some sectors. Starting in 2030, 25 percent of the plastic components used in new cars must be made from recycled materials, and at least a quarter of these recycled materials must come from old car parts. Starting in 2030, packaging should contain between ten and 35 percent recycle—and from 2040 on 25 to 65 percent. Similar requirements are planned for synthetic fibers for textiles. These targets cannot be achieved through mechanical recycling alone. Chemical recycling, including the pyrolysis of plastic waste, will therefore become increasingly important.

Where to put the plastic waste?

Waste recycling streams 2022, in million of tons



Source: Communications Earth & Environment 6/2025



The starting material for pyrolysis consists of materials that are difficult to recycle, such as packaging film. These materials are delivered in shredded form and fed into the system using a suction device



“We get 600 to 650 kilograms of oil from one ton of waste”

MARCO TOMASI MORGANO, CTO AT ARCUS



money with this black liquid, which is purchased by operators of steam crackers, who use it to replace part of their crude oil-based raw material.

Steam crackers are used to produce feedstocks such as ethylene and propylene that are needed to synthesize new plastics. These substances not only form the building blocks of polyethylene and polypropylene (PP); they are also used in the production of many other polymers, such as polyvinyl chloride (PVC) and polystyrene (PS). The oil from the shreds of old yogurt containers or soap dispensers thus provides the raw material for new yogurt containers and soap dispensers.

Steam crackers are normally operated with naphtha, a specific fraction that comes from crude oil refining. In principle, steam crackers can also process pyrolysis oil. However, the oil requires pre-treatment. This is because mixed plastic waste does not consist of pure hydrocarbons. If the waste contains PVC, for example, the oil will also contain chlorine. Nitrogen, in turn, can be introduced via polyamides, polyurethanes or ABS copolymers. Polycarbonates and polyesters bring oxygen bring oxygen and silicones silicon. Plastic waste also contains impurities such as food waste.

SMALL AMOUNTS, BIG PROBLEMS

“The three main problems in pyrolysis oil are chlorine, nitrogen, and oxygen,” says Tomasi Morgano. These can cause corrosion or poison the catalyst in the steam cracker, which is why the operators set strict specifications for the quality of the pyrolysis oil fed in. “The limit for chlorine is generally a maximum of tens of ppm,” says Morgano. The abbreviation ppm stands for parts per million, so five ppm is just 0.0005 percent. Some of the waste delivered to Arcus contains more than one →



The result of pyrolysis is an oil that can be used in the synthesis of plastic polymers

percent chlorine by mass. As some of the impurities are deposited in the solid fraction during pyrolysis, oil from the Arcus facility still has a chlorine content in the double-digit ppm range. Steam cracker operators can handle this at present. That's because up until now, they have only added small amounts of pyrolysis oil to their regular raw material—naphtha—so that the chlorine and other accompanying substances are sufficiently diluted.

Things are unlikely to stay this way, however. The chemical recycling of plastics is likely to become even more important as the political environment increasingly demands a shift away from fossil raw materials (see box on p. 40). Many companies also want to be able to advertise that their products boast a high amount of recycled content. A company that sells its shampoo in a plastic bottle made with polypropylene containing 20 percent pyrolyzed plastic waste can use this figure to promote the product.

That's why Hendrik Rasch also expects pyrolysis oil to become increasingly available. Rasch is VP Circular Packaging & Plastic Recycling of the Global Next Markets Program at Evonik, and in this capacity he deals with recycling strategies for the plastics industry. "Many



“It costs millions of euros per day when a steam cracker has to shut down”

HENDRICK RASCH, VP CIRCULAR PACKAGING & PLASTIC RECYCLING AT EVONIK

new pyrolysis plants are currently being built around the world,” says Rasch. This will also increase the incentive for steam cracker operators to mix in larger quantities of pyrolysis oil from plastic waste.

However, new technical solutions are needed because the impurities pose a risk for the operators. “It costs millions of euros per day when a steam cracker has to shut down,” Rasch explains. The aim is therefore to remove unwanted impurities from pyrolysis oils. “We have developed products for exactly this purpose,” says Rasch.

By “we,” he primarily means an Evonik team in the city of Little Rock, almost 8,000 kilometers away. Colleagues in the capital of the U.S. state of Arkansas have been working on catalysts and adsorption materials for many years. “Pyrolysis processes are in vogue, so a few years ago we asked ourselves whether we could use our expertise to provide something for the treatment



The Evonik site in Little Rock, Arkansas, specializes in reprocessing spent catalysts so that they can be reused



In drums like these, catalytically active metals are distributed on an adsorption material that can separate undesirable substances from the starting material and bind them

of pyrolysis oils,” recalls Dan Miskin, Evonik chemical engineer in Little Rock. “A survey of pyrolysis operators then showed that chlorine contamination is their biggest problem.”

Products that separate chlorine compounds from liquids or gas streams have been around for a long time. Evonik also has its own product line for this—CHLOROCCEL™. However, the chlorine in pyrolysis oils is organically bound, and this is where conventional chlorine scavengers reach their limits.

TWO PROCESS STEPS IN ONE

To address this market need, the Evonik team first delved deep into the history of chlorine adsorbents. “We wanted to understand how they were originally designed so that we could then further develop them in a suitable way,” Miskin explains. Several years and many series of tests later, this is exactly what has been achieved. At the beginning of 2025, Evonik launched three types of chlorine adsorbent in its Purocel™ product line specifically for the purification of pyrolysis oils. Purocel™ 505 stands out among them. Evonik’s developers designed it in such a

way that it combines two separate process steps. “First the material catalyzes the removal of hydrogen chloride from the organic molecules,” says Miskin, “and then this HCl is captured directly.” According to Miskin, it is important to enable the second step to take place there and then, as the reactive HCl could otherwise form organochlorides again. Then nothing would be gained.

“Test series have shown that Purocel™ 505 extracts three times as much chlorine from pyrolysis oils as conventional products,” says Hendrik Rasch. It is supplemented in the Evonik portfolio by Purocel™ 510 and 515. Which type a user chooses depends on the respective requirements. Purocel™ 510 is not as powerful as 505 when it comes to chlorine, but it also removes other impurities such as silicon, nitrogen, phosphorus or any acids from the oil. In addition, the product can be used at room temperature and can be regenerated—and thus reused—by heating it intensively. →



The production process in Little Rock is continuously monitored and product quality is ensured by taking samples

Steam cracker operators on several continents are already testing the new products on pyrolysis oils. According to Rasch, there is also a complete package for Purocel™ 510. “That’s where we offer our Rocket technology. This consists of customized and preconfigured column modules with the adsorbent, which we supply together with pumps and complete process control systems.” Similar solutions from Evonik are already being used in oil refining, for example to eliminate odor and color problems.

For example, users can connect a Rocket unit to the outlet of a pyrolysis reactor or immediately upstream of the inlet of a steam cracker. Thanks to the pre-configuration, customers don’t have to do much. Rasch calls this “convenient plug-and-play technology.” The Rocket columns heat up Purocel™ 510 at regular intervals in order to regenerate it.

A SECOND LIFE FOR CATALYSTS

The new Purocel™ types and the Rocket unit are also finding favor at Arcus in Frankfurt. However, the company does not currently want to purify the pyrolysis oils itself. This makes more sense and is more economical when larger quantities are involved, i.e. at the steam cracker operators. Managing Director Odenthal sees Evonik products as nothing less than “a success factor for making non-fossil raw materials available for the existing petrochemical infrastructure”—and thus increasing the quantities of pyrolysis oil used there. “Today’s steam



The adsorbents are white when freshly manufactured. They will turn gray during their use purifying pyrolysis oil

crackers have been optimized over decades,” says Odenthal, “but they’ve been optimized for the conventional fossil types of naphtha. Pyrolysis oils will only become even more widely accepted if we succeed in matching them as closely as possible to these standardized types.”

In traditional petrochemistry, there is another process that could complement the adsorption process in connection with the purification of pyrolysis oils: Hydro-treating. This process involves adding hydrogen, which then reacts with impurities containing chlorine, nitrogen or oxygen to form volatile compounds. Evonik’s experts in Little Rock have developed metal catalysts for this technology, and these are now marketed in the “Purocel™ H” series.

Unlike other catalysts on the market, these are recycled products. Evonik uses a specially developed technology to regenerate catalysts that have become weak with age. The resulting catalysts are in no way inferior to new materials in terms of performance. Users who rely on these types of Purocel™-H not only save money

Samples from crude oil products: The Little Rock location benefits from years of cooperation with the petroleum industry



“Chlorine contamination is the biggest problem for pyrolysis operators”

DAN MISKIN,
CHEMICAL ENGINEER AT EVONIK

compared to newly manufactured catalysts; they also improve their CO₂ footprint by reusing them.

With the new Purocel™ and Purocel™-H products, Evonik has further expanded its range of additives for the petrochemical industry. That industry has long known and used other additives from Evonik, such as the pour point depressants from the VISCOPLEX® brand. These are products that system operators use to keep oils liquid by preventing crystallization so that the oils remain pumpable even at low temperatures. Arcus in Frankfurt also uses VISCOPLEX® to keep the waxes that are produced during pyrolysis free-flowing. Evonik has brought together other additives, especially for cracker operators, in the product range known as SiYPro™. The abbreviation stands for “Simplify Your Process”—and that says it all because the purpose of each of these products is to counteract disruptive effects in the cracking process.

Everything is therefore in place to use pyrolysis oils made from plastic waste in order to ensure that more plastic remains in the cycle. The potential here would be

huge: Theoretically, around 120 million tons of pyrolysis oil could be extracted from the more than 200 million tons of plastic waste that was incinerated or sent to landfills worldwide in 2022. However, the capacity for processing such quantities is not yet available. Arcus, for example, currently processes just 4,000 tons a year, but is planning to build a plant with six times this capacity.

For the time being, most steam cracker operators will only add pyrolysis oil to their naphtha. However, Hendrik Rasch believes there is a good chance that the proportion will continue to rise: “I think that ten percent oil is conceivable in the medium term.” Evonik products will then ensure that traces of chlorine, nitrogen, oxygen or silicon do not spoil the process here. —



Karl Hübner has a doctorate in chemistry and is a journalist. He works as a freelance author and frequently writes about research topics

Another time around

When plastics are chemically recycled, the quality of the resulting pyrolysis oil is what counts. The purer the product, the more options there are for further processing. That's how the cycle works

PYROLYSIS

The plastic polymers in the **waste mix ①** are processed into smaller molecules at 400 to 550 degrees Celsius in a **pyrolysis reactor**. Most of the decomposition products are initially gaseous. Some of them then condense into **pyrolysis oil, ②** and some are used as gases to heat the pyrolysis furnace. Any resulting **solids ③** are discharged.

INFOGRAPHIC MAXIMILIAN NERTINGER

PREPARATION

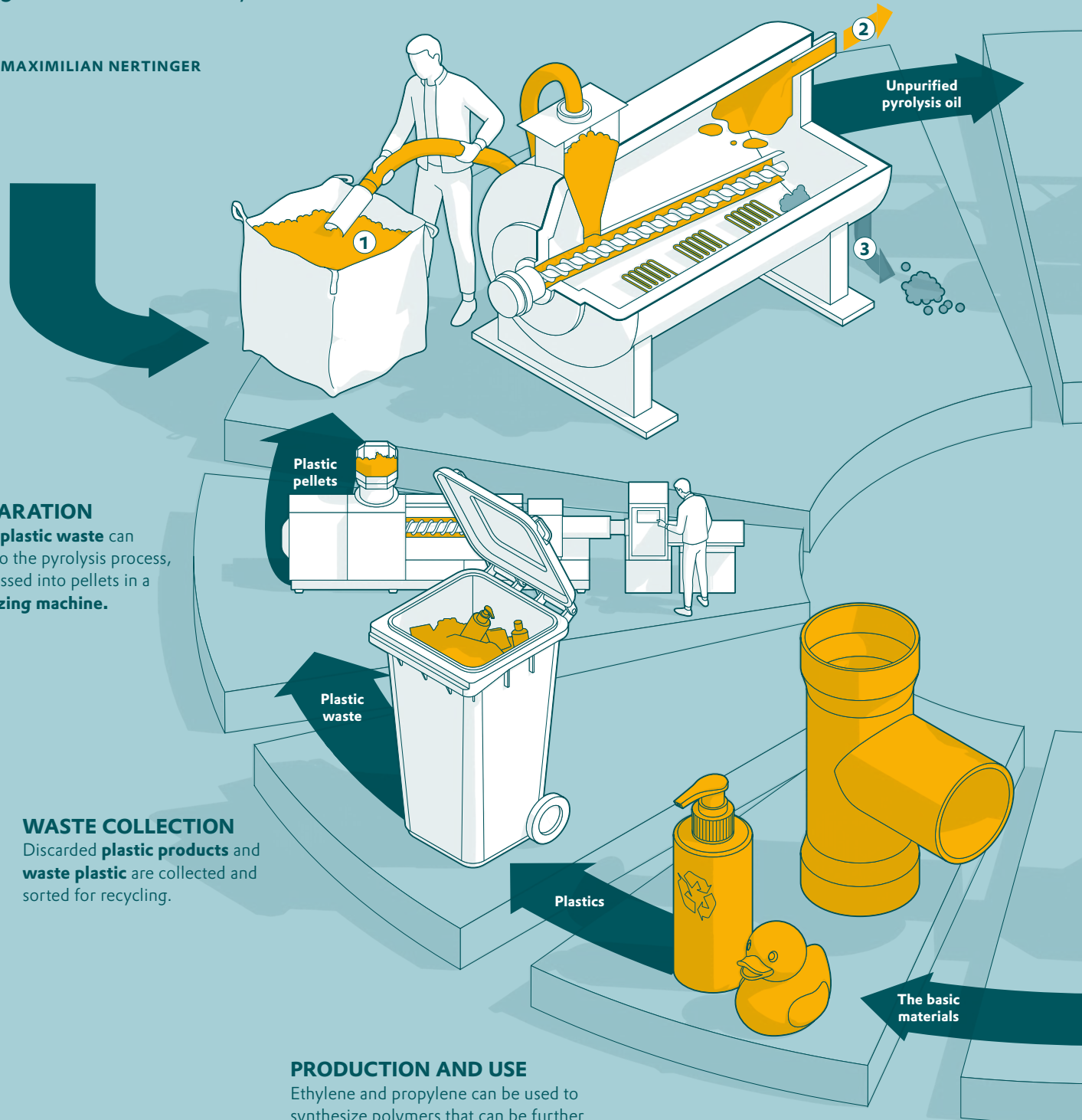
Before **plastic waste** can undergo the pyrolysis process, it is pressed into pellets in a **pelletizing machine**.

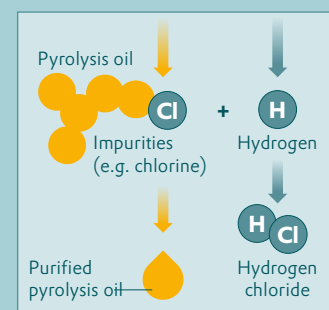
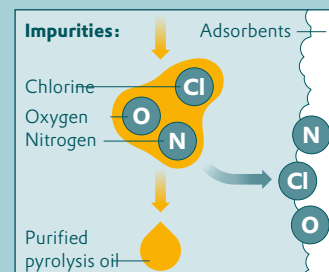
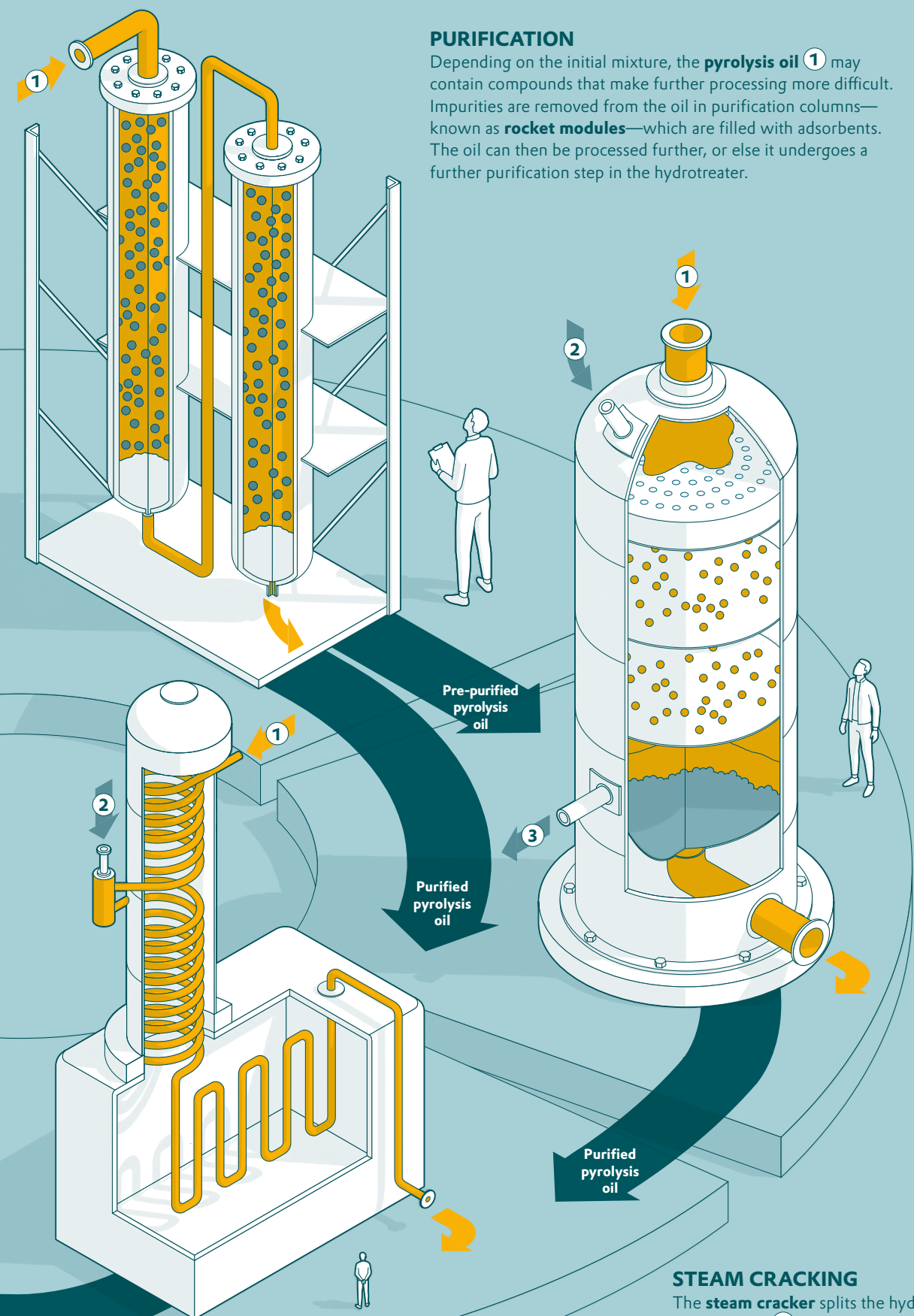
WASTE COLLECTION

Discarded **plastic products** and **waste plastic** are collected and sorted for recycling.

PRODUCTION AND USE

Ethylene and propylene can be used to synthesize polymers that can be further processed into **plastic products**.







LIKE A NEW PERSON

Medicine may be on the verge of a new era. In the future, instead of treating diseases in the traditional way, doctors might be able to rejuvenate their patients: first cells and organs—and later, perhaps, the entire person. Will the Fountain of Youth become a reality?

TEXT BJÖRN THEIS

The clinical trial, which was approved by the U.S. Food and Drug Administration (FDA) earlier this year, could spark nothing less than a medical revolution. The Life Biosciences company has been granted permission to test a gene therapy that could halt the aging process in certain cells on human subjects. The drug ER-100 is designed to rejuvenate aged cells in the optic nerve. The goal is to reverse the previously irreversible loss of vision caused by glaucoma or by what is known as an “ocular infarction” (non-arteritic anterior ischemic optic neuropathy), thereby making it curable. What both diseases have in common is that they are caused by age-related cell damage.

One of the co-founders of Life Biosciences is Harvard professor David Sinclair. A biochemist and molecular geneticist, he is considered one of the most renowned researchers in the field of aging processes. For years, he has been drawing attention with bold statements about the future of gerontology—most recently at the World Governments Summit (WGS) in Dubai. There, Sinclair not only announced the clinical trial for ER-100, but also predicted that today’s

therapies will seem outdated in ten to twenty years. Instead of curing diseases in the traditional way, medicine will focus on preventing or even reversing aging.

BLIND MONKEYS REGAIN THEIR SIGHT

The gene therapy technology used by Sinclair and his team is known as “partial epigenetic reprogramming.” It is based on the Japanese stem cell biologist Shinya Yamanaka’s discovery in 2006 that four specific proteins—the Yamanaka factors—can revert adult cells to a stem cell-like state. Yamanaka was awarded the Nobel Prize for this work in 2012. This discovery paved the way for numerous stem cell-based therapeutic approaches. Researchers such as David Sinclair have taken a step further and are pursuing this idea: If these factors are activated only briefly and then deactivated again, cells might be rejuvenated without completely reverting to a stem cell state. This approach has proved extremely successful in animal experiments—it was able to restore vision in blind primates.

The initial results of the clinical trial in humans are expected to be available in just a few months. If the results are positive, this could mark the beginning of a new era: an

age of preventive medicine in which diseases are prevented before they even develop. Following the treatment of the optic nerve, Life Biosciences has already planned its next step. This will focus on the liver, followed by other organs—until, eventually, it may be possible to rejuvenate the entire human body.

This is a good reason for Evonik Foresight to take a closer look at this topic as part of the “GameChanger 2035” study. Evonik is already well-positioned for the future of medicine. The company has extensive experience with lipid nanoparticles and nanoparticle processing—key technologies that enable the active ingredients in modern gene therapies to be delivered to their site of action in a targeted, reliable manner and at the correct dosage. In addition, Evonik is already active in the research field of epigenetics. We need to continue building on this lead. —



Björn Theis heads the Foresight department at Evonik’s innovation unit Creavis

The hope for immortality is a central theme of Art Nouveau—as seen in this stained-glass window, which was created in Mainz around 1900



“Tin gives organ pipes their tone”

LOG ENRICO GERHARTH
PHOTOGRAPHY ROBERT EIKELPOTH

It's sometimes jokingly said that organ builders can do everything—but nothing particularly well. That's because our craft is so wide-ranging. Every organ is a work of art in its own right: Architecture and mechanics, structural engineering and acoustics—for an organ to sound good in the end, everything has to come together. For me, it's this diversity that makes my craft so fascinating. And yet there is one material that ultimately matters most: tin. Without this element, an organ would be nothing more than a beautiful machine that produces wind.

An alloy of tin and lead gives the organ pipe its vibrancy and lends it a soft, full-bodied tone. We mix the alloy in a crucible and first cast it into slabs. This results in a crys-

talline structure. For pipes that will be visible, I add more tin to the mixture so they have a nice shine. But beauty isn't everything—too much lead will cause pipes to lose their shape over the years; too much tin will falsify the tone. The right blend is crucial, and from about a hundred alloys, I choose the one that best shapes the tone of each pipe. It all comes down to subtle differences, which is why experience, consistent quality, and precision are essential from the very beginning.

But the secret of success when you're working with tin lies not only in meticulous craftsmanship—it comes down to frequent

repetition and patience. An average church organ contains about 2,500 pipes, every one of them custom-made. I solder them and round them off with a wooden mallet. I cut the tuning slot by hand in exactly the right spot, which gives it its voice. It takes 151 steps to make each pipe. That can feel repetitive and monotonous. And that's why some people prefer to stick with wood or use computer-aided design.

The first time I hear an organ I helped build is a very special moment for me. Its sound bears witness to all the experience and dedication that went into its making. It bears the properties of the metal I cast and the meticulous care that went into every step of the process. The pipes are the heart of every organ—and that's why tin is my element.

Martin Hiltmann is the managing director of Orgelbau Merten in Remagen. With a staff of seven, he designs, builds, and maintains church organs. The pipes, which are the heart of the instrument, have been manufactured in the company's own workshop since it was founded in 2003.

Masthead

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elements.evonik.com

“An ounce of prevention is worth a pound of cure”

With these words, Benjamin Franklin, one of the Founding Fathers of the United States, urged the residents of Philadelphia in 1736 to take greater care in fire prevention.

Prevention is also the key to solving one of humanity's major current problems: antibiotic resistance, which claims hundreds of thousands of lives every year. Evonik is helping to reduce the use of antibiotics in animal husbandry. The probiotic feed additives support the microbial balance in the poultry gut—and thus also benefit human health.